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Factors Affecting the Geographical Distribution of the Bee Moth, *Aphomia sociella*, Utilizing Species Distribution Modeling Approach

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ABSTRACT

The bee moth *Aphomia sociella* is considered a pest of managed bee colonies. In this study, its current and future potential distribution was modeled using MaxEnt to improve understanding of the climatic factors governing its range. The model performed reliably with area under the curve = 0.809±0.003, showing low omission rates and spatial agreement across replicates. Variable importance analyses identified precipitation of driest quarter (50–250 mm) and annual mean temperature (3–12°C) as the key predictors, suggesting that the species' distribution is strongly governed by a narrow set of climatic factors. Present-day suitability patterns show a well-defined range in temperate western and central Europe, with suitability decreasing toward the warmer and more arid regions. Future projections under both future shared socio-economic pathway (ssp126 and ssp585) indicate a noticeable shift of suitable habitat toward higher latitudes. Western and central Europe remain highly suitable in these scenarios, while northern and northeastern areas become increasingly favorable. In contrast, southern Europe and nearby arid regions are projected to remain mostly unsuitable. Overall, the findings suggest that *A. sociella* is likely to move northward and eastward by 2070, with a decline in habitat suitability across its southern range.

Keywords: MaxEnt, Modeling, GIS, bee moth, climate change.

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INTRODUCTION

The insect *Aphomia sociella* (Linnaeus, 1758), a lepidopteran species belonging to the family Pyralidae, is commonly known as the bee moth or bumble bee wax moth. Although it is native to Europe, it has also been recorded outside its traditional range (Williams, 1997). The species is closely tied to the nests of social insects—especially bumblebees, honeybees, and social wasps (Williams, 1997; Goulson et al., 2002). Females lay their eggs within these nests, where the larvae feed on wax, pollen stores, brood remains, and other nest debris (Gekiere, Habay, & Michez, 2022; Goulson et al., 2002). While *A. sociella* is generally considered less harmful than the greater and lesser wax moths, it can still damage colonies and disturb nest structure in both wild and managed pollinator systems (Ellis, Graham, & Mortensen, 2013; Krams et al., 2025). Its life cycle—typically univoltine in temperate climates and bivoltine in warmer regions—shows strong sensitivity to climate and host availability, a pattern common among nest-associated insects (Villemant et al., 2011; Mulieri & Patitucci, 2019). This indicates that the broader geographic risk remains largely potential and predictive.

Earlier work has largely focused on species biology, host associations, and colony-level impacts, while large-scale ecological modeling of its potential geographic distribution has not been conducted. Understanding the geographical distribution of *A. sociella* is becoming increasingly important in light of ongoing environmental change. Environmental variability in temperature, humidity, habitat structure, and host density can significantly influence the persistence of a species within a given area (Parmesan, 2006; Sunday, Bates, & Dulvy, 2012; Hosni, Nasser, Al-Ashaal, Rady, & Kenawy, 2020; Abou-Shaara et al., 2021). Insects are particularly well known for shifting or expanding their ranges in response to climate change or human-assisted movement, a pattern widely documented across many taxonomic groups (Walther et al., 2002; Hickling et al., 2006). This is evident in invasive species such as the small hive beetle *Aethina tumida*, which has spread far beyond its native African range (Neumann & Elzen, 2004; Lee et al., 2017), as well as in numerous other insects showing rapid distributional changes under warming conditions (Bellard et al., 2013). Similar processes may allow *A. sociella* to colonize new regions wherever suitable climates and host nests are available. Identifying the environmental factors that shape its distribution is therefore essential for predicting future range shifts and evaluating potential risks to managed pollinator colonies (Guisan & Thuiller, 2005; Elith & Leathwick, 2009).

Despite the ecological association of *A. sociella* with pollinator nests and its documented occurrence beyond its native European range, no comprehensive species distribution modeling (SDM) study has yet evaluated the climatic determinants of its distribution or projected its potential range under future climate scenarios. SDM offers a valuable approach for examining how environmental factors shape the distribution of a species and how that range might shift under future climate conditions. MaxEnt is widely used to model distributions by combining species occurrence records with environmental predictors (Phillips, Anderson, & Schapire, 2006; Wei et al., 2018), such as in studies analyzing the distributions of *Plecia nearctica* (Abou-Shaara, Amiri, & Parys, 2022) and wax moths (Hosni et al., 2022). SDMs are valuable in

ecological research because they effectively use presence-only data to infer species–environment relationships (Elith et al., 2011; Merow, Smith, & Silander, 2013). These models commonly integrate biodiversity database records with geographic information systems and mapping tools such as GIS and DIVA-GIS to visualize spatial patterns (Phillips, 2017; Abou-Shaara, Amiri, & Parys, 2022; Kalboussi & Achour, 2018; Nasser et al., 2025). High-resolution bioclimatic datasets such as WorldClim further improve predictions by providing detailed climate layers (Hijmans et al., 2005).

Applying SDMs to *A. sociella* makes it possible to identify the key climatic factors shaping its current distribution and to project how its range may shift under future climate scenarios. These insights are crucial for understanding the species' potential expansion into new areas and for assessing ecological risks to pollinator communities, especially in light of the widespread climate-driven range shifts documented in insects worldwide (Parmesan, 2006; Hickling et al., 2006; McCain & Garfinkel, 2021). Anticipating the possible spread of *A. sociella* also supports proactive management strategies for bees, contributing to conservation planning and helping to protect pollination services in an era of rapid environmental change (Guisan & Thuiller, 2005; Elith & Leathwick, 2009). It is expected that the current distribution of *A. sociella* is strongly associated with temperature- and precipitation-related climatic variables. Additionally, future climate scenarios may potentially expand suitable habitats toward higher latitudes or previously cooler regions. To the best of our knowledge, no previous SDM studies have specifically modeled the distribution of *A. sociella*. The present study therefore seeks to map the distribution of *A. sociella* across its native European range and surrounding regions, while identifying the climatic variables that shape this distribution under both current and projected future conditions.

METHODS

Occurrence data

Occurrence records of *Aphomia sociell*a were obtained from Global Biodiversity Information Facility (GBIF.org: https://doi.org/10.15468/dl.4npub6), initially comprising 55,784 records from 181 datasets based on human observations collected between 2015 and 2025. These records underwent a multistep cleaning and preprocessing workflow to ensure suitability for species distribution modeling. Taxonomic validation was performed using the GBIF backbone taxonomy to ensure that all retained occurrence records correspond to the accepted species name. All entries with missing, invalid, or zero coordinates were removed, and spatial duplicates were eliminated by retaining only one record per unique latitude–longitude point. To further minimize spatial sampling bias and reduce spatial autocorrelation, spatial thinning was applied to the European subset of records, enforcing a minimum inter-point distance of 10 km based on great-circle distances calculated using a KD-tree algorithm implemented in R (version 4.5.1). This procedure removed clusters of observations from heavily surveyed regions, resulting in a more spatially balanced dataset. Using a thinning distance approximately two times the environmental raster resolution helps ensure that multiple occurrences within a

single environmental grid cell do not disproportionately influence model calibration. The final dataset (Fig. 1) —consisting of 3,870 unique, geographically valid, and spatially filtered presence records—was used for MaxEnt modeling.

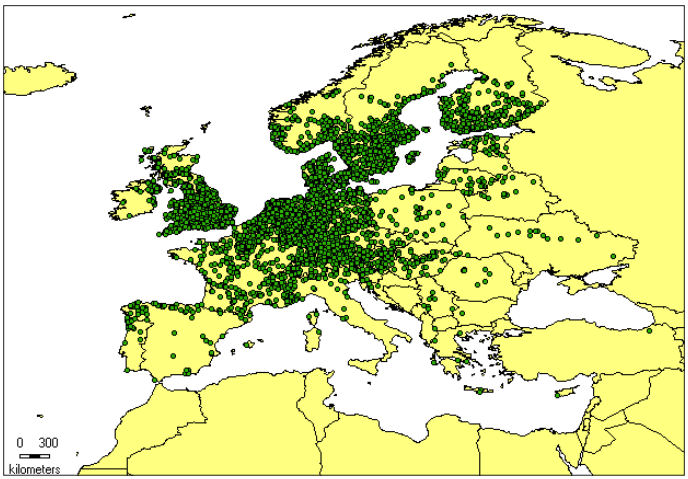

Figure 1. Geographic occurrence records of the bee moth *Aphomia sociella* across Europe and adjacent regions.

Environmental variables

To reduce multicollinearity and improve ecological interpretability, the 19 WorldClim bioclimatic variables (lay1–lay19; 2.5-minute (~5 km) spatial resolution, WorldClim v2.1; Fick & Hijmans, 2017) were screened prior to model fitting. Variables were first assessed for ecological relevance to the species' physiology, with emphasis on temperature extremes, annual thermal trends, and seasonal precipitation patterns. Pairwise Pearson correlation coefficients were then calculated for all predictors, and when two variables were strongly correlated ($|r| \geq 0.7$), only the biologically more interpretable variable was retained. Additionally, layers (lay 18, and lay 19) were excluded due to documented spatial artifacts (e.g. Hosni, Nasser, Al-Ashaal, Rady, & Kenawy, 2020). To verify that the remaining variables were sufficiently independent, a variance inflation factor (VIF) analysis was performed, and only predictors with VIF < 10 were retained. This multistep procedure yielded a reduced, non-collinear subset of environmental predictors appropriate for MaxEnt modeling. For the historic/current climate model, five variables were selected: annual mean temperature (lay1) reflects general thermal suitability influencing development rates and voltinism; minimum temperature of the coldest month (lay6) is associated with winter survival of overwintering stages; annual precipitation (lay12) and precipitation of the driest quarter (lay17) influence nest microclimate and the persistence of host colonies; and precipitation seasonality (lay15) captures variability in moisture conditions that may affect both host availability and larval development within nests. The same predictor set was used for modeling future climatic suitability under projected conditions for the year 2070 (average for 2061–2080), using data at 2.5-minute (~5 km) spatial

resolution. Future climate predictions were based on two Shared Socio-economic Pathways (ssp126 and ssp585) from the Beijing Climate Center Climate System Model (BCC-CSM2-MR).

Modeling using MaxEnt

Species distribution modelling was conducted using MaxEnt v3.4.1 (Phillips, Dudík, & Schapire, 2020). Of the 3,870 presence records available, 3,096 were used for training and 774 for testing. Five environmental predictors (lay1, lay6, lay12, lay15, lay17) were incorporated into the model, each loaded from the project directory and converted to MaxEnt's internal .mxe format prior to model execution. Models were run using cumulative output, five replicates, jackknife evaluation, and response curves, as specified in the MaxEnt command line. Regularization multipliers were applied uniformly across feature classes (linear, quadratic, product = 0.05; categorical = 0.25; hinge = 0.5). Resulting suitability rasters were processed in ArcGIS 10.8, where suitability values were classified into four categories: rarely suitable (0–1), moderately suitable (1–20), highly suitable (20–50), and very highly suitable (50–100) (Phillips, 2017; Abou-Shaara, Amiri, & Parys, 2022). For future predictions, separate suitability maps were generated for ssp126 and ssp585, after which an averaged projection was produced to represent the combined outcomes of both scenarios. Spatial changes between the historic/current suitability map and the averaged future projection were then quantified. This comparison allowed identification of areas of stability, habitat gain, and habitat loss under projected climate conditions, thereby illustrating the potential biogeographical responses of *A. sociella* to future environmental change.

Evaluations

Model performance was assessed using several complementary metrics, including the area under the receiver operating characteristic curve (AUC) and omission rate analyses across cumulative thresholds. Variable importance was evaluated through MaxEnt's percent contribution and jackknife tests, which together helped determine both the unique and overlapping influence of each predictor. To explore species–environment relationships, univariate response curves were generated to highlight the optimal environmental ranges for *A. sociella*. Replicated model outputs were averaged to produce suitability maps, which were then classified into suitability categories and visualized using ArcGIS. This workflow provided a rigorous foundation for identifying the environmental factors shaping the current and potential distribution of *A. sociella*. In addition, the True Skill Statistic (TSS) was included as an independent metric to further evaluate the reliability and predictive strength of the model. TSS provides a threshold-dependent measure that integrates both sensitivity and specificity and is less affected by prevalence, making it a useful complement to AUC when evaluating model predictive performance. The TSS calculation was based on the threshold that maximizes the sum of sensitivity and specificity (maxSSS), which is commonly used in species distribution modelling studies. Future research incorporating geographically structured cross-validation or independent regional datasets would further improve assessment of spatial transferability.

RESULTS

Model outcomes

The MaxEnt models produced consistent and robust predictions for the potential distribution of *A. sociella*. The test AUC was 0.809±0.003, indicating good discriminatory power and model stability (Fig. 2). ROC curves confirmed performance well above random expectations, and test omission rates closely matched predicted rates, demonstrating good model calibration (Fig. 3). Suitability patterns were spatially structured and highly consistent among replicates. Environmental predictors contributed hierarchically to model performance (Fig. 4). Variable (precipitation of driest quarter) dominated overall contribution (81.8%), followed by annual mean temperature (10%). Jackknife tests supported this: precipitation of driest quarter produced the highest gain when used alone.

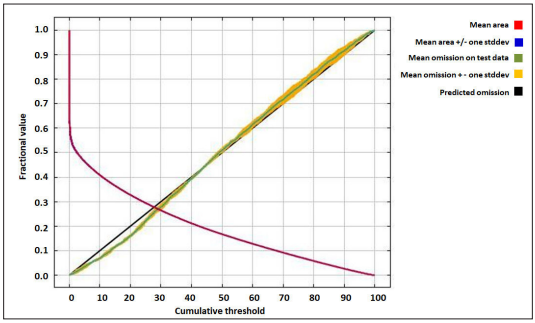

Figure 2. Cumulative threshold test showing omission, predicted omission, and fractional area for the MaxEnt model.

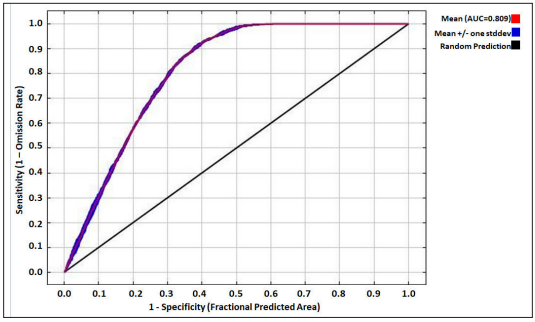

Figure 3. Receiver operating characteristic (ROC) curve and AUC values for the MaxEnt model of *Aphomia sociella*.

Response curves (Fig. 5) showed strong, nonlinear species responses to precipitation of driest quarter, with other variables exerting weaker or narrower effects. Annual mean temperature values are largely concentrated between 3–12°C, with peak responses around 7–8°C. Minimum temperature of the coldest month exhibits an even narrower effective range, centered between approximately –12 and 0°C. Annual precipitation displays a right-skewed distribution, with most model

output associated with regions receiving roughly 600–1,600 mm of rainfall per year, declining at higher values. Precipitation seasonality (coefficient of variation) is concentrated at low to moderate levels (0–30 CV). Precipitation of the driest quarter shows its primary response between about 50–250 mm, beyond which suitability declines sharply. Threshold-dependent metrics further confirmed reliability. At the 10th percentile training presence threshold, test omission remained low, reflecting strong agreement between predictions and withheld test data. Overall, the models indicate that the distribution of A. sociella is primarily influenced by a limited number of environmental variables, particularly precipitation of the driest quarter and annual mean temperature. The predicted suitability patterns were robust, consistent across replicates, and associated with low omission rates. The model achieved a TSS value of 0.5371, indicating moderate but meaningful predictive performance. Model evaluation was based on multiple metrics, including AUC, omission rates, and TSS, to provide a comprehensive assessment of model reliability.

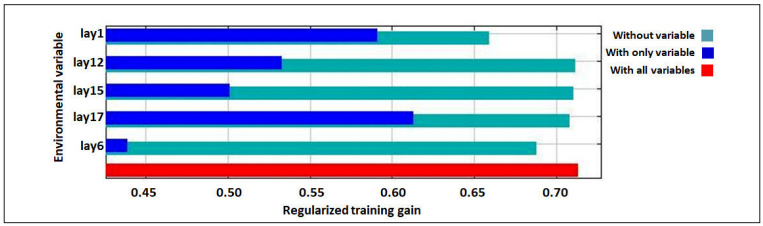

Figure 4. Contribution of environmental variables to MaxEnt model performance for *Aphomia sociella.* The variables are annual mean temperature (lay 1), minimum temperature of coldest month (lay 6), annual precipitation (lay 12), precipitation seasonality (coefficient of variation) (lay 15), and precipitation of driest quarter (lay 17).

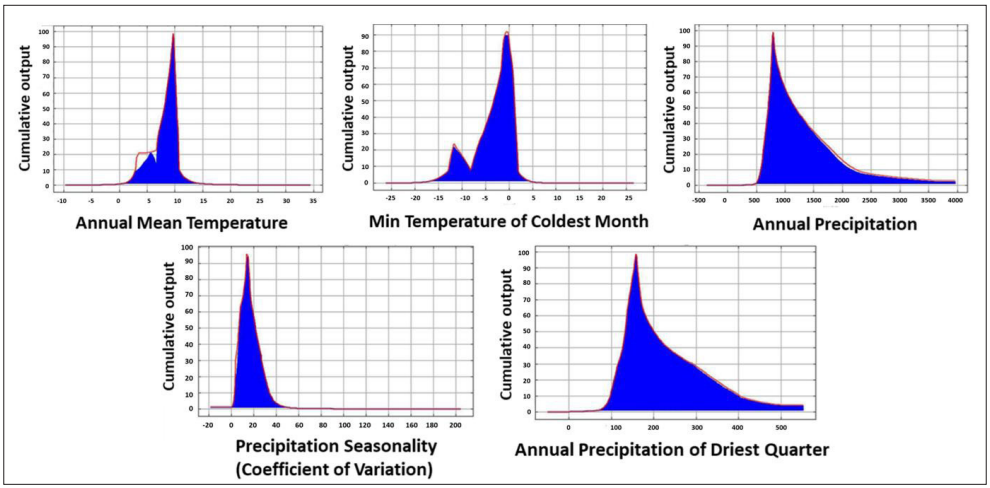

Figure 5. MaxEnt response curves showing the effect of climatic variables on *Aphomia sociella* suitability. The variables are annual mean temperature (lay 1), minimum temperature of coldest month (lay 6), annual precipitation (lay 12), precipitation seasonality (coefficient of variation) (lay 15), and precipitation of driest quarter (lay 17).

Historic/current distribution

The classified habitat suitability map (Fig. 6) shows a clear geographic pattern in the potential distribution of *A. sociella* across Europe, North Africa, and the Middle East. Very highly suitable areas are concentrated in western and central Europe—including the United Kingdom, France, Belgium, the Netherlands, Germany, Denmark, Poland, and southern Scandinavia—forming the species' areas of high climatic suitability. Highly suitable zones extend this southward and eastward into northern Spain, northern Italy, the Alpine region, central Europe, and parts of the Baltic countries. Moderately suitable areas create a transitional belt across eastern Europe, the Balkans, and parts of Turkey, offering limited but potentially viable habitat. In contrast, large portions of North Africa, the Middle East, and southern and eastern Europe are classified as rarely suitable, reflecting environmental conditions outside the species' tolerance, particularly in arid and semi-arid regions. Therefore, the MaxEnt prediction map (Fig. 6) reveals a clear geographic pattern in the potential distribution of *A. sociella* across Europe and adjacent regions. The highest suitability values occur in central and northern Europe, representing the environmental niche of *A. sociella*. Moderate suitability extends across southern Europe and the Mediterranean Basin. Suitability declines sharply toward northern Africa, the Middle East and the Arabian Peninsula, where predicted probabilities indicate largely unsuitable habitat. Overall, the spatial pattern suggests that *A. sociella* is most strongly associated with temperate European climates, with suitability decreasing progressively toward warmer and more arid regions.

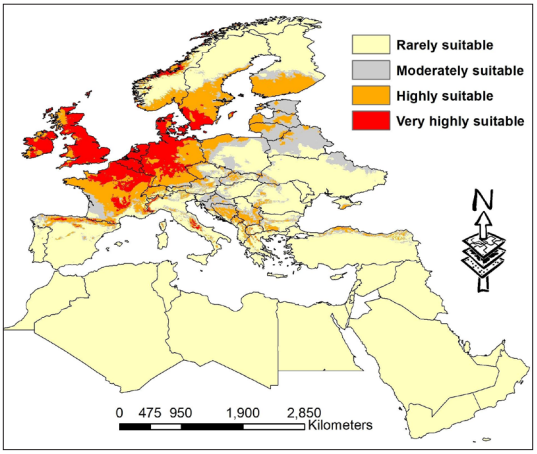

Figure 6. Historic/Current suitability map for *Aphomia sociella* based on MaxEnt modeling

Future distribution

The projected habitat suitability for *A. sociella* under the ssp126 low-emissions scenario (Fig. 7) shows notable geographic shifts relative to current climatic conditions. Very highly suitable areas remain centered in western and central Europe—including the United Kingdom, France, Belgium, the Netherlands, Germany, and northern Italy. Highly suitable areas also broaden into northern and northeastern Europe, particularly Poland, the Baltic

states, southern Sweden, indicating a moderate northeastern range expansion facilitated by mild climate change. Central Europe continues to provide favorable conditions, although some areas shift from very high to high suitability, reflecting subtle climatic changes. In contrast, southern Europe, including Spain, Greece, and the Mediterranean coastal region, shows a marked decline in suitability, transitioning primarily into rarely or moderately suitable classes. The Middle East and North Africa remain predominantly unsuitable. Overall, the ssp126 projection indicates a northward shift of suitable habitat, with stable regions in western and central Europe and increasing suitability in northern areas.

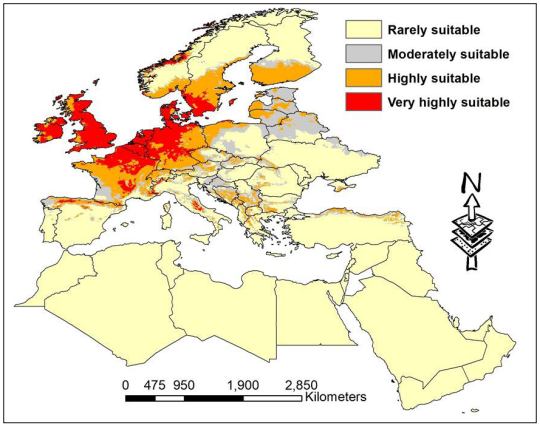

Figure 7. Future habitat suitability map for *Aphomia sociella* in 2070 under the low-emission ssp126 climate scenario.

Under the ssp585 high-emission scenario (Fig. 8), the projected changes in the distribution of *A. sociella* are substantially greater. Very highly suitable areas continue to cluster in western and central Europe—especially the United Kingdom, France, Belgium, the Netherlands, Germany, and northern Italy—although the extent of these areas becomes more fragmented. Highly suitable zones expand further into northern and northeastern Europe, including southern Sweden, the Baltic region, reflecting a stronger poleward redistribution driven by more intense warming. Central European regions that are currently very highly suitable shift into high or moderate classes. Suitability declines sharply across southern Europe: Spain, southern France, Greece, and parts of Turkey increasingly fall into the rarely suitable category. North Africa and the Middle East remain largely unsuitable. Under the high-emissions scenario, projections indicate a marked poleward shift and substantial habitat losses in southern regions.

The averaged 2070 projection (Fig. 9), which integrates outcomes from both emissions scenarios, presents an intermediate but clearly shifted pattern of future suitability. Very highly suitable areas remain concentrated in western and central Europe, including the United Kingdom, Belgium, France, the Netherlands, Germany, Switzerland, and northern Italy, demonstrating strong resilience of the areas of high climatic suitability. Highly suitable regions expand northward and eastward into southern Scandinavia, the Baltic states, indicating a robust poleward shift consistent across both emissions pathways. Moderately suitable areas form a wide transitional

belt across eastern Europe, the Balkans, and western Turkey. These regions represent environments that may support the species. In contrast, southern Europe—including southern France, Spain, Greece, and the Mediterranean coastline—as well as most of North Africa and the Middle East, remain predominantly rarely suitable. Overall, the averaged projections indicate a clear northward expansion of suitable habitat, accompanied by declining suitability in southern and drier regions.

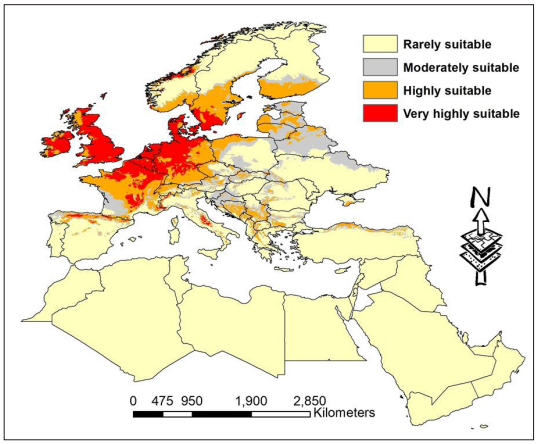

Figure 8. Future habitat suitability map for *Aphomia sociella* in 2070 under the high-emission ssp585 climate scenario.

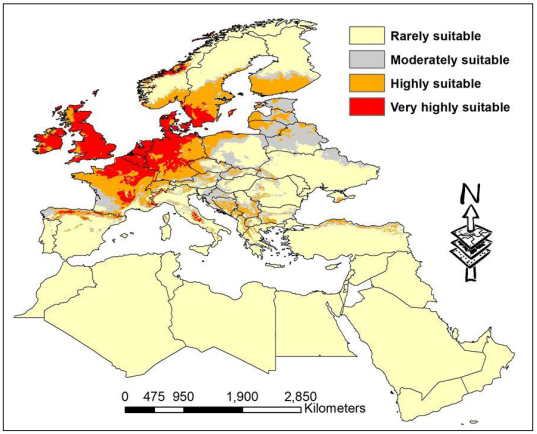

Figure 9. Future habitat suitability map for *Aphomia sociella* in 2070, based on the averaged projections of the ssp126 and ssp585 climate scenarios.

Change than current

The spatial comparison between historic/current conditions and the averaged 2070 projections under both the lowest (ssp126) and highest (ssp585) emission scenarios (Fig. 10) reveals clear geographic patterns of change across Europe. Most of the continent is projected to remain stable, with large regions showing no detectable shift

in suitability by 2070. Nonetheless, distinct zones of suitability loss and gain emerge. Losses are relatively limited in extent but occur mainly in western and southern Europe, including parts of France, the Iberian Peninsula, and localized areas in Greece, as well as portions of northern Scandinavia where several currently suitable zones are expected to become unsuitable. These declines indicate a moderate contraction of suitable habitat along the western and northern edges of the species' range.

In contrast, suitability gains are more widespread and concentrated in eastern Europe. Significant increases are projected across Belarus, and parts of Ukraine, forming a continuous belt of gains that extends into central Europe, including Poland, Slovakia, and the Czech Republic. Smaller isolated gain areas also appear in the Iberian Peninsula and Scandinavia. These regions represent areas currently unsuitable that are expected to become favorable under future climatic conditions. Overall, the spatial pattern suggests a broad eastward and northeastward shift in environmental suitability by 2070, driven by emerging favorable conditions in eastern Europe and decreasing suitability in select western, southern, and northern regions. Despite these changes, the predominance of no-change zones highlights substantial spatial stability across much of Europe, even under contrasting emissions trajectories.

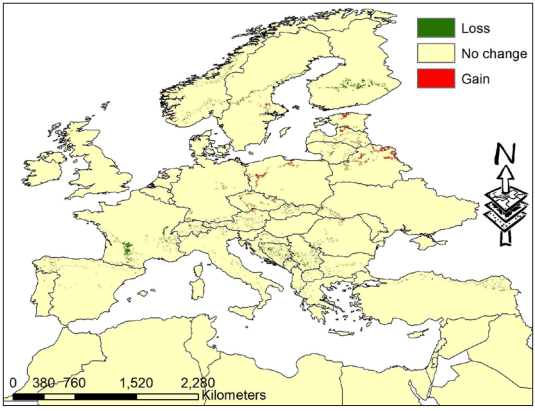

Figure 10. Changes between the historic/current habitat suitability map and the averaged future suitability map for *Aphomia sociella*, illustrating spatial patterns of stability, gain, and loss in suitable habitat under projected climate scenarios.

DISCUSSION

The habitat suitability patterns predicted for *A. sociella* closely match the expected ecological responses of species whose distributions are largely governed by climatic variables. The good model performance, indicated by AUC values exceeding the widely accepted threshold of 0.75 (Mulieri & Patitucci, 2019; Hosni, Nasser, Al-Ashaal, Rady, & Kenawy, 2020; Abou-Shaara et al., 2021; Abou-Shaara & Darwish, 2021), suggests that the results reliably capture the species' environmental preferences. Similarly, the obtained TSS value—considered indicative of a good model fit when equal to or greater than 0.5 (Hosni, Nasser, Al-Ashaal, Rady, & Kenawy, 2020)—confirms that the

model provides a good representation of the species' realized climatic niche. This level of performance supports the model's use for interpreting spatial patterns of habitat suitability under both current and future climate conditions. The prominent influence of temperatu re- and precipitation-related variables on habitat suitability reflects the well-established role of climate in shaping insect distributions, including those of stingless bees such as *Tetragonisca angustula* (Abou-Shaara, 2024). In the case of *A. sociella*, temperature and precipitation were also the main determinants of suitability, consistent with findings that temperature is a key factor governing the distribution of honeybee pests like the greater wax moth *Galleria mellonella* (Makori et al., 2017; Hosni et al., 2022).

The concentration of very highly suitable areas in western and central Europe indicates that *A. sociella* requires moderate, stable climatic conditions, similar to other insects that thrive under specific temperature and moisture ranges. Suitability declines progressively toward the warmer and more arid regions of North Africa and the Middle East, reflecting an ecological pattern comparable to that observed for other insects such as the stingless bees *T. angustula*, whose distribution is tightly linked to high precipitation and optimal thermal conditions (Malerbo-Souza & Halak, 2016). The presence of moderately suitable zones across eastern Europe and western Turkey suggests regions close to the species' climatic limits, where populations may persist only under favorable local conditions—similar to the marginal habitats predicted for other species modeled under MaxEnt approaches (Abou-Shaara et al., 2021). The prominence of western and central Europe as highly suitable areas for *A. sociella* mirrors similar findings reported for the greater wax moth, whose suitability is exceptionally high across the European mainland (Hosni et al., 2022). The concentration of highly suitable areas of *A. sociella* in western and central Europe corresponds with regions where the species is most frequently reported, while the predicted decline in suitability toward North Africa and the Middle East aligns with the species' limited presence in hotter and drier climates.

Future climatic scenarios reveal clear trends in potential distributional shifts. Under a lower-emission pathway, *A. sociella* is projected to maintain its distribution with minimal change, resembling the stability predicted for other insects such as *T. angustula* under future conditions, which is expected to preserve its historical distribution (dos Santos et al., 2022). However, under more intense warming scenarios, a northward expansion of suitable habitat is evident, while suitability declines in the southern regions where temperatures exceed the species' tolerance range. Comparable biogeographical responses have been documented in insects whose distribution is highly dependent on climatic thresholds, such as *Plecia nearctica*, which showed limited expansion under future projections (Abou-Shaara, Amiri, & Parys, 2022), whereas others like the small hive beetles, the greater wax moth and the Asian hornet exhibit stronger invasion potential under suitable climatic conditions (Abou-Shaara et al., 2021; Abou-Shaara & Al-Khalaf, 2022; Hosni et al., 2022).

The averaged 2070 projection across scenarios highlights persistent suitability in western and central Europe, confirming the resilience of the species' areas of high climatic suitability. Extensive declines in southern Europe and North Africa reflect the constraining

effects of excessive heat and insufficient moisture—patterns consistent with the reduction in suitability of species requiring adequate precipitation for survival (Hosni, Nasser, Al-Ashaal, Rady, & Kenawy, 2020). Increasing suitability in northern and northeastern Europe suggests that future warming will facilitate poleward expansion, a trend consistent with the ecological principle that insects often track their thermal optima under climate change. These findings are further supported by recent studies demonstrating that warming-induced shifts in thermal suitability can accelerate invasive spread in pollinator-associated insects (Hulme, 2017) and alter ecological interactions across temperature gradients (Boukal, Bideault, Carreira, & Sentis, 2019). In addition, updated climate-niche assessments indicate that many insect species are already migrating poleward or upward in elevation as global temperatures rise (Bässler, Hothorn, Brandl, & Müller, 2013; Wagner, 2020), highlighting the broader consistency of these projected patterns.

The spatial comparison between current and future conditions reveals a mixture of stable, gain, and loss areas. Stability dominates much of Europe, while losses are primarily restricted to southern and western regions where warming becomes ecologically limiting. Gains appear largely in eastern Europe, forming potential new habitats for future colonization. Although much of Europe remains climatically stable, projected losses in southern Europe likely reflect conditions exceeding the species' thermal and moisture tolerance limits. In contrast, gains in northern and eastern Europe occur where warming shifts climatic conditions closer to the species' optimal range, enabling a northward expansion of suitable habitat. However, localized declines in some northern areas may result from changes in precipitation patterns or seasonal climatic variability that shift conditions outside the species' optimal range. These patterns of *A. sociella* parallel the modeled distributional dynamics of *T. angustula*, which is expected to expand into suitable climatic zones such as parts of the southern USA while remaining absent from areas beyond its thermal and rainfall tolerances unless artificially introduced (Quiroga-Murcia et al., 2017). This comparison was intended only as a conceptual example illustrating how climatic variables such as temperature and precipitation can structure insect distributions.

The results demonstrate a stable potential habitat in central and western Europe, potential future expansion to northern regions, and a decline in suitability toward regions where heat and aridity intensify. As noted in other insect modeling studies (Abou-Shaara et al., 2021; Abou-Shaara & Darwish, 2021; Hosni et al., 2022), such changes underscore the importance of climate-driven shifts in species distributions and highlight the need for continued monitoring of emerging habitats under future climatic conditions. Overall, the predicted distribution of *A. sociella* emphasizes the critical role of climatic variables —particularly precipitation of driest quarter and annual mean temperature —in shaping its ecological niche. In broader research demonstrating that temperature and moisture gradients are key drivers of insect range dynamics under climate change (Bale et al., 2002; Parmesan & Yohe, 2003; Deutsch et al., 2008). It is worth mentioning that factors such as host hive availability, beekeeping practices, anthropogenic transport of colonies, and local habitat conditions may influence the occurrence and spread of this species.

CONCLUSION

This study shows that *Aphomia sociella* occupies a well-defined climatic niche, primarily in the temperate regions of western and central Europe, with habitat suitability decreasing toward hotter, drier, and more continental areas. Future climate projections consistently suggest a northward and eastward shift in suitable habitats, driven by rising temperatures and changing moisture patterns. Under the low-emissions scenario (ssp126), these shifts are relatively modest, mainly involving gradual expansion into northern latitudes. In contrast, the high-emissions scenario (ssp585) predicts more pronounced and disruptive changes, including significant losses across southern Europe and substantial gains in northern and eastern regions. The averaged projection for 2070 reinforces this trend, showing a stable potential distribution, declining suitability in southern areas, and increasing potential for colonization in northern and eastern Europe. Overall, the results indicate that *A. sociella* is likely to undergo a climate-driven redistribution by 2070, highlighting the importance of ongoing monitoring and the need to account for shifting range boundaries in future ecological assessments and management strategies. The findings also underscore the critical role of precipitation in determining the occurrence of this pest.

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