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ORIGINAL PAPER

Current and future distribution of the invasive oak processionary moth

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Abstract Predicting shifts in the distribution and abundance of pest organisms relies on an accurate forecasting of their response to climate change. The oak processionary moth (OPM) *Thaumetopoea processionea* causes serious damages to oak trees in forest, urban and other landscapes as well as severe allergic reactions to humans and animals. In the 1990's and 2000's, the OPM extended its range from mainland Europe and the Middle East into northern Europe. In 2005, it was also accidentally introduced in the United Kingdom. Moreover, the intensity and the frequency of OPM outbreaks are thought to have recently increased in several countries of Europe including Belgium, the Netherlands, Germany and Austria. In the present study, we aimed at forecasting the potential distribution of the OPM in Europe under current and future climate conditions. We thoroughly compiled available records of established populations all across Europe and fitted MaxEnt and BIOCLIM models to infer bioclimatic requirements for this species. Both models showed good predictive performance under current climate conditions. In particular, the surroundings of London where the OPM recently got established were predicted as highly climatically suitable. Models also predicted that many parts of northern Europe where the OPM currently does not occur (e.g. central UK, Wales, Ireland, southern Scotland, Denmark, southern part of the Scandinavian Peninsula, etc.) might become climatically suitable by 2050. Our predictions warrant the need for proper communication and management planning around the risks associated with the potential expansion of the OPM in Europe.

Keywords Biological invasion · Species distribution models · *Thaumetopoea processionea* · *Quercus* · Pest risk assessment · Invasion risk assessment · MaxEnt

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Introduction

Range shifts of pests and pathogens are arguably one of the most significant threats to ecosystems and human activities worldwide. Over the last decades, species shifts have occurred at unprecedented rates, notably in response to new introductions through human transportation networks (Hulme 2009) and changes in environmental suitability due to global warming (Walther et al. 2009). Invasive organisms affecting human health (McMichael and Bouma 2001) or natural and agricultural ecosystems (Williamson 1996; Pejchar and Mooney 2009), are particularly concerned.

The oak processionary moth (OPM) *Thaumetopoea processionea* (L.) (Lepidoptera: Notodontidae) is a pest of oak trees native from Europe and the Middle East. It is characterized by unpredictable outbreaks (Groenen and Meurisse 2012; Battisti et al. 2015), which may cause severe defoliations of oak trees in forests, urban and other landscapes (Stigter et al. 1997; Roversi 2008; Wagenhoff and Veit 2011; Battisti et al. 2015). This species is notorious as a public health and veterinary threat because the urticating setae of its larvae can trigger severe allergic reactions to humans and animals (Neumann and Koekkoek 1996; Maier et al. 2003; Battisti et al. 2011, 2017; Mindlin et al. 2012).

The OPM host range comprises several oak species including *Quercus cerris*, *Q. boissieri*, *Q. frainetto*, *Q. robur*, *Q. petraea*, *Q. pubescens*, *Q. pyrenaica* and *Q. calliprinos* (Pascual 1988; Stigter et al. 1997; Démolin and Nemer 1999; Halperin and Sauter 1999; Battisti et al. 2015). It has a univoltine life cycle (Dissescu and Ceianu 1968; Pascual 1988; Wagenhoff and Delb 2011). Eggs usually hatch in April or early May, and caterpillars gregariously feed until mid-June or early July. Neonate caterpillars feed on swollen and flushing oak buds, whereas older larvae can feed on fully developed leaves (Wagenhoff and Veit 2011). They later pupate in large communal tents in the branches or on the trunk. Adult generally emerge from mid-July to mid-September (Dissescu and Ceianu 1968; Pascual 1988; Wagenhoff and Delb 2011), and females lay egg masses comprising 50–200 eggs on the terminal oak branches (Dissescu and Ceianu 1968). The OPM overwinters as an embryo and egg hatching occurs next spring synchronously with oak bud flushing (Stigter et al. 1997; Wagenhoff and Delb 2011).

Increasing winter and spring temperatures in Europe may explain the stronger and more frequent OPM caterpillars outbreaks observed in several countries including Belgium, Germany, Austria and the Netherlands (Stigter et al. 1997; Groenen and Meurisse 2012). However, the OPM is not present in the northern part of the range of two of its preferred hosts, namely *Quercus petraea* and *Q. robur* (Groenen and Meurisse 2012). This is apparently because cold winter and/or spring temperatures have a detrimental effect on OPM eggs and larvae (Meurisse et al. 2012). For instance, no established colonies (i.e. nests and larvae) have ever been recorded across some northern regions of Germany and throughout Scandinavia, despite recurrent interception of males in pheromone- and light traps (Skule and Vilhelmsen 1997; Franzén and Johannesson 2005; Lövgren and Dalsved 2005).

Nevertheless, milder winters and an increased frequency of warm and dry springs in the recent decades could have played a role in the northern range expansion of the OPM (Meurisse et al. 2012; Wagenhoff et al. 2013). This has been shown for the congeneric pine processionary moth (PPM), which has expanded northwards and to higher altitudes in response to an increase in the mean of minimum temperature in winter (Battisti et al. 2005; Robinet et al. 2007).

The unintentional transportation of processionary caterpillar colonies into new areas is another cause of range shifts. Human-aided dispersal in regions that already became climatically suitable has been recently shown to accelerate the range expansion of the PPM in northern France (Roques et al. 2015b). In 2006 OPM colonies accidentally imported from the continent were recorded for the first time in the British Isles (Townsend 2008). The species was presumably introduced into West London with imported ornamental cypress oak trees (*Quercus robur* "*Fastigiata Koster*") from the Netherlands (Townsend 2013). Since then and despite control measures and eradication attempts, the OPM has colonized the surroundings of this city. It is now considered that the range of the OPM will continue to increase in the United Kingdom (Townsend 2013).

The OPM being of serious concern for forestry and public health, the present study aims at exploring its response to climate changes and estimating its potential range. Although attempts have been made to forecast the potential range of OPM in UK (EFSA, 2009), no study explicitly compiled full information on the OPM range to accurately forecast its future spread in Europe. To achieve this goal, we compiled records on OPM occurrence in order to fit species distribution models (SDMs). We used the resulting models to estimate both current (2000) and future (2050 and 2070) potential geographic distributions. Our predictions provide crucial information for the design of future management and communications strategies in affected regions, notably in the UK.

Materials and methods

We used correlative SDMs, which aim at establishing statistical relationships between species' presence/absence and environmental conditions in order to predict their potential distribution in new geographic regions and/or under climate change scenarios (Peterson 2011). As oak distribution exceeds OPM range (Groenen and Meurisse 2012), we assume that climate is the main constraint acting on OPM distribution and thus fitted SDMs with climate descriptors only. Although SDMs depict the *realized* niche of species (*sensu* Hutchinson 1957) thereby occasionally failing to fully capture their environmental tolerances (Broennimann et al. 2007), these approaches usually perform well in predicting the range of invasive species (Peterson and Vieglais 2001; Peterson 2003; Petitpierre et al. 2012; Rey et al. 2012; Strubbe et al. 2013; Godefroid et al. 2016a) and the response of species to global change (Araújo et al. 2005).

Bioclimatic variables

We modelled the distribution of the OPM using bioclimatic descriptors available from the Worldclim 2.0 database at a resolution of 2.5 arc-min ($\sim$ 5 km in latitude and 1.5 to 3.75 km in longitude) (Fick and Hijmans 2017). Specifically, we used the maximum temperature of the warmest month of the year (bio5), the minimum temperature of the coldest month of the year (bio6), the precipitation of the wettest quarter (bio16) and the precipitation of the driest quarter (bio17). These four bioclimatic data were derived from monthly temperatures and rainfall averages for the period 1970–2000 (Fick and Hijmans 2017). We used two climatic datasets, referred to as CLIM1 and CLIM2 respectively, to fit the models. The CLIM1 dataset comprised bio5 and bio6, only accounting for temperature extremes [which presumably induce the strongest physiological stresses to the OPM (Meurisse et al. 2012)]. The CLIM2 dataset also includes bio16 and bio17, in order to account for a rainfall regime that could affect the growth of OPM populations directly or indirectly (via an effect on oak hosts). Within the region under study, descriptors were not highly correlated (all between pair Pearson's correlation indices < 0.75).

Occurrence data

A total of 6537 records were collected from the scientific literature, field surveys, museum collections and different national databases (Fig. 1). We removed records: (1) whose coordinates were missing or erroneous, (2) that were not indicative of an established population (i.e. males only), (3) that were collected after 2000 (because we wanted to match the bioclimatic dataset which relates to the 1970–2000 period) and (4) that were duplicated. We additionally controlled for occurrence spatial clustering by removing points close to each other in the bioclimatic spaces defined by the variables in CLIM1 and CLIM2 (Varela et al. 2014). This was performed to reduce the possible negative impact on the predictive performance of models due to spatial heterogeneity in oak abundance and uneven sampling effort throughout the native range of the OPM (Kramer-Schadt et al. 2013; Varela et al. 2014). In the case of CLIM1, we removed records aggregation in a bi-dimensional plan whose axes are the bioclimatic descriptors values extracted at each pixel throughout the European continent bioclimatic rasters (i.e., a square comprised between longitudes − 10° W and 50° E and latitudes 30° N and 72° N—excluding sea). Each axis of this bi-dimensional plan was then divided in 100 intervals and we allowed only one OPM occurrence by pixel in this 100 × 100 intervals grid. In the case of CLIM2, we removed records aggregation in a bi-dimensional plan whose axes are the two first axes of a Principal Component Analysis (PCA) conducted on the bioclimatic descriptors extracted at each pixel throughout the European continent bioclimatic rasters. Similarly, each axis of this bi-dimensional plan was then divided in 100 intervals and we allowed only one occurrence by pixel in this 100 × 100 intervals grid. The final occurrence dataset comprised a total of 92 records for

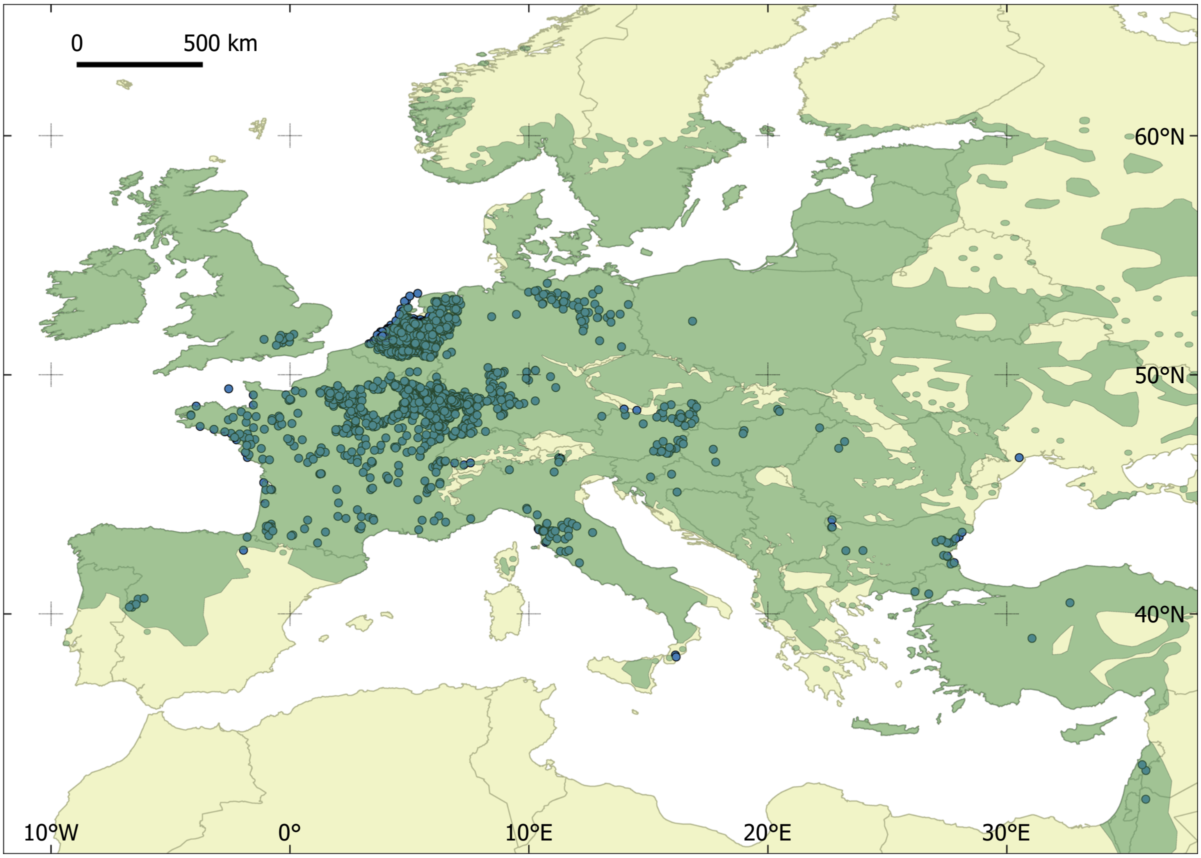

Fig. 1 Occurrences of the oak processionary moth *Thaumetopoea processionea* collected from the scientific literature, field surveys, museum collections and different national databases. The green-shaded area represents the cumulative distribution of the host trees *Quercus boissieri*, *Q. calliprinos*, *Q. cerris*, *Q. frainetto*, *Q. petraea*, *Q. pubescens*, *Q. pyrenaica* and *Q. robur*. Occupancy for *Q. robur* and *Q. petraea* was obtained from the EUFORGEN database (EUFORGEN 2019). Occupancy for *Q. cerris, Q. pubescens* and *Q. pyrenaica* was obtained from the forest trees grid maps from the Joint Research Center database (JRC 2019). Occupancy for *Q. boissieri, Q. calliprinos* and *Q. frainetto* was obtained from Seigue (1985)

CLIM1 and 137 records for CLIM2 bioclimatic datasets (Online Appendices 1a and 1b).

Species distribution modelling

We modelled the distribution of the OPM using the BIOCLIM and MaxEnt models. Both methods attempt to infer species bioclimatic requirements based on presence data points (here OPM records in the two aforementioned climatic datasets CLIM1 and CLIM2). BIOCLIM does not make any assumption about the potential absence of the organism under study and relies on a bounding box to determine the climatic envelope (Busby 1991; Booth et al. 2014). The MaxEnt approach is based on the maximum entropy method (Phillips et al. 2006). We selected the MaxEnt modelling approach because it was ranked among the best-performing presence-only SDM methods (Elith et al. 2006; Wisz et al. 2008). Unlike BIOCLIM, it also considers the climatic conditions encountered in a set of locations where no records exist for the species (usually called background locations). The selection process of background locations and the extent of the background area is crucial in MaxEnt as it may significantly alter the predictions of the models (VanDerWal et al. 2009). We generated 10,000 random background points within a wide area (i.e. a square comprised between longitudes − 10° W and 50° E and latitudes 30° N and 72° N—excluding sea and the British Isles, as well as all presence locations for OPM). Before running the models, we first searched for the best MaxEnt parameters to avoid model overfitting (Radosavljevic and Anderson 2014). To achieve this, we fitted MaxEnt models with different rate multiplier values (from 0.5 to 4 with increments of 0.5) and six feature classes (1. Linear; 2. Linear + quadratic; 3. hinge; 4. linear + quadratic + hinge; 5. linear + quadratic + hinge + product; 6. linear + quadratic + hinge + product + threshold) using the R package ENMeval (Muscarella et al. 2014). The selection of the best combination of MaxEnt parameters was based on AICc (see Muscarella et al. 2014 for a full explanation of this method). Then, we fitted 10 replicated BIOCLIM models and 10 replicated MaxEnt models (i.e., with the previously selected MaxEnt best settings) using training datasets constituted by random subsets of 90% of the relevant occurrences and with 10,000 background points. Models were replicated 10 times (i.e., each model was performed with a newly-generated evaluation/training partitioned dataset) to account for the uncertainty arising tenfold cross-validation. The predictive performance of each model was evaluated using the remaining 10% of available occurrences and 1000 randomly selected background points. For each replicate model, we calculated the area under the receiver–operator curve (AUC Fielding and Bell 1997) and the continuous Boyce index, which is a presence-only evaluation measure that is relatively insensitive to species prevalence (Hirzel et al. 2006).

We mapped the average climate suitability for OPM presence predicted by the 10 model replicates across Europe, and based on average climate records for the period 1970–2000. We replicated this for the two climatic datasets CLIM1 and CLIM2, and using both the BIOCLIM and the MaxEnt approaches. For each model, we also derived a map of potential distribution based on presence/absence binary predictions for all model replicates. The binary predictions were obtained for each model replicate, by implementing the threshold that maximized the sum of sensitivity and specificity from the performance evaluation (Fielding and Bell 1997). We performed models, computations and mapping using the "dismo" (Hijmans et al. 2013), "ecospat" (Broennimann et al. 2014) and ENMeval (Muscarella et al. 2014) packages in R (R Core Team 2018).

Predictions under future climate conditions

We predicted maps of average climate suitability and potential distribution for OPM under future climate conditions, for years 2050 and 2070 according to predictions reported in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). Prediction data from the Model for Interdisciplinary Research on Climate version 5 MIROC5 (Watanabe et al. 2010) were extracted from the WorldClim database, at a resolution similar to the one used for model calibration (2.5 arc-min). These estimations of future climate are considered among the most reliable (Flato et al. 2013). For each global climate model (GCM), we mapped predictions of the future climate suitability for OPM as well as estimates of the potential distribution of OPM for two representative greenhouse gas concentration pathways (RCP4.5 and RCP8.5, which speculate moderate and extreme future greenhouse gas emissions respectively) (Van Vuuren et al. 2011). We replicated this for the two climatic datasets CLIM1 and CLIM2, and using both the BIOCLIM and the MaxEnt approaches.

Results

All models had substantial predictive power displaying AUC and Boyce index greater than 0.79 and 0.38, respectively, indicating a better prediction of species presence than a random model. Based on AICc, a rate multiplier of 1 and the feature class 'linear + quadratic + hinge + product' were the best settings for MaxEnt models fitted with CLIM1. Based on AICc, a rate multiplier of 1.5 and the feature class 'linear + quadratic + hinge + product + threshold' were the best settings for MaxEnt models fitted with CLIM2.

All MaxEnt and BIOCLIM models accurately predicted the current range of the OPM in mainland Europe and in the UK as climatically suitable for the period 1970–2000 (Figs. 2a, b, 3a, b; Online Appendices 2, 3, 4 and 5). A good agreement between models was also observed for countries in the Scandinavian Peninsula, which were overall predicted as climatically unsuitable (Figs. 2a, 3a; Online Appendices 2, 3, 4 and 5).

Conversely, mismatches between models were observed for several other regions located at the limits of the current range of the OPM (Figs. 2a, 3a; Online

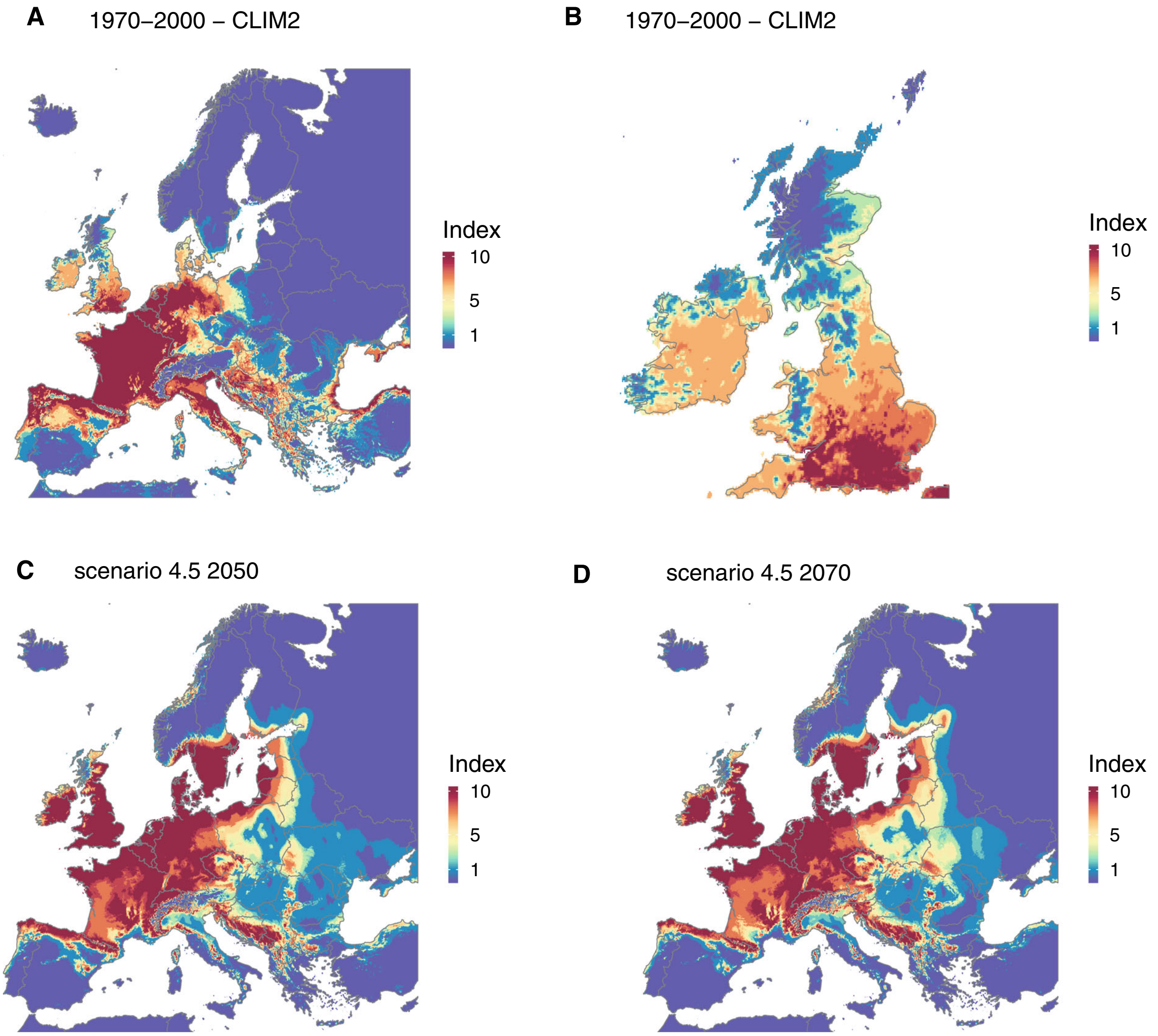

Fig. 2 Climate suitability for the oak processionary moth *Thaumetopoea processionea* in Europe as predicted by MaxEnt models fitted with the climatic dataset CLIM2 (i.e. maximum temperature of the warmest month of the year, the minimum temperature of the coldest month of the year, the precipitation of the wettest quarter and the precipitation of the driest quarter) under climate conditions relative to the period 1970–2000 (**a**, **b**) and under predicted climate conditions in 2050 (**c**) and 2070 (**d**). Predictions under future climate conditions are provided for the RCP4.5 greenhouse concentration pathways. Maps yield the number of models (out of 10 replicates) predicting a presence when implementing a threshold maximizing the sum of sensitivity and specificity. Maps were projected using a lambert azimuthal equal-area projection

Appendices 2, 3, 4 and 5). In the northern countries, the northern parts of the Netherlands and Germany, and most of Denmark, were generally considered more suitable by MaxEnt than by BIOCLIM. The Western part of Poland, on the contrary, was generally considered more suitable by BIOCLIM than by MaxEnt. The two models also diverged in Portugal (MaxEnt predicting a wider potential distribution), and in most low- to moderate-altitude areas in eastern Europe (BIOCLIM predicting a wider potential distribution) (Figs. 2a, 3a; Online Appendices 2, 3, 4 and 5).

In the UK, most of MaxEnt models considered large parts of England as suitable (Fig. 2b; Online Appendices 2–4), whereas the majority of BIOCLIM models estimated London and its surroundings and some parts of southern England as the only area suitable for OPM establishment (Fig. 3b; Online Appendices 3–5). Wales and Scotland were

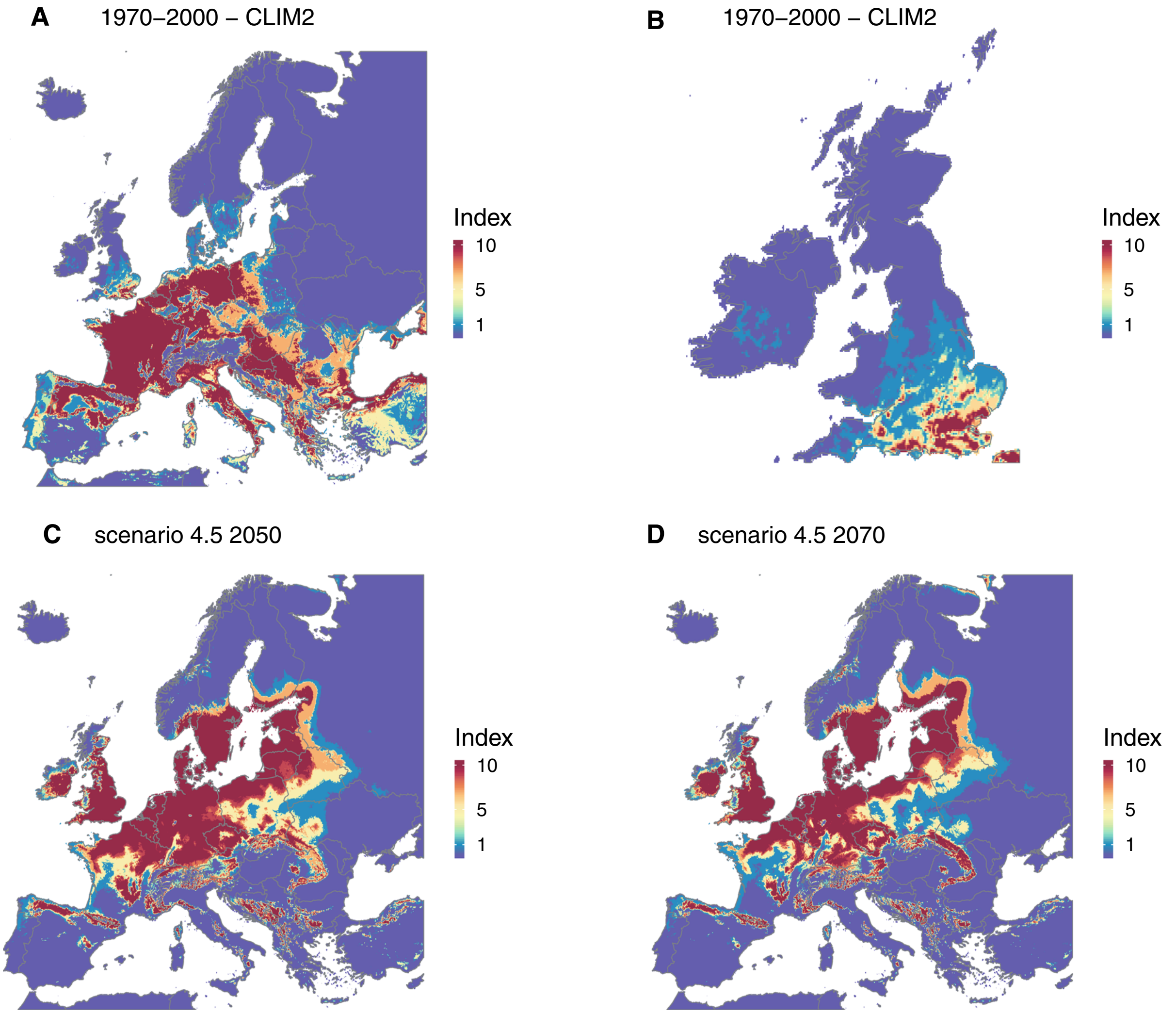

Fig. 3 Climate suitability for the oak processionary moth *Thaumetopoea processionea* in Europe as predicted by BIOCLIM models fitted with the climatic dataset CLIM2 (i.e. maximum temperature of the warmest month of the year, the minimum temperature of the coldest month of the year, the precipitation of the wettest quarter and the precipitation of the driest quarter) under climate conditions relative to the period 1970–2000 (**a**, **b**) and under predicted climate conditions in 2050 (**c**) and 2070 (**d**). Predictions under future climate conditions are provided for the RCP4.5 greenhouse concentration pathways. Maps yield the number of models (out of 10 replicates) predicting a presence when implementing a threshold maximizing the sum of sensitivity and specificity. Maps were projected using a lambert azimuthal equal-area projection

considered largely unsuitable by both approaches (Figs. 2b, 3b; Online Appendices 2, 3, 4 and 5). We observed slightly contrasted predictions for Ireland, with the MaxEnt predictions differing when considering only temperature (CLIM1 model, most of the island suitable) or temperature and precipitations (CLIM2 model, inland areas suitable), while BIOCLIM considered the entire island unsuitable (Online Appendices 2, 3, 4 and 5).

While addressing future temperature scenarios, both bioclimatic models predicted that the North of Germany, large parts of the British Isles and large regions in northern Europe (Denmark, Sweden, the coastal areas of Norway and the countries in the Baltic region) might become highly suitable by 2050 and 2070 (Figs. 2c, d, 3c, d; Online Appendices 6, 7, 8, 9, 10, 11, 12 and 13). Similar predictions were made for some high-altitude areas and mainland regions of continental Europe. These trends were globally similar when calibrating SDMs with the climatic datasets CLIM1 and CLIM2, but stronger when considering the scenario 8.5 that assumes high temperature increase (Online Appendices 6, 7, 8, 9, 10, 11, 12 and 13). Models also predicted that the southern parts of the current range of the OPM might become unsuitable by 2050 and 2070, in particular in Italy, Spain, southern France, Turkey, Greece and in the Balkans (Figs. 2c, d, 3c, d; Online Appendices 6, 7, 8, 9, 10, 11, 12 and 13).

Discussion

Potential distribution of the OPM in the UK

Our study provides the first forecast of the potential distribution of the OPM in Europe. Such estimations are crucial for the design of future containment strategies in northern Europe, notably in the UK where the species has been expanding since the early 2000s. Interestingly, both MaxEnt and BIOCLIM point towards bioclimatic similarities between south-eastern England and parts of the native range of the OPM. This suggests that the current establishment and spread of this species in the UK is neither associated to a climatic niche shift nor a direct consequence of global change. However, our bioclimatic models forecast that most of the UK (including central England, Wales, southern Scotland and Ireland) is currently less suitable for the establishment of the OPM than the southeastern part of England. These regions are expected to become highly climatically suitable for the OPM establishment by 2050 and 2070. One can thus expect that this pest will expand its range from London and neighbouring counties to most of the country in the near future.

Climatic suitability in other countries in Europe

In some countries where the OPM is considered as native, a concern is also rising since the frequency and intensity of OPM outbreaks are thought to have increased during the last decades (Stigter et al. 1997; Maier et al. 2003; Jans and Franssen 2008; Wagenhoff and Delb 2011). These outbreaks have become particularly intense in some regions at the northern edge of the OPM distribution range (Belgium, Netherlands, Germany). A process of recolonization has also been described following an apparent disappearance of all local populations during the early twentieth century and was suggested to be a consequence of a recent local increase of temperature (Groenen and Meurisse 2012). Indeed, the North of the Netherlands was predicted as moderately climatically suitable for OPM during the period 1970–2000 (Figs. 2a, 3a). While addressing the potential effects of climate change on the OPM distribution, both MaxEnt and BIOCLIM models predicted a substantial shift in climatically suitable regions in mainland Europe by 2050 and 2070. In particular, several European regions where the OPM is currently not present despite the presence of oak trees are expected to become climatically suitable in the near future (e.g. northern Germany, southern Scandinavia, Baltic countries, northern Poland, etc.).

Climatic suitability in southern Europe

Warmer regions of Europe where the OPM is presently distributed (e.g. southern France, Italy, Greece, Turkey and the Balkans) could become unsuitable by 2050 and 2070 according to model projections. We suggest that predictions of future potential OPM range in warm southern regions of Europe should be guardedly interpreted. MaxEnt discriminates presence of OPM against background regions where the presence/absence status of the OPM is unknown. While we are confident that tolerances to low temperatures were well captured by the models since the OPM does not occur in many cold northern regions where its preferred host *Q. robur* occurs (Groenen and Meurisse 2012), higher uncertainty might be associated to model inferences regarding the response of OPM to high temperatures. Indeed, the absence of the OPM in southern Europe might be firstly explained by the absence of its preferred hosts in these regions. In addition, while the detrimental effect of cold temperatures on the life cycle OPM is gaining an understanding (Meurisse et al. 2012), little is known on the species tolerance to high temperatures, which suggests that caution is needed in interpreting model outputs predicting OPM disappearance in southern regions.

Model accuracy

Because predicting potential species distributions under scenarios of climate change is a difficult task, we reduced occurrence aggregation in the environmental space and purposely calibrated models with a small number of bioclimatic descriptors to avoid overfitting and enhance models transferability in space and time (Peterson and Nakazawa 2008). Estimates of the potential range of the OPM were overall highly similar among models fitted with different climatic datasets. In addition, although AUC values need to be guardedly interpreted (Jiménez-Valverde et al. 2011), our models yielded good evaluation measures and adequately predicted the invaded areas in the UK and elsewhere, suggesting good model transferability.

At this stage however, it remains challenging to ascertain whether the currently limited distribution of the OPM in the UK reflects solely on climate unsuitability or also on dispersal constraints. This precludes a strict model selection procedure based on a presence/absence dataset in the UK. It is also worth noting that SDMs do not account for biotic interactions and dispersal constraints thereby depicting a subset of species environmental tolerances (Araújo and Peterson 2012).

Climate interactions with host plants

Changes in seasonal weather patterns may also indirectly affect phytophagous insects by disrupting phenological synchrony with their hosts. For instance, larval survival of the winter moth *Operophthera brumata* is strongly reduced if oak budburst occurs more than 5 days after egg hatching (Visser and Holleman 2001; Tikkanen and Julkunen-Tiitto 2003). As synchrony between oak bud flushing and egg hatching appears crucial for OPM larval development (Wagenhoff et al. 2013), such phenological constraints should be accounted for when estimating the potential distribution of OPM under future climate. If oak budburst occurs more than 2–3 weeks after egg hatching, starvation may cause mortality or hamper proper development of the neonate caterpillars, hence possibly causing the collapse of the entire OPM colony (Meurisse et al. 2012; Wagenhoff et al. 2013) Retrospective studies conducted so far have shown only a moderate increase in the phenological mismatch between oak budburst and egg hatching (Meurisse et al. (2012), for northeastern France, based on oak flushing and egg hatching models), or no influence at all (Wagenhoff et al. (2014), for southwestern Germany, based on phenological data and OPM egg hatching models). Although these findings suggest that the on-going climate change would not strongly affect this asynchrony, additional studies should be performed with extended datasets to consider other parts of the OPM range and/or future temperature scenarios. Egg hatching and oak budburst are driven by similar environmental cues, such as photoperiod and temperature, and could differ notably at high latitudes, or in regions where day lengths differ from the current range occupied by the OPM.

In addition to host phenology, many factors including extreme climatic events (Meurisse et al. 2012; Robinet et al. 2013), landscape structure (Cowley et al. 2015), intraspecific diversity (Peterson and Holt 2003; Rey et al. 2012; Godefroid et al. 2015), dispersal abilities (Godefroid et al. 2016b) and potential adaptations (Lavergne and Molofsky 2007) might also affect the spread of OPM and thus should be considered in further studies.

Conclusion

While the control of pests is a difficult task, the availability of accurate estimations of their response to climate change is a crucial prerequisite for the design of cost-effective and environment-friendly management strategies. In particular, predicting changes in distribution ranges is necessary to prevent or slow down the invasion of new territories and to communicate towards the human populations that are likely to be affected in the future.

Potential distribution maps of invasive pest organisms provide useful information for the design of containment strategies and the prioritization of regions to be monitored. In the case of the OPM, Tomlinson et al. (2015) underlined the difficulty of assessing and managing the combined risks for trees and people and the challenge of harmonizing the responses by private and public stakeholders. Mapping the areas with the highest likelihood of OPM spread and establishment improves the perception and evaluation of risk issues, hence facilitates communication with a wide range of actors (general public, private and public land owners, etc.) (Rossi et al. 2016). This could valuably improve risk governance and coordination in decision-making for pest management. Further, other tools such as spread and population models could be developed in order to better understand and predict the spatial dynamics and expansion of insect pest species such as the OPM (Roques et al. 2015a). Maps are efficient element of communication that may also foster citizen involvement in the process of reporting occurrences of the OPM hence improving early detection and pest management (Pocock et al. 2017).

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Author contribution All authors collected the data and MG performed the statistical analyses; all authors designed the study and contributed to writing.

Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

Human and animal rights This article does not contain any studies with human participants or animals performed by any of the authors.

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