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Tree damage and population density relationships for the pine processionary moth: Prospects for ecological research and pest management

Luis Cayuela [a,*], Rodolfo Hernández [b], Jose Antonio Hódar [c], Gerardo Sánchez [d], Regino Zamora [c]

[a] Área de Biodiversidad y Conservación, Departamento de Biología y Geología, Universidad Rey Juan Carlos, c/Tulipán s/n, E-28933 Móstoles, Madrid, Spain
[b] Laboratorio de Sanidad Forestal, Servicio Provincial de Agricultura, Ganadería y Medio Ambiente de Teruel, Diputación General de Aragón, c/Agustín Planas Sancho 10, E-44400 Mora de Rubielos, Teruel, Spain
[c] Grupo de Ecología Terrestre, Departamento de Ecología, Facultad de Ciencias, Universidad de Granada, E-18071 Granada, Spain
[d] Servicio de Sanidad Forestal y Equilibrios Biológicos, Dirección General de Sanidad de la Producción Agraria, Ministerio de Agricultura, Alimentación y Medio Ambiente, c/Almagro 33, E-28010 Madrid, Spain

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ABSTRACT

The pine processionary moth (*Thaumetopoea pityocampa*, PPM) is one of the most destructive pests in Mediterranean woodlands. Assessment of PPM impact involves the quantification of pest damage at the stand level from visual evaluations by forestry technicians, using different infestation indices. One such index, widely used in national and regional forest monitoring programmes, is an ordinal index that ranges from no infestation (0) to massive defoliation (5). This index now offers an outstanding opportunity to investigate patterns and processes in PPM population dynamics. Its use as a proxy for insect population density requires, however, knowledge on the relationship between stand defoliation and population density-related measures, which is something that has not been explored to date. In this study, we investigated the relationship between the infestation index, quantifying damage at the stand level by the PPM, and fined-grained measures of PPM population size (number of egg batches, number of hatched caterpillars, number of winter tents) within and between generations. We used data from a long-term monitoring programme conducted in three pine woodland stands at Mora de Rubielos, Spain, for a 19-year period. Generalized linear models (GLM) were fitted in order to test the following hypotheses: (1) high values of population density-related variables, on a log basis, will cause high defoliation in the coming winter (within generation); and (2) high defoliation rates will be associated with high stocks of population size at the next generation of PPM (between generations). Our results indicate that, within the same generation, there was a poor relationship between the infestation index and all three fine-grained measures of population size (maximum $R^2 = 0.442$), possibly as a result of post-sampling larval survival over winter due to climatic factors. Goodness of fit was higher for PPM population density-related measures in the next generation and the infestation index (maximum $R^2 = 0.735$). Overall, the results suggest that visual evaluation of pest damage by PPM at the stand level provides an accurate proxy for population size at the next generation, and therefore opens the potential to the use of this index to investigate PPM population dynamics where no direct measures of population size exist.

1. Introduction

Quantitative assessment of forest pest impact is a key element in designing forest management programmes. Rapid assessments can involve the quantification of tree defoliation and/or mortality at the stand level from in-the-field visual evaluations by forestry technicians (Innes, 1988; Redfern and Boswell, 2004; Cayuela et al., 2011; Hódar et al., 2012; Eickenscheidt and Wellbrock, 2014) or, more typically, from interpretation of remote sensing data or aerial photographs or surveys (Wulder et al., 2006; Eklundh et al., 2009; Mozgeris and Augustaitis, 2013; see Rullan-Silva et al., 2013 for a review). These measures, though typically used to aid forest managers in assessing the damage across large areas, have been also used as a proxy for insect population density in order to investigate the spatio-temporal dynamics of the pest and to forecast potential outbreaks (e.g. Aukema et al., 2006,

* Corresponding author. Tel.: +34 91488 8517.
E-mail address: luis.cayuela@urjc.es (L. Cayuela).

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2008; Foster et al., 2012; Sambaraju et al., 2012; Allstadt et al., 2013). The latter process requires knowledge of the relationship between tree damage and population density-related measures (Sutherland, 1996), which can occur only if a number of populations has been studied while simultaneously measuring both tree damage and the actual number of insects. Studies that attempt to relate insect density to individual tree or stand damage within forested systems often compare natural egg or larval densities to defoliation (e.g. Gansner et al., 1985; Lysyk, 1990; Williams et al., 1991; Carroll and Quiring, 1993; Parsons et al., 2005). Unfortunately, investigations of such relationships are scarce in the scientific literature, due mostly to lack of fine-grained population density-related data available, especially when pest management programs are conducted across large areas. Thus, in the absence of proper calibration, this relationship may be held as true when it is not, leading to erroneous conclusions about the dynamics of the target species.

This study investigates the relationship between an ordinal index widely used in Mediterranean woodlands to quantify tree damage at the stand level by the pine processionary moth (*Thaumetopoea pityocampa*, Lepidoptera: Thaumetopoeidae; henceforth PPM), and fined-grained measures of population size, using data from a long-term monitoring programme conducted in Mora de Rubielos, Spain, for a 19-year period. PPM is one of the most damaging pests in Mediterranean pine woodlands. Their larvae (caterpillars) feed on the needles of pine trees over winter and, in large numbers, they can severely defoliate trees, reducing tree growth, weakening trees and making them more susceptible to attack by other pests or diseases, or to environmental stress caused by drought (Hódar et al., 2003; Arnaldo et al., 2010; Erkan, 2011; Jacquet et al., 2012, 2013). In the last few decades, the area affected by PPM outbreaks in Europe has expanded northwards and upwards in the mountains, and the pest is now affecting higher altitude and latitude areas where it used to be absent (Hódar and Zamora, 2004; Battisti et al., 2005; Robinet and Roques, 2010). This has resulted in high attack rates in areas hardly affected by this insect in the past (Battisti et al., 2005).

In Spain, forest monitoring programmes from the 1970s onwards have consistently evaluated damage by PPM at the stand level by means of an ordinal index (henceforth infestation index), with value ranges from no infestation (0) to massive defoliation (5). This index has been typically used to evaluate tree damage and determine threshold values above which to recommend the application of treatments – mostly biological insecticides – to control PPM outbreaks. To date, the relationship between the infestation index and population density-related measures are unknown for the PPM. Thus, this is the first study to investigate the relationship between defoliation at the stand level and different measures of PPM population density, namely number of egg batches, number of hatched caterpillars, and number of winter tents. In particular, we tested the following non-mutually exclusive hypotheses: (1) high stocks of population size at the beginning of the cycle will cause high defoliation (H_1); and (2) high defoliation rates will be associated with high stocks of population size in the next generation of PPM (H_2; Fig. 1). The reason for testing such relationships is twofold. From a research perspective, this opens the possibility of using this index to investigate patterns and processes in PPM population dynamics where no direct fine-grained measures of population density exist. This can be particularly useful since the collection of such data is indeed a hard and time-consuming task, and time series are typically short, making it difficult to analyse spatio-temporal population dynamics. From a management perspective, it might support current protocols of action (e.g. application of insecticides) when threshold values are reached (i.e. infestation index $\geqslant 3$). Since tree damage in late winter is evaluated at the end of larvae development, and PPM insecticides target early larval stages, the application of insecticides must be applied at the beginning of the next PPM cycle, by late summer or early autumn (Cayuela et al., 2011). Thus, it is implicitly assumed that there is a positive relationship between tree damage caused by PPM and population density in the next generation, but this has not been demonstrated to date.

In the case of PPM, damage is measured at the end of larval development, whereas population density is often measured through male captures in pheromone traps, counts of the number of egg batches or caterpillars that hatch at the beginning of the cycle, or number of winter tents later in winter, and therefore closer in time to the estimation of tree damage at the stand level. A number of biotic and abiotic factors might thus affect post-sampling survival (Wainhouse, 2005), weakening the relationship between population density-related measures and the infestation index. Post-sampling survival would imply mortality of late larval instars, pupae, and moths, which together with possible fluctuation in fecundity, can introduce considerable variation into the relationship between defoliation and larvae density at the next generation (Lysyk, 1990). Likewise, winter climatic conditions have been shown to influence PPM outbreaks (Démolin, 1969; Hódar and Zamora, 2004; Battisti et al., 2005, 2006; Hódar et al., 2012), and therefore it is not clear whether fine-grained measures of population density will relate to tree damage at the stand level within the same cycle. As for the relationship between the infestation index and population density-related measures at the next generation, this might be likewise affected by factors acting on the survival of pupae after their burial, such as soil moisture (Markalas, 1989).

Overall, our study is meant to help elucidate the potential of the infestation index in ecological research, as there are many long-term databases held by public administrations that might be used to investigate different issues related to PPM population dynamics, provided that it accurately reflects measures of population density. In addition, given that the application of control methods for aggressive pests, such as PPM, is a key issue in Mediterranean forestry, we aim to provide a practical evaluation of the utility of the infestation index for decision making in current PPM control protocols.

2. Material and methods

2.1. Study area

The area of study is located in Mora de Rubielos, in Teruel province, north-eastern Spain (Fig. 2a). It was established in the 1970, in response to a call from an international meeting held in Teruel, sponsored by the International Organization for Biological Control (IOBC). As a result of this meeting, the Working Group on "Integrated Pest Management in Mediterranean Woodlands" of the IOBC was created, as part of a joint effort to investigate the ecology of the PPM and develop proposals for integrated management of forest insect pests (Démolin, 1970). No insecticides have been applied in the area at least since the early 1970s. The area is managed by the Forest Lab of Mora de Rubielos, a research centre currently under the administration of the Forest Health Lab of the Aragón Regional Government.

The site has a northern Mediterranean climate, with cold, wet winters and hot, dry summers. Average annual rainfall between 1971 and 2012 was 487 mm, with a maximum yearly precipitation of 733 mm and a minimum of 323 mm. The average temperature was 10.4 °C, with mean monthly summer temperatures of 21.5 °C and mean monthly winter temperatures of 5.7 °C. The area covers approximately 13,000 ha of naturalized pine woodlands, dominated mostly by *Pinus nigra salzmanii*, *P. sylvestris,* and *P. pinaster*.