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Spatiotemporal monitoring of pine processionary moth defoliation employing field databases, remote sensing, and dendrochronology

Seguimiento espaciotemporal de la defoliación por procesionaria del pino mediante bases de datos de campo, teledetección y dendrocronología

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Abstract

The pine processionary moth (*Thaumetopoea pityocampa*) is a lepidopter species of significant social and forestry interest, with its distribution potentially expanding in recent decades. However, the climatic and ecological drivers behind its expansion remain unclear. Cambium Group undertakes research to investigate the causes and patterns of pine processionary moth distribution by integrating field data, remote sensing, and dendrochronology. Our aim is to assess forest vulnerability, enhance monitoring of pine processionary moth populations, and develop early detection tools. The population dynamics of the species are closely linked to climatic conditions. Mild winters favour larval development and population growth, while heatwaves negatively affect the eggs viability and the survival of early-stage larvae. Forest structure also plays a role in susceptibility, with homogeneous stands experiencing more severe defoliation. Analyzing long-term population records from forest regional administrations provides a comprehensive view of outbreak patterns. Detailed spatiotemporal monitoring, using remote sensing time series, helps to identify vegetation phenological anomalies associated with defoliation. These canopy changes, which result in reduced leaf area index, can be detected using high-density LiDAR point clouds. To contextualize current trends and predict future impacts, a long-term perspective on pine processionary moth incidence is essential. Dendrochronological analysis, examining features such as tree ring width, early- to latewood ratio, and water-use efficiency, enables the reconstruction of moth-related disturbances over a tree´s lifespan. This multidisciplinary approach deepens our understanding of the pine processionary moth´s impact on Spanish forests and is key for improving forest damage prevention systems.

Keywords: climate change, defoliation, monitoring tools, *Thaumetopoea pityocampa*.

Resumen

La procesionaria del pino (*Thaumetopoea pityocampa*) es un lepidóptero de gran interés social y forestal, que en las últimas décadas podría haber ampliado su área de distribución. No obstante, aún no comprendemos los factores climáticos y ecológicos determinantes en su desarrollo. En esta comunicación presentamos la investigación del grupo Cambium destinada a comprender las causas y patrones de distribución de la procesionaria. Para ello integramos bases de datos de sanidad forestal, dendrocronología y teledetección. Nuestro propósito es determinar la vulnerabilidad de los bosques, mejorar el seguimiento de las poblaciones de procesionaria y desarrollar herramientas de detección temprana. La dinámica poblacional de la procesionaria está relacionada con las condiciones climáticas: temperaturas invernales templadas favorecen el desarrollo de las larvas y su expansión poblacional, mientras que las olas de calor afectan a la viabilidad en fases tempranas. La estructura forestal determina la susceptibilidad de los bosques, observándose defoliaciones más intensas en formaciones más homogéneas. Analizando los registros anuales de infestación a largo plazo se obtiene una visión integral de los patrones de brotes a escala nacional. El seguimiento espaciotemporal de las defoliaciones mediante series temporales de teledetección permite identificar anomalías fenológicas asociadas a defoliaciones. Los cambios en el dosel forestal, asociados a una reducción en el índice de área foliar, pueden ser cuantificados mediante nubes de puntos LiDAR de alta densidad. La caracterización de la anchura, la ratio de madera tardía y la eficiencia de uso del agua en los anillos de crecimiento permite reconstruir eventos de procesionaria. Este enfoque multidisciplinar ayuda a entender el impacto de la procesionaria en bosques españoles, contribuyendo a optimizar los sistemas de prevención de daños forestales.

Palabras clave: cambio climático, defoliación, herramientas de seguimiento, *Thaumetopoea pityocampa*.

1. Introduction

The pine processionary moth (*Thaumetopoea pityocampa* Den. & Schiff.), hereafter PPM, is a native lepidopter in Mediterranean forests that plays a significant role in forest ecosystems. Throughout its various developmental stages, PPM contributes to nutrient cycling and serves as an important food source for wildlife during the winter (Verma *et al.*, 2023). When occasional outbreaks of PPM populations occur, it represents a significant defoliator of pine and cedar trees in Spain, leading to reduced tree growth (Jacquet *et al.*, 2013), and negatively affecting overall forest health and the ecosystem services provided.

The dynamics of forest insect populations are intricately regulated by environmental factors, such as climate (Bale *et al.*, 2002) or host-insect relationships (Bernays 1992). PPM populations typically exhibit periodic outbreak patterns, with cycle lengths ranging from 5 to 14 years (Geri and Miller, 1985; Hódar *et al.*, 2012; Gazol *et al.*, 2019; Camarero *et al.*, 2022). This periodicity varies by region (Li *et al.*, 2015) and is influenced by trophic interactions and intrinsic population dynamics (Hódar and Zamora, 2004; Myers and Cori, 2013). PPM populations normally grow until feeding conditions deteriorate, driven by factors such as host plant availability, quality, and environmental temperature, which ultimately lead to a population collapse (Battisti, 1988).

The expansion of pine plantations in the second half of the 20th century (Montero, 1999), combined with favourable climate conditions has significantly increased the PPM distribution, establishing it as a major pest. In Spain, over 500000 hectares of pine forests experience varying degrees of defoliation each year due to the PPM infestations (Montoya Moreno *et al.*, 2020). Beyond its ecological impact, PPM poses health risks to animals and humans. The larvae release urticant setae when disturbed, causing allergic reactions (Moneo *et al.*, 2015). These larvae, which are the most destructive stage for pine trees, feed primarily on needles during the winter and early spring, with daily peak feeding occurring in the evening and night. PPM follows an annual development cycle, though some individuals can remain in diapause as pupae in the soil for several years (Battisti, 1988). Throughout the egg and larval stages, PPM exhibits highly gregarious behaviour, enhancing its ability to cause widespread damage (Battisti *et al.*, 2015).

PPM live cycle and behaviour are strongly influenced by temperature (Démolin 1969, Domingo *et al.*, 2024a), with specific thresholds identified as critical for its survival and development (Romanyk and Cadahia, 1981). For example, individual moths die when temperatures exceed 32 °C or drop below -7 °C, while entire colonies can perish at temperatures as low as -12 °C. Forest structure, particularly tree age, stand density, and composition, also plays a key role in PPM population dynamics (Régolini *et al.*, 2014). The species´ ability to enter diapause under adverse environmental conditions allows overlapping generations to coexist, adding complexity to its population cycles. In Spanish forests, *P. nigra* and *P. sylvestris* are the most vulnerable to defoliation by the PPM, followed by *P. pinaster*, *P. halepensis*, and *P. pinea* (Romanyk and Cadahia, 1981).

Understanding the ecological behaviour of PPM in response to global change,

and its impact on pine populations across a broad geographical scale, is essential for developing effective adaptive management strategies. In this communication, we describe key research activities undertaken by the Cambium Group that focus on studying PPM population dynamics.

2. Field databases

In line with the Spanish Forestry Strategy (1999), several regional administrations have implemented a Plan for Integrated Control (PIC) to manage PPM populations over recent decades (Ros-Candeira *et al.*, 2019). A key component of the PIC is a monitoring program, which informs future management actions. Environmental agents conduct annual inspections of permanent monitoring units, with the collected data stored in specialized databases. Most administrations continue to use the six-level infestation scale, ranging from 0 to 5, as proposed by Montoya 1998, though some have expanded the number of levels. At Cambium Group, we have compiled and harmonized medium- to long-term spatial databases (spanning 10-40 years) from regional pest monitoring programs to enhance the consistency of these assessments. These databases provide detailed information on PPM abundance at the forest stand level (average 150 ha) allowing us to assess PPM population dynamics and variations at regional to national scales. This includes tracking potential shifts in incidence toward higher altitudes and more temperate pine forests.

To analyze population dynamics, each stand polygon is assigned an average altitude derived from a digital elevation model, along with the dominant pine species as indicated in the Spanish Forest Map. We provide annual summaries of infestation levels based on host species (*P. nigra*, *P. sylvestris*, *P. pinaster*, *P. halepensis*, *P. pinea*) and altitude.

Our findings, based on data from ten regional administrations *(Fig. 1a)*, indicate that the increased inspection area in Spain since 1992, particularly from 2008 onwards *(Fig. 1b)*, has significantly improved PPM monitoring at a medium spatial scale. This improvement facilitates better statistical reporting and aids in identifying medium to large outbreaks. Notably, significant outbreaks were recorded in 1991, 1998, 2007, and 2016, affecting *Pinus nigra*, *P. pinea*, and *P. pinaster (Fig. 1c)*. Additionally, there are signs of shorter outbreak periods at lower spatial scales, especially in southern regions, alongside the PPM´s expansion to higher altitudes in areas dominated by *P. nigra*. While more precise spatial records are necessary for detailed studies and mapping of infested areas, the harmonized database offers valuable insights into the spatial patterns of PPM distribution. It underscores the importance of regional monitoring programs in understanding PPM behaviour on a broader scale, particularly in the context of ongoing global change.

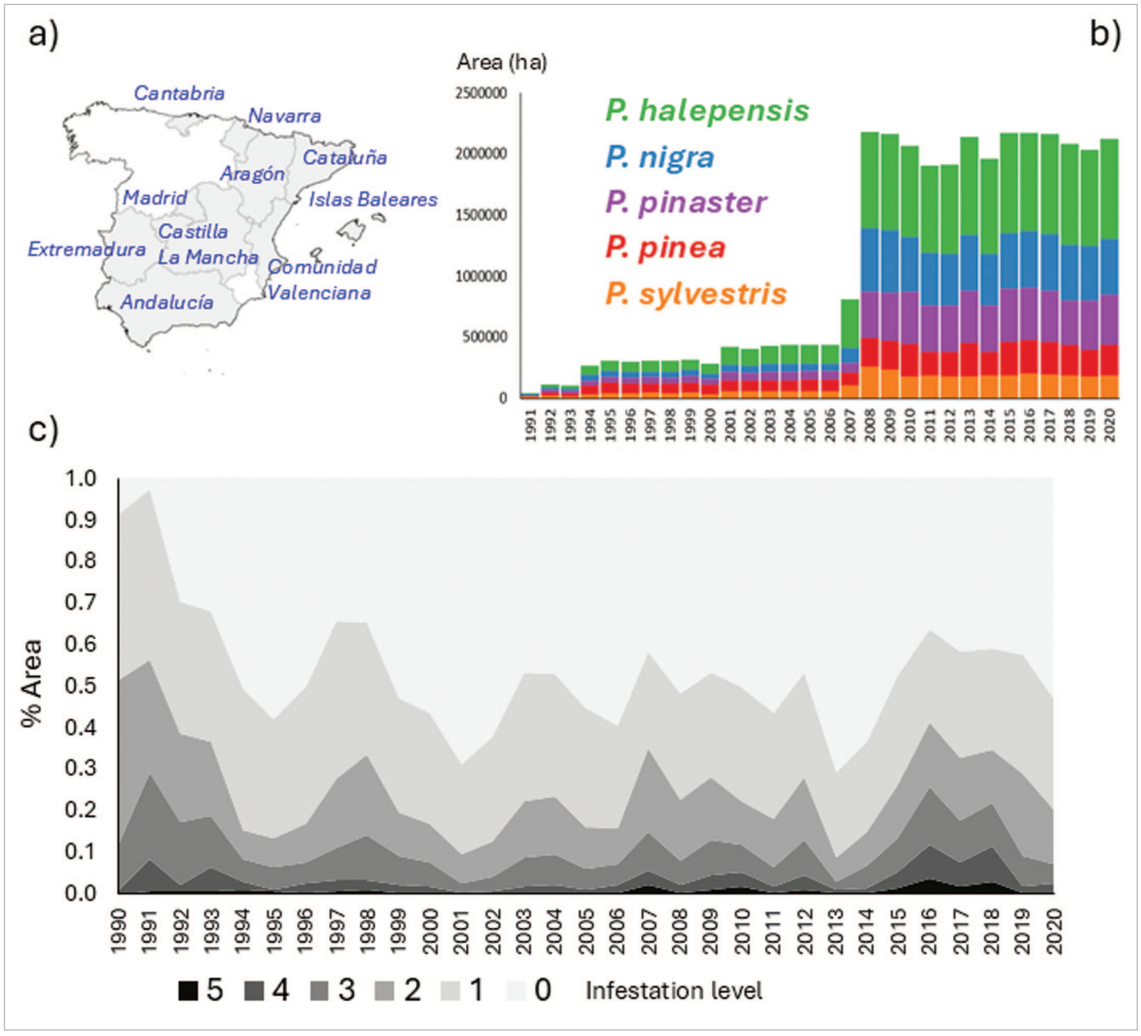

Figure 1. Overview of national PPM incidence over time from regional PPM monitoring programs. a) Regions with active monitoring programs which data are included here. b) Nationwide trends in the total monitored area for each species. c) Proportion of permanently monitored areas impacted by infestations across infestation levels 0 to 5.

Domingo *et al.* (2024a) integrated field records with climate data to gain deeper insights into how climate influences PPM populations. Their analysis, based on data from a latitudinal gradient (37º to 42º N) across regional databases, aimed to assess whether warmer temperatures modulate PPM outbreaks. Specifically, the study examined the relationships between PPM population dynamics and climatic conditions during the moth´s most vulnerable development stages in Andalucía, Castilla-La Mancha, and Navarra. The central hypothesis proposed that warmer winter temperatures would promote PPM growth during the larval feeding stage, while extreme summer heat would reduce survival at the egg and early larval stages, resulting in the counterbalancing effects of climate warming.

The study analyzed 26 years of monitoring data from 2465 forest stands dominated by *P. nigra* and *P. sylvestris*. Cumulative Link Mixed Models (CLMM) were

used to assess the impact of climatic variables on four levels of PPM defoliation severity. The findings revealed that warmer winter conditions enhance PPM larval survival and increase infestation rates, while high summer temperatures reduce population size in the early life stages *(Fig. 2)*. Specifically, the population growth driven by warmer winters during the larval defoliation stage was offset by declines caused by extreme summer heat affecting eggs and early larvae. This research underscores the need to consider abiotic factors throughout the entire PPM life cycle to fully understand how climate change shape insect outbreaks. Such insights are critical for assessing the implications for wood production and carbon sequestration in Mediterranean forests.

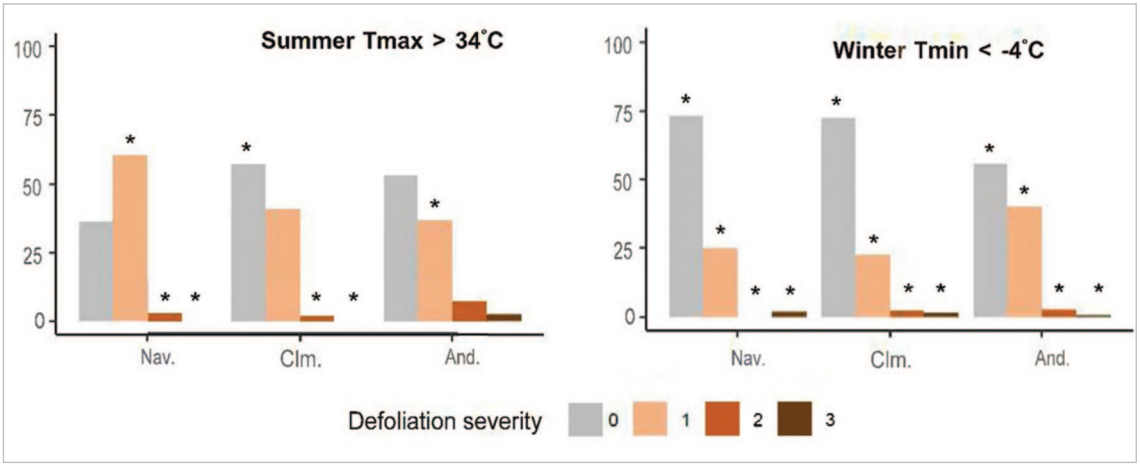

Figure 2. Average percentage of forest stands affected by defoliation severity levels under selected maximum (34 °C) and minimum (–4 °C) weekly temperatures. Asterisks indicate that statistically significant differences exist ($P<0.05$), based on Willconson tests, between summer Tmax <34 °C *vs* summer Tmax >34 °C, or between winter Tmin>–4 °C *vs* winter Tmin <–4 °C. Source: Domingo *et al.*, 2024a

3. Remote sensing tools

Remote sensing is a uniquely capable tool for monitoring forest canopy changes at a range of spatial resolutions, from tree level scale to entire landscapes. Using data gathered from drones, airplanes, or satellites—especially in the optical range of the electromagnetic spectrum—this technology can detect subtle shifts in vegetation vigor. Transitioning between spatial scales requires synthesizing information from diverse data sources to form a cohesive understanding of forest dynamics. For example, drone imagery provides detailed insights into tree-level conditions, while satellite data delivers a broader, landscape-wide perspective. Integrating these datasets, collected through different sensors and platforms, enables model calibration and validation across scales, significantly improving the precision of canopy change assessments. The growing availability of high-resolution, high-frequency temporal data has enabled the development of advanced time series algorithms. When trained with accurate reference data, these algorithms can precisely identify and quantify

changes in pine canopies potentially associated with PPM activity. Our research aims to evaluate the performance of algorithms such as BEAST (Bayesian Estimator of Abrupt change, Seasonality, and Trend, Zhao *et al.*, 2019) or EdyN (Exponentially Weighted Moving Average Change Detection, Brooks *et al.*, 2017) in detecting large-scale PPM winter defoliations, with the goal of producing long-term outbreak maps dating back to 1990. These algorithms analyze dense time series of spectral data to establish baseline patterns spanning multiple seasons. This approach allows for the detection of subtle anomalies that can occur at any time of the year, providing reliable indicators of defoliation events. By capturing deviations from the established seasonal norms, these algorithms enhance the ability to identify and monitor changes in vegetation health.

At smaller spatial scales, Cambium Group conducts extensive research using drone data to monitor defoliation and track changes in forest health over time. For instance, since December 2022, we have been acquiring multispectral and thermal data monthly over two experimental plots in Cañón de Río Lobos, Soria, Spain. Remote sensing active sensors, particularly LiDAR, allows for a detailed characterization of forest structure and canopy density. Thus, in these experimental plots, high-density drone-based LiDAR data, collected both before and after the 2023 defoliation season, enabled Domingo *et al.* (2024b) to assess morphological changes in tree canopies affected by PPM. Their study revealed that PPM reduced needle density by an average of 23 % during a moderate defoliation episode, when comparing affected trees to unaffected ones *(Fig. 3)*. Additionally, LiDAR offers valuable insights into the relationship between forest stand structure and PPM incidence, aiding in the identification of planting conditions that may reduce vulnerability to infestations. LiDAR-derived structural data reveal that pine stands are more

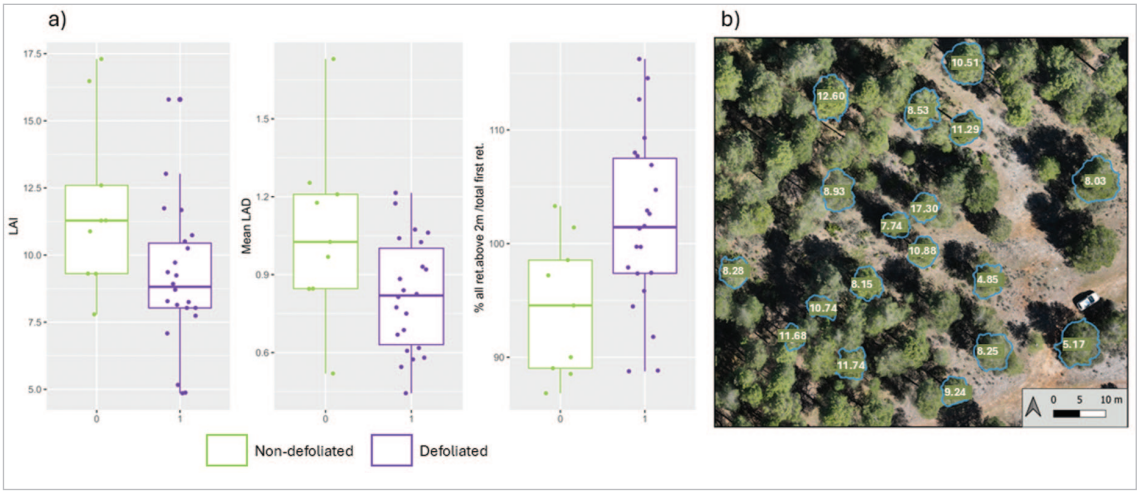

Figure 3. Structural impact of PPM on individual tree canopies in experimental plots at Cañón de Río Lobos, Soria, Spain. a) Boxplots of LiDAR metrics comparing non-defoliated and defoliated trees. LAI: Leaf Area Index; Mean LAD: Mean Leaf Area Density; % all ret. above 2m/total first ret.: Percentage of all returns above 2m relative to total first returns. b) Aerial view of one experimental plot showing individual tree LAI loss due to PPM. Source: Domingo *et al.* (2024b).

susceptible to PPM when the canopy exhibits structural continuity and lacks heterogeneity. This information is critical for developing management strategies that promote canopy diversity and disrupt the conditions that facilitate PPM outbreaks.

4. Dendrochronology

PPM winter defoliation results in the formation of narrow tree rings, as the tree reallocates resources to generating a new crown in the following spring. This resource shift, combined with the crown's diminished capacity for carbon capture, reduces the tree's secondary or radial growth for at least one year after the defoliation event (Sangüesa-Barreda *et al.*, 2014). Consequently, analyzing tree rings from PPM affected pines using dendrochronology enables to trace the history of PPM defoliations over centuries. However, the challenge lies in distinguishing these growth rings related to PPM outbreaks from those caused by other disturbances like droughts.

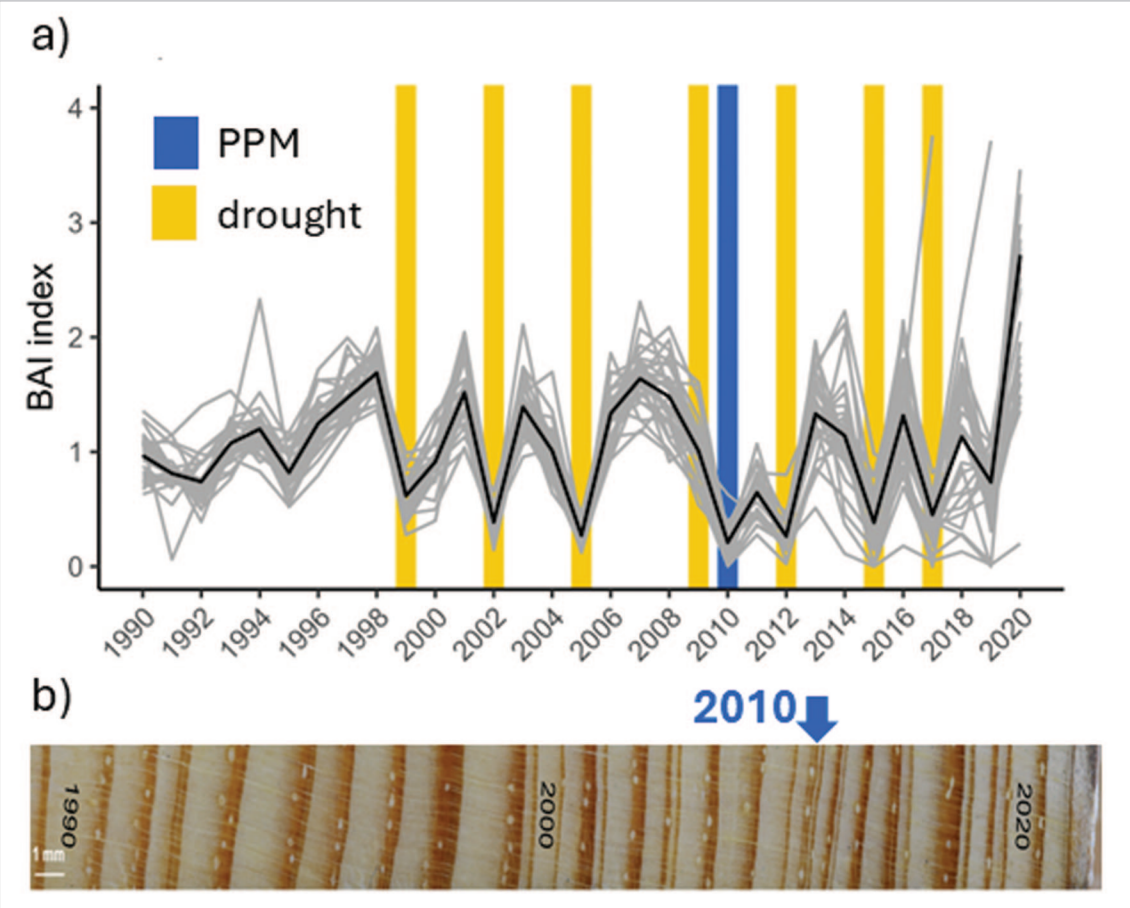

Figure 4. Impact of disturbance on tree-ring growth. a) Example of variation in detrended Basal Area Increment (BAI) for a *P. nigra* stand from 1990 to 2020, with disturbance events highlighted. The black line represents the mean detrended BAI. b) Close-up view of tree rings from a sample.

Houdas *et al.* (2024) tackled this issue by studying affected pine stands of *P. nigra* and *P. sylvestris* in Spain, employing a multiproxy approach that included within stand tree growth variability, latewood percentage, and intrinsic water-use efficiency. This research identified specific characteristics of PPM-related tree rings that set them apart from those formed due to drought stress. For example, the authors conclude that PPM outbreaks cause greater variability in tree growth within a stand compared to droughts, due to the uneven intensity of defoliation affecting individual trees. Additionally, wood´s functional parameters such as water-use efficiency showed distinct changes, with significantly lower values during PPM events. This decrease is attributed to a higher sapwood-to-needle ratio compared to drought years. Furthermore, PPM events influence the proportion of earlywood, formed in spring and early summer, and latewood, formed in late summer and autumn, differently than droughts do *(Fig. 4)*.

This dendrochronology-based framework combining various tree ring traits offers a reliable method for identifying PPM defoliation events over trees' lifespan, covering several centuries for some of the oldest Mediterranean pines.

5. Concluding remarks and prospects

The pine processionary moth (*Thaumetopoea pityocampa*) poses an increasing threat to Mediterranean forests, with its spread and impact closely linked to climate variability. Cambium Group studies the underlying causes and distribution patterns of this species using a combination of field data, remote sensing, and dendrochronology. Their research aims to enhance understanding of the moth´s populations and ultimately to develop advanced monitoring and early detection tools.

The effectiveness of remote sensing tools with spatial resolutions of 10-30 meters for monitoring and early detection of forest damage is enhanced when combined with field data, which plays a critical role in calibrating and validating these systems. Precise field observations, such as pinpointing the location of defoliated trees within stands, are essential for fine-tuning algorithms that enable accurate monitoring and near real-time damage assessments. Regional monitoring programs in Spain, while valuable, often operate at spatial scales that are too large and contain varying levels of defoliation, limiting their usefulness for effectively training detection algorithms. To address this, more precise spatial localization of field data is necessary. Cambium group supplements this need by collecting its own field observations for calibration and advocating for administrations to identify PPM hotspots more accurately within monitored units. Expanding databases with precise locations will enhance model calibration, leading to improved algorithm performance and more reliable forest damage detection.

Recent advancements in dendrochronology, both in software and hardware, have significantly accelerated the processing and analysis of xylem samples. Alongside progress in identifying PPM defoliation events through distinctive tree-ring characteristics, these developments offer the potential to rapidly reconstruct the historical

occurrence of PPM. When combined with remote sensing technologies, this method could provide forest managers with more precise tools to adapt their management strategies based on detailed PPM incidence data.

Cambium Group continues its efforts to deepen our understanding of how forest structure influences vulnerability to PPM, recognizing that the interaction between climate, forest management practices, and PPM dynamics is critical for fostering more resilient forest ecosystems. We are working on the development of technological tools for monitoring PPM populations at various scales, from individual trees to entire stands, using a range of sensors, including multispectral, thermal, and LiDAR. Our research highlights the potential of established technologies such as remote sensing and dendrochronology to effectively diagnose forest health. Incorporating these technologies into operational monitoring systems offers a practical solution to complement and alleviate the demanding tasks associated with traditional methods. Furthermore, these tools hold promise for monitoring and tracking other forest pests and diseases, broadening their applicability. Addressing the threats posed by PPM and other forest pests requires a multidisciplinary approach that integrates ecological research, climate modelling, and advanced monitoring technologies. To this end, Cambium Group collaborates with the private sector and forest administrations in developing an alert system that leverages historical data, expert knowledge, climate predictions, and modelling. This system aims to provide early warnings and robust tools for monitoring PPM impacts, contributing to proactive forest management and pest mitigation strategies.

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