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Is drought the main decline factor at the rear edge of Europe? The case of southern Iberian pine plantations

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ABSTRACT

Drought has been frequently discussed as a trigger for forest decline. Today, large-scale forest decline is observed at the rear edge of Mediterranean forests, with drought identified as the most likely driver. The vulnerability of Mediterranean mountain plantations to regional climatic variations; however, is poorly understood. In this paper, we analyze the impact of biotic and abiotic factors on the growth and vigor of two pine species in drought-prone areas. We assess the main factors influencing crown defoliation and radial growth to develop a predictive model of forest decline risk for pine plantations at the dry edge of the species range. Dendrochronological data were collected on 50 plots for *Pinus nigra* subsp. *salzmanii* and 40 plots for *Pinus sylvestris*. We examined tree size, competition, site characteristics and climate variables related to decline of pine plantations. Correlation and principal component analysis (PCA) were used to identify the correlates of decline with crown condition and growth, separately. Logistic regression and generalized linear models were used to study the relationship between canopy defoliation and growth, respectively, for *P. nigra* and *P. sylvestris*. Explanatory variables were introduced in a stepwise selection. The PCA revealed three main axes, associated with climate, competition and physiographic variables. Those three axes were associated with crown damage and basal area growth, respectively. Probability of crown damage was associated with tree size, competition and climate conditions. *P. sylvestris* was more sensitive than *P. nigra* to summer potential evapotranspiration effects. Also, climate and competition were the two main drivers affecting basal area growth. Unlike crown defoliation, physiography had an important effect. Within each species, there was a divergence between healthy and damaged trees, mainly related to competition factors. On the other hand, growth trends as an independent variable were not included in the crown damage probability model in a stepwise selection. However, declining growth found in trees at higher crown defoliation and drier sites may imply a greater vulnerability to decline, suggesting an enhanced die-off risk. The sharp growth reduction and widespread defoliation in declining pine plantations make their future persistence in xeric sites subject to frequent and severe droughts unlikely under expected warmer and drier conditions in the future.

1. Introduction

Global climate change is expected to cause a progressively increased frequency and severity of mortality rates and episodes of forest dieback (Allen et al., 2010). As the Mediterranean Basin climate is becoming warmer and drier (IPCC, 2007), an increase in drought-induced mortality of pine plantations is expected (Sarris et al., 2010; Sánchez-Salguero et al., 2012). In addition, "rear edge" tree populations (i.e., populations at or near the species range limits) are likely to be particularly sensitive to the effects of increasing aridity and management release (Hampe and Petit, 2005). Rear edge forest mortality and decline processes have been related to stand density and lack of silvicultural practices (Linares et al., 2009, 2010; Camarero et al., 2011). Denser stands normally result in stronger plant competition (Gómez-Aparicio et al., 2011) and "natural" self-thinning processes (Chen et al., 2008), because of the corresponding reduction in soil water availability per unit of basal area (Sabaté et al., 2002). This scenario seems to be particularly relevant in dense pine plantations in the Mediterranean Basin.

The Mediterranean Basin is one of the world regions with the largest proportion of planted forests (e.g., Spain, FAO, 2006). Pines were the tree species most commonly planted due to their fast

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growth rates in open, xeric conditions, promoting rapid canopy closure and eventual facilitation of the establishment of late successional hardwoods (Zavala and Zea, 2004). Lack of post-plantation practices – due to their elevated costs and low timber production – has often resulted in high-density pine stands with limited dynamic succession (Gómez-Aparicio et al., 2011). Moreover, those plantations have shown a high risk of dying under water stress (drought) conditions (Martínez-García, 1999; Galiano et al., 2011).

Tree decline in Mediterranean stands is a complex process that has been attributed to a wide range of potential causes, often involving prior droughts that initiate a growth decline and a lengthy chain of interacting events (Camarero et al., 2004; Das et al., 2007; Galiano et al., 2010). A multi-factor, sequential decline hypothesis has commonly been considered to describe and explain this process (Manion, 1991): (1) "predisposing factors" expose plants to long-term stress (e.g., poor soil conditions and/or high stand density, Vilá-Cabrera et al., 2011); these predisposing factors increase the susceptibility of trees to (2) severe short-term stresses, known as "inciting factors" (e.g., an extreme drought); and (3) eventually the "contributing factors" (e.g., parasites and/or additional climatic events) produce tree mortality events. Despite the compelling theoretical background of this hypothesis, the empirical support is relatively weak because the studies documenting drought-induced decline rarely analyze the relative importance of all the factors that are potentially involved (but see Galiano et al., 2010). This is particularly the case in studies of decline in Mediterranean forest plantations (Sánchez-Salguero et al., 2010, 2012).

Forest decline can be linked to two main processes: a progressive growth reduction (radial, height, or volume, etc.) and a rapid defoliation, both used as descriptive variables to study impact of environmental factors on forest decline (Bréda et al., 2006; Drobyshev et al., 2007; Carnicer et al., 2011). Defoliation is one of the main factors used to indicate future mortality and forest health and it integrates the effects of other factors such as relative water and nutrient availability (Dobbertin and Brang, 2001; Dobbertin, 2005). In forest decline studies defoliation refers to reduction of overall crown volume, and usually visually estimated via a visual assessment and systematic rating system applied to individual trees assessed their vigor using a semi-quantitative scale based on the percentage of crown defoliation (Mueller and Stierlin, 1990). Several studies have suggested the existence of a relationship between negative growth trend and crown defoliation in a decline process (Dobbertin, 2005; Jump et al., 2006; Drobyshev et al., 2007). A negative trend in a recent basal area may be a strong indication of overall tree growth and physiological decline (Jump et al., 2006). Several studies demonstrated that tree crown conditions at the time of sampling was correlated with tree growth over the preceding decade, and from this relationship it was possible to predict the decline process with significant statistical precision (i.e., about 90% variance explained in the models) by at least 5 years beforehand (Duchesne et al., 2003; Bigler and Bugmann, 2003; Drobyshev et al., 2007). There are few studies, however, that have evaluated growth and crown dieback separately, while also assessing the effects of environmental and competition factors, and particularly in Mediterranean pine stands (Bravo-Oviedo et al., 2006; Kantavichai et al., 2010).

In this study, the objectives are: (i) to identify the main abiotic and biotic factors that may be causing pine plantation decline in southern Spain. *Pinus sylvestris* L. and *Pinus nigra* Arnold. subsp. *salzmannii* stands have undergone severe decline (i.e., extensive tree dieback) in the southern limit of their natural distribution area in the Iberian Peninsula (Navarro-Cerrillo et al., 2007; Galiano et al., 2010; Sánchez-Salguero et al., 2012). (ii) to determine the relationship of these factors to tree growth decline processes;, (iii) to evaluate relationship between crown defoliation and growth decline, and (iv) to assess interspecific differences in the responses to these two processes. A combination of growth trend, crown condition and those environmental variables could improve predictions of the tree decline process using statistical models.

2. Materials and methods

2.1. Study area and species

The study area is located in "Sierra de Los Filabres" (37° 22′ N, 2° 50′ W, 150.000 ha. between 300 and 2186 m.a.s.l) (hereafter abbreviated as Filabres), which represents the southern natural distribution limit of *Pinus nigra* (Fig. 1). Mean annual precipitation is 320 mm and moderately mild temperatures (13.1 °C, 1000 m.a.s.l) were recorded for the 1940–2009 periods (Sánchez-Salguero et al., 2010), with prolonged drought during the summer. Dominant soils are regosols and topography is characterized by steep slopes (>35%) (LUCDEME, 2004).

P. sylvestris and *P. nigra* subsp. *salzmanii* plantations were studied. In the study area, forests were planted in the 1970s using seeds from South and Central Spain, and afterwards they were managed through selective thinning that involved harvesting depressed trees while retaining dominant trees for future natural seeding (Rodríguez Gutiérrez, 2003; Serrada et al., 2008). Silvicultural features of these stands are summarized on Tables 1 and 2.

2.2. Field procedures and tree ring analysis

A stratified sampling was made by species and crown damage classes, live and dead trees (Dobbertin and Brang, 2001), and tree size (dbh, height) following a stratified sampling according to the altitudinal gradient of the study area; taking into account the surface occupied by each pine species and its recent defoliation levels (Table 1 and Fig. 1). We sampled at least one stand within each 1-km^2 grid in the study area. Sampled stands in those grids with multiple stands were randomly selected. For each tree measurements and observations were made of physiographic variables (elevation, slope and aspect), size (dbh, height and crown height), age (number of rings at 1.3 m) and crown damage (percentage of defoliation) using a semi-quantitative scale based on the percentage of crown defoliation (Mueller and Stierlin, 1990) (Table 2) and the ICP (International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests) monitoring methodology (UN/ECE, 1994) since it has been used in similar decline studies in Europe (see for example Heikkilä et al., 2002). Percent crown defoliation (as proxy indicator of damage) was assessed visually by the first author because estimates of defoliation vary among observers. Since these estimates may also vary among sites we used as a reference a tree with the maximum amount of foliage at each location (Dobbertin, 2005). In this study, a tree was regarded as declining if its crown showed a needle loss greater than 50%. Two defoliation classes were reclassified from the initial scale: class 1 (H) (slightly damaged trees and trees without evident defoliation <50%) and 2 (D) (severely damaged trees or dead ones ⩾50%) (Drobyshev et al., 2007; Sánchez-Salguero et al., 2012).

In this study, damage levels were directly related to crown defoliation (Table 1), which permitted one to accept that current defoliation levels were linked to the severity of recent droughts (Dobbertin, 2005). This assumption was supported by physiological data since stomatal conductance and water potential were significantly lower in defoliated than in non-defoliated trees in both species (Hernandez-Clemente et al., 2011).

A wood section at 1.3 m from each tree was obtained, and two radii located perpendicular to the maximum slope and in opposite directions were selected for cross-dating and measuring. Wood