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Remote-sensing and tree-ring based characterization of forest defoliation and growth loss due to the Mediterranean pine processionary moth

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ABSTRACT

Outbreak insects are among the major biotic disturbances affecting Mediterranean forests by reducing their growth and vitality through severe defoliations. Despite their relevance for the management of these drought-prone areas, we lack information on the relationships between growth, canopy cover and insect defoliations at ample spatial and temporal scales. Here, we combine remote sensing (vegetation indexes) and dendrochronological information (basal area increment, BAI) to assess the effects of pine processionary moth (*Thaumetopoea pityocampa*, PPM) defoliations on growth and cover changes of several pine species, mainly focusing on *Pinus nigra*. We compared both datasets with a long-term field survey of PPM stand defoliations carried out in eastern Spain during the period 1970–2012. Lastly, we fitted linear-mixed models of BAI using as predictors climatic variables and a multi-scalar drought index to distinguish drought-related growth reductions from those attributed to PPM outbreaks. PPM severe defoliations mainly affected edge or low-density stands. Several vegetation indices (Moisture Stress Index, Normalized Burn Ratio and Normalized Difference Infrared Index) reflected the cover decrease corresponding to severe PPM defoliations. We found that trees affected by various severe PPM defoliations took at least 2 years to recover BAI values similar to those observed before the outbreak. The combined use of remote sensing and dendrochronology allows monitoring the impact of PPM defoliations from stands to trees, and these are valuable approaches to forecast outbreaks and their effects on Mediterranean forest. We consider both powerful tools to further assess the interacting effects of climate warming and PPM dynamics on drought-prone forests.

1. Introduction

Outbreaks of defoliating insects represent one of the major biotic disturbances of Mediterranean forests negatively influencing the growth and persistence of damaged trees (Hódar et al., 2003). Outbreaks may affect extended areas and represent a major stressor of these drought-prone forests (Dajoz, 2000; Barbosa et al., 2012). Despite their relevance, there are no studies based on wide spatial scales (50–150 km^2) and over long temporal scales (10–50 years). The integration of several source of information can answer questions on how outbreaks affect long-term forest dynamics. Nowadays, the few available datasets are field observations of stand defoliation which usually lack precise data on the loss in vigour and the growth reduction of affected areas (but see Montoya and Hernández, 1998). Thus, we need more robust information on how defoliating insects and outbreaks disturb Mediterranean forests, and to ascertain if some stands or periods are more prone to experience outbreaks than others. These data should allow determining if outbreaks are increasing or decreasing in

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severity, frequency and extent as related to climate warming (Raffa et al., 2008) or due to changes in land-use (Lockwood and DeBrey, 1990).

The outbreak effects on forest growth and vigour at large spatio-temporal scales may be inferred by using remote sensing or aerial survey datasets (Goodwin et al., 2008; Dennison et al., 2010; Eklundh et al., 2009), and dendrochronological reconstructions of past outbreaks (Esper et al., 2007). To our knowledge, no study has attempted to combine both sources of information to assess the occurrence of insect outbreaks across Mediterranean drought-prone forests (but see examples from boreal and subalpine forests in Babst et al., 2010; DeRose et al., 2011; Magnussen and Alfaro, 2012). If successful, the combination of both approaches would allow: (i) determining if outbreaks are related to specific climatic or site conditions, (ii) evaluating the effects of outbreaks on growth and vigour of affected forests, and (iii) developing a robust methodology to assess canopy and growth losses across wide areas and intervals thus reducing the costs of field surveys by focusing on specific areas or periods.

The pine processionary moth (*Thaumetopoea pityocampa* Dennis & Schiff., hereafter abbreviated as PPM) is one of the most important defoliator insects in the Circum Mediterranean area, mainly affecting evergreen conifers such as *Pinus* and *Cedrus* species (Devkota and Schmidt, 1990; Masutti and Battisti, 1990; Montoya and Hernández, 1998). Therefore, the PPM constitutes a good model species to analyze the effects of outbreaks on forest cover and growth changes at large scales. PPM larvae usually feed on needles during autumn and winter (Démolin, 1969). Defoliations negatively affect the height and radial growth, increase the mortality rate of saplings and reduce the reproductive ability of trees (Hódar et al., 2003; Carus, 2004; Hernández Alonso et al., 2005; Kanat et al., 2005; Palacio et al., 2012; Jacquet et al., 2012). It is know that PPM outbreaks show fluctuations, but the periodicity of those dynamics are unclear. Some authors describe PPM outbreaks occurring every 6 years on average (Battisti, 1988; Hódar and Zamora, 2004), while others suggest no cyclic behavior of the PPM populations (Gery and Miller, 1985; Tamburini et al., 2013).

Here, we perform a multi-proxy assessment of the effects of PPM outbreaks on defoliation and growth of Mediterranean pine forests by comparing fine-resolution remotely sensed vegetation indices and dendrochronological reconstructions of wood production. The remote-sensing assessment of defoliations is related to spatially derived information (topography, forest features, and soil types) to define areas prone to PPM outbreaks. Further, the tree-ring reconstructions of PPM outbreaks are compared with local climate data to infer the effects of climatic stressors (e.g., drought) on growth. We aim: (i) to determine the vegetation indices which better reflect the effects of PPM outbreaks on defoliation intensity in Mediterranean drought-prone forests, and (ii) to perform dendrochronological reconstructions of severe PPM defoliations. Finally, any assessments of defoliations must necessarily be calibrated with field data. Such calibration is performed by comparing the inferences described in both objectives with a 43-year long field survey of stand defoliations (period 1970–2012). Such unique long-term dataset allows characterizing the PPM defoliation dynamics at the assessed scales.

2. Materials and methods

2.1. Study area, defoliation degree and analysis

The study area is located in eastern Spain (Sierra de Gúdar, Teruel, Aragón; Fig. 1). It includes forests of several pine species, namely: *Pinus sylvestris* L., *Pinus nigra* Arn. subsp. *salzmannii* (Dunal), *Pinus pinaster* Ait. and *Pinus halepensis* Mill. This area covers 128 km^2 and it was selected because it encompasses a wide elevational gradient from 1000 to 1800 m a.s.l. where all the aforementioned pine species are naturally distributed (Montoya, 1970; Démolin, 1970). The understory vegetation is dominated by junipers (*Juniperus sabina* L., *J. communis* L.) and shrubs (*Berberis vulgaris* L., *Genista scorpius* L.). The soils are basics and calcareous. The climate is Mediterranean with continental influence. Based on a regional mean for the study area calculated using six local meteorological stations the mean annual temperature is 10.2 °C and the total annual precipitation is 519 mm (see Supplementary information Fig. S1 and Table S1).

PPM defoliations were annually recorded in late winter by the Aragón Forest Health Laboratory located at Mora de Rubielos (Teruel, Spain) from 1970 up to 2012. They carried out field surveys by following the existing forest demarcation according to silviculture and topographical features, and using a PPM damage visual scale recorded at the stand level considering six levels (see Montoya and Hernández, 1998). To simplify further analyses, we re-classified the PPM damage scale into three stand defoliation degrees (hereafter abbreviated as DD): undamaged trees with some PPM nests but no defoliation in the crown (DD = 1, class DD1), partial to moderate defoliation, mostly affecting stand edges and isolated trees (DD = 2, class DD2), and severe defoliation affecting the whole stand (DD = 3, class DD3; Fig. 2).

2.2. Climate data

To obtain a regional climatic series characterizing the study area, local data from six meteorological stations were combined into a regional mean from the period 1970–2012 (Supplementary information Fig. S1 and Table S1). To estimate the missing data for each station and to combine them, we used the MET program from the Dendrochronology Program Library (Holmes, 1994). For each station, monthly variables (temperature and total precipitation) were transformed into normalized standard deviations to give each station the same weight in calculating the average monthly values for each year.

To estimate the drought intensity experienced by the study forests we used the Standardised Precipitation-Evapotranspiration Index (SPEI). This drought index shows the cumulative water stress for several months on different time scales with negative and positive values corresponding to dry and wet periods, respectively (Vicente-Serrano et al., 2010). The SPEI values for the period 1971–2010 and the 0.5° grid including the study area were obtained from the website http://sac.csic.es/spei/index.html. According to that index, the driest years of the area for the study period were: 1979, 1983, 1999, 2005 and 2009.

2.3. Remote sensing images and derived vegetation indices

To perform remote-sensing analyses we selected Landsat images because they show an adequate temporal, spectral and spatial resolution for both regional and local scales. Landsat images have been used in numerous studies on forest defoliation induced by insects (Royle and Lathrop, 1997; Heikkilä et al., 2002; Franklin et al., 2008; Thayn, 2013). Besides, the Landsat program currently offers the longest and more consistent historical archive of satellite images (Hantson and Chuvieco, 2011).

Images were taken in 15 different years (path 199, row 32) from 1987 to 2011 (Table 1). We selected images without clouds or with minimum cloud coverage. Images were always captured between March and May, when the maximum period of PPM defoliation occurs (Montoya and Hernández, 1998). These images were obtained from three different datasets: (i) the U.S. Geological Survey (USGS, http://earthexplorer.usgs.gov/), (ii) the European Space Agency