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Defoliation triggered by climate induced effects in Spanish ICP Forests monitoring plots

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ABSTRACT

In a context of global change, climate impacts can trigger defoliation processes in different forest species. The ICP Forests network estimates the level of forest defoliation over time in different European countries. Those data are used to related defoliation with potential causal factors. In European Southwestern forests, climate change appears to be the detonating factor of generalized defoliation. The objectives of this study were: (i) identity defoliation trends in forest trees at network of Spanish ICP Forests monitoring plots and, (ii) find out if there are underlying climate factors that trigger defoliation process along the time.

The spatiotemporal synchronization of the defoliation response was analyzed with cross-correlation using COFECHA software. The relationship between the 88 climatic variables proposed and defoliation was analyzed using Correlated Component Regression models (CCR models) and Discriminant Analysis (DA). The significance of the variables in each model was compared using contingency tables. A peak of defoliation was observed in the mid-1990s with no recovered to the initial values of the early 1990s. The behavior of the different tree species with respect to defoliation, synchronized both in time and space, involves one or several factors that have a general and similar effect on forests in Spain. The most significant factors related to defoliation were the thermal-related factors, particularly average temperatures in April and June and the thermal oscillation of both the current year and the previous year. Only one drought indicator as statistically significant was identified (*A*, duration of aridity in months) and suggests that it is of limited relevance in the Spanish forest defoliation conditions.

1. Introduction

Climate acts as a basic driving force behind the different ecosystem processes (Bertini et al., 2011), although the most appropriate scientific approach to quantify the induced gradients and their impacts has yet to be determined (Bonan, 2008; Chapin et al., 2008). As demonstrated by paleoclimatological studies, climate change as well as prolonged climatic episodes and their impacts have evident repercussions for many terrestrial and aquatic ecosystems (Parmesan, 2006). Alterations in the behavior of ecosystems due to the continuous rise in temperatures are currently being detected (Grimm et al., 2013). Both individual species and populations tend to respond to threatening conditions with various adaptation strategies to mitigate the negative effects of disturbances. In forest systems, the most potentially damaging factors are the effects of intense drought and global warming (Allen et al., 2010). Thus, species must respond to environmental changes within their autoecological tolerance by adapting toward a new equilibrium (Bertini et al., 2011).

Defoliation is one of the strategies used by plant to reduce the risk of mortality under conditions of extreme heat and drought. In water deficit conditions, defoliation offsets the drain on resources involved in maintaining leaf area, minimizes water loss through transpiration and avoids overheating from radiation (Barker and Caradus, 2001). A priori, defoliation is not an indicator of mortality but rather a physiological strategy that is a specific protection mechanism used under conditions of stress. When prolonged defoliation occurs and a "point of no return" is reached, permanent damage is caused to plants and such defoliation is then considered an indicator of forest decline (Dobbertin, 2005).

A forest damage evaluation process was initiated in Europe in 1985 (Lorenz, 1995) to assess the effect of chemical contaminants

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on conifers forests in the northern hemisphere during the second half of the 20th century. This initiative involved the creation of a European network of monitoring plots known as "ICP Forests" (International Co-operative Program on Assessment and Monitoring of Air Pollution Effects on Forests operating under UNECE and supported by the European Commission). The network of sampling points in different European countries represents a unique long term monitoring system to assess forest damage and apply appropriate harmonized measures on a large geographical scale (ICP Forests, 2014).

The defoliation data obtained from the forest monitoring plots of the European network have led to the publication of numerous studies in various countries such as Finland (Nevalainen et al., 2010), France (Ferretti et al., 2014), Italy (Bussotti et al., 2003), Lithuania (Augustaitis et al., 2007), Norway (Aamlid et al., 2000) and Spain (Peñuelas et al., 2001). In forest regions of Northern and Central Europe, woodlands have suffered serious damage due to chemical contaminants in the atmosphere (Juknys et al., 2013). By contrast, in Southern Europe, particularly in highly vulnerable areas such as the Mediterranean (Ferretti et al., 2008; Scarascia-Mugnozza et al., 2000), forest decline and mortality have been linked to climatic alterations (Sánchez-Salguero et al., 2013), fires (Pausas et al., 2008) and pests (Hodar et al., 2012; Jacquet et al., 2012) rather than to pollution from acid rain (Bussotti and Ferretti, 1998; Molina et al., 2013).

While admitting that climate change and climatic disturbance underlie forest decline, preliminary studies suggest that drought is the factor that induces defoliation and subsequent forest mortality (Bréda and Badeau, 2008; Sánchez-Salguero et al., 2012). Research based on data from monitoring plots in Spain has also linked defoliation and forest mortality to drought associated with climate change (Carnicer et al., 2011; Peñuelas et al., 2001). However, the temporal patterns of defoliation of tree species show a consistently increasing trend (Ferretti et al., 2014) that in some cases does not tie in with years of scarce precipitation (Carnicer et al., 2011). Hence, regardless of the specific adaptations of each taxon, it is still unclear which are the basic climatic factors impacting tree health before drought that trigger the defoliation process and make it persist over time. In line with Allen et al. (2010), we consider that it is necessary to conduct further research on climate-induced forest decline, focusing particularly on variables related to temperature, precipitation and indices associated with water stress in trees.

Moreover, bearing in mind that one of the negative effects of climate change is that tree growth is halted, it is taken as proven that the interruption of growth is significantly related to defoliation and crown transparency (Dobbertin, 2005; Drobyshev et al., 2007). Therefore, similarly to growth rings, defoliation data collected from the network of ICP Forests plots in Spain could be considered as a historical record of previous forest damage (i.e., lower leaf mass will result in narrower rings). The methodology would involve a spatial analysis of defoliation synchronization patterns as if these were time series of tree-rings. The dendroclimatic response function would indicate the relationship between crown defoliation and precipitation and temperature, since the spatiotemporal records provide information on the variability of these climatic factors (Allen et al., 2010). Based on these premises, our aim was to conduct a comprehensive study of the specific climatic conditions that induce defoliation in Spanish forests. We addressed the following specific objectives: (i) identity defoliation trends in forest trees at network of Spanish ICP Forests monitoring plots and, (ii) find out if there are underlying climate factors that trigger defoliation process along the time. These objectives are vital if we want to understand the behavior of forests under climate change and implement measures which mitigate its effect on these forests.

2. Material and methods

2.1. The ICP Forests data set in Spain

The network of ICP Forests plots is organized on two levels of monitoring (Hauβmann and Fischer, 2004):

(i) *Level I:* Large scale systematic monitoring network (Large-scale Level I plots). Plots are established on a 16 × 16 km virtual grid projected over the European study area. Each plot is placed on the intersection or node of each cell containing forest cover. There are currently 620 Level I systematic monitoring plots in Spain.
(ii) *Level II:* Intensive monitoring network with a total of 54 permanent intensive monitoring plots established in forest stands that represent the major forest habitats in Spain. Each plot has an area of 2500 m^2.

Defoliation data were collected on the two monitoring levels using the approach chosen by the ICP Forests (Eichhorn et al., 2010). In the Level I network, defoliation was measured since 1987 in 24 predominant, dominant and co-dominant trees per plot. Sample trees in each plot were not selected at random but according to strict criteria: six trees per quadrant (NE, SE, SW and NW) were selected, taking into consideration their proximity to the center and their position in the canopy. If any of the trees died due to either anthropogenic or natural causes, another similar tree was selected within the plot in order to continue with the defoliation estimation over the time period of assessment. Similarly, if there were forest fires or logging activities, the plot was moved to another nearby forest stand or was eliminated from the study. The initial database included 20,761 trees of 79 different species for the Level I network.

In the Level II network, defoliation was measured from 1994 onwards in all the trees of each of the 54 intensive monitoring plots (i.e. 5545 trees of 30 different species). Using the above-mentioned criteria, 24 trees were selected among all those studied to homogenize the data with the Level I network. The analysis started with a total of 26,306 sample trees of 80 different species in 674 monitoring plots (Fig. 1).

2.2. Tree species, study area and time period

Most forests in Spain have either been subjected to substantial human intervention or are the result of artificial restocking, particularly in the case of conifers. Such forests include: (1) mixed or monospecific formations of sclerophyllous (evergreen forests), marcescent or deciduous broadleaved species, (2) mixed or monospecific conifer forests and (3) mixed stands of broadleaves and conifers (Table 1).

To facilitate the research, 12 of the most representative and geographically widespread forest species found in Spanish forest stands were chosen for the purposes of the study: *Fagus sylvatica* L., *Juniperus thurifera* L., *Pinus halepensis* Mill., *P. nigra* J.F. Arnold, *P. pinaster* Aiton, *P. pinea* L., *P. sylvestris* L., *Quercus faginea* Lam., *Q. ilex* L., *Q. pyrenaica* Willd., *Q. robur* L. and *Q. suber* L. The defoliation assessment was conducted for each species; data were always collected from the same trees at each point of the network. Above-mentioned species were classified first into conifers (6 species) or broadleaves (6 species), and further, broadleaves were classified according to physiognomic attributes into deciduous (2 species), marcescent (2 species) or sclerophyllous (evergreen) species (2 species) (Table 2).

The study area in which the plots are located comprises forest land on the Spanish mainland as well as on the Spanish Mediterra-