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Spodoptera frugiperda (J.E. Smith) (Lepidoptera: Noctuidae): Risks for Slovenian agriculture and feasibility of conducting pre-emptive risk assessment for some of its natural enemies

Zala Žnidaršič, Tjaša Pogačar, Stanislav Trdan, Miha Curk *

University of Ljubljana, Biotechnical Faculty, Department of Agronomy, SI-1000 Ljubljana, Slovenia

HIGHLIGHTS:

- High-resolution spatial assessment shows an increasing climate suitability of Slovenia for FAW in the future.
- Models predict significant overlap between the potential distribution of FAW and its parasitoids *Telenomus remus* and *Trichogramma pretiosum* in Slovenia in the future.
- A foundation for evidence-based decisions and research to address the challenges posed by invasive pests such as FAW is set.

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ABSTRACT

The invasive species *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), also known as fall armyworm (FAW), has emerged as a significant threat to agriculture globally, causing considerable economic losses and ecological disruptions. This paper examines the potential risk that FAW poses to Slovenian maize production. Using the maximum entropy algorithm, the climate suitability of Slovenia for FAW as well as for four of its parasitoids is calculated. The data used for the model calculations include species occurrence data, past climate data and regional climate projections for the 21st century. The climate suitability assessments in this study indicate an increasing risk of FAW occurrence in Slovenia in the 21st century, especially in regions with extensive maize cultivation. Projections under different climate change scenarios show that, the likelihood of FAW parasitoids thriving in Slovenia is particularly high, especially for *Telenomus remus* and *Trichogramma pretiosum* and overlaps with the regions with the largest areas of maize cultivation. In this context, pre-emptive biological control presents a promising approach. However, consideration of the full impacts associated with the introduction of non-native natural enemies is crucial, highlighting the need for further research and collaboration between stakeholders. Furthermore, this study lays the foundation for evidence-based decision making and emphasises the importance of integrated pest management strategies tailored to the Slovenian agricultural landscape.

1. Introduction

Spodoptera frugiperda (J.E. Smith) (Lepidoptera: Noctuidae), commonly known as the fall armyworm (FAW), is an invasive insect pest species that originates in tropical and subtropical regions in the Americas (EPPO, 2020), and has spread to most continents in the last decade, presenting a major risk for agricultural production. The warmer Southern and Western Europe have been identified as potential areas of further establishment, especially in the light of climate change and raising temperatures (Masson-Delmotte et al., 2021). Several occurrences of FAW were reported in southern Europe in 2023 (Cyprus and Crete, but recently also mainland Greece) (EPPO, 2023). The species' presence was also confirmed in Malta in September 2023 (Seguna et al., 2024). Considering the moth's ability to fly over long distances (100 km/night; Song et al., 2020), it may only be a matter of time before FAW makes its way further north to other Mediterranean countries. Slovenia, geographically located next to the Adriatic Sea and climatically influenced by it, might come under increasing risk in this regard in the future

* Corresponding author.
E-mail address: miha.curk@bf.uni-lj.si (M. Curk).

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and the situation might call for a solution by classical biological control as it has been the case with two other invasive pests in the past (Trdan, Laznik and Bohinc, 2020). Recent studies have discussed the possibility of the spread of FAW and its parasitoids on a global and continental scale based on the use of predictive modelling (Tepa-yotto et al., 2021; Kenis, 2023; Ramasamy et al., 2022). Results show that the global suitability for the pest is predicted to increase, with the highest risk of spread of FAW expected under the SSP5-8.5 climate change scenario (Ramasamy et al., 2022). Shared Socioeconomic Pathways (SSPs) are climate change scenarios of projected socioeconomic global changes up to the end of the 21st century, defined by the IPCC (Abram et al., 2019). Additionally, assuming global climate data resolution is valid for Slovenia, conditions for FAW spread are most likely met, especially under the highest emissions scenario (Tepa-yotto et al., 2021).

Being a polyphagous pest with a large host range, FAW presents a significant threat to agricultural production. Studies from the Americas indicate that it can target over 350 plant species, including maize (*Zea mais* L.), forage grasses (*Panicum* spp. and *Sorghum* sp.), sugar cane (*Saccharum officinarum* L.), rice (*Oryza sativa* L.) and others, mainly belonging to Poaceae, Asteraceae and Fabaceae families (Montezano et al., 2018, Overton et al., 2021). Conventional FAW pest management approaches usually rely on the use of pesticides, but several of them are either highly toxic, or no longer effective since the FAW has developed resistance to their active ingredients, including some *Bacillus thuringiensis* toxins (Lira et al., 2020). Alternatively, many studies have highlighted the effectiveness of implementing biological control against FAW (Abbas et al., 2022; Ahissou et al., 2021; Kenis et al., 2023; Varshney et al., 2021; Wyckhuys et al., 2024). Classical biological control was formulated as a control method for plant protection, where the use of synthetic pesticides is replaced by the introduction and release of natural enemies of pests (Pimentel, 2002). Research in the field of biological control in Slovenia has been underway for over 30 years now, and this article expands previous efforts to minimize the damage caused by further introductions of invasive pest species (Trdan, Laznik and Bohinc, 2020, 2023). A vast number of studies have recognized biological control as a safe, cost-effective and environmentally sound alternative to pesticides, especially in association with the FAW (Wyckhuys et al., 2024). Articles on biological control of FAW mention several different biological control agents (BCA), like viruses (nucleopolyhedrovirus) or entomopathogenic fungi (*Metarhizium rileyi*) (Gómez-Valderrama et al., 2022), but also parasitoids, including *Aleiodes laphygmae* Viereck (Hymenoptera: Braconidae), *Campoletis* spp. (Hymenoptera: Ichneumonidae), *Chelonus insularis* Cresson (Hymenoptera: Braconidae), *Eiphosoma laphygmae* Costa Lima (Hymenoptera: Ichneumonidae), *Archytas marmoratus* Townsend (Diptera: Tachinidae), *Cotesia marginiventris* Cresson (Hymenoptera: Braconidae) (Kenis, 2023), *Telenomus remus* Nixon (Hymenoptera, Scelionidae), *Trichogramma pretiosum* Riley (Hymenoptera, Trichogrammatidae) (Tepa-yotto et al., 2021), etc. Most of those parasitoids originate from similar tropical and sub-tropical climates as the FAW, but recent modeling studies (Tepa-yotto et al., 2021; Kenis, 2023) have shown that Mediterranean regions of Europe might have a climate suitable for several of them. Considering that recent genomic analyses have revealed greater diversity in FAW than previously believed (Tay et al., 2023), and that geographical variations in natural selection forces probably exist, addressing this global pest will necessitate region-specific strategies for control.

This paper aims to take the global data from pioneering modeling studies on the species and re-assess them with regional measured long-term and climate change model data in order to prepare high resolution assessment for Slovenia. Following the newly proposed strategy of pre-emptive assessment of natural enemies (Avila et al., 2023), this study will assess the viability of such a pre-emptive assessment of introduction of natural enemies of FAW to Slovenia. To estimate the potential distribution of FAW in Slovenia, in the present study we developed a species distribution model (SDM) using the Maximum Entropy algorithm (Maxent) (Phillips et al., 2006). The Maxent model predictions in this study are based on the downscaled and bias-corrected regional climate projections for Slovenia. Results of this study can later support pre-emptive assessment of FAW natural enemies.

2. Materials and methods

A previous study (Tepa-yotto et al., 2021) showed that, according to global models built using Maxent, Slovenia has a moderately suitable climate for the establishment of a number of known FAW parasitoids. Of those mentioned, *Campoletis* spp. was not included in this particular study, as the large number of species in the genus have a very diverse geographical distribution and some of them are morphologically very conservative, which makes the species delimitation considerably difficult (Townes, 1970). This would make the process of pre-emptive analysis and legal procedures for the introduction of a single species very challenging. Of the parasitoids species evaluated by Tepa-yotto et al. (2021), modelled climatic suitability for the establishment in Slovenia of the larval parasitoid *Cotesia marginiventris* and the egg parasitoid *Trichogramma pretiosum* is high, while the climatic suitability for the egg parasitoids *Telenomus remus,* and the larval parasitoids *Eiphosoma laphygmae* and *Chelonus insularis* is expected to be moderate to low. This suggests that *T. pretiosum* and *C. marginiventris* could be deployed sequentially to enhance the success of biocontrol programs, and the same could be done with *T. remus* and *E. laphygmae* (Tepa-yotto et al., 2021). We chose these four species for further analysis, as based on the reported compatibility of a larval and egg parasitoid release, we expect that a concurrent releases of *T. remus* and *C. marginiventris*, and *T. pretiosum* and *E. laphygma* would also show promising results.

2.1. Species occurrence data

We used the last available data on the global occurrence of *S. frugiperda* (FAW) and the four selected parasitoid natural enemies (*C. marginiventris*, *T. pretiosum*, *T. remus* and *E. laphygmae*) in order to develop distribution models. The algorithm was applied to occurrence data of the species which was obtained from the Global Biodiversity Information Facility (GBIF) data portal (GBIF, 2018, accessed 23 February 2024) via the “dismo” package in R. Presence records of the modelled species used in this study are provided in the appendix (Table A.1). After obtaining the raw data from the GBIF, we filtered out the location duplicates in the records of occurrence data. By doing this, the number of occurrences decreased significantly but remained above 27 for all of the analysed species, which fulfils the minimum occurrence size for SDM models (Jiménez-Valverde, 2020; Hernandez et al., 2006). Information on occurrence data with duplicates removed is also presented in Table A.1.

2.2. Model calibration and evaluation of the predictive performance of the model

The aim of the study was to assess the potential distribution in Slovenia for FAW and four of its natural enemies. To this end, we used a Maximum entropy algorithm (hereafter Maxent model), a machine-learning based method developed by Phillips et al. (2006). To assess how well the species distribution model of Maxent can predict the occurrence of a species at a given location, we used 5-fold cross-validation. Of all the species occurrence observation data, 80 % of the observation data were randomly selected and used to calibrate (train) the model, while the remaining 20 % of the data were used to validate (test) the model. The k-fold validation procedure then involved fitting the model five times, and finally calculating the average performance. Finally, the algorithm was run on the full set of occurrence data, to create the best estimate of the species’ probability of occurrence that will be presented in the main figures. To define the background for our Maxent model, we generated the absence data by using the randomPoints() function in R, which assures that the absence locations occur only in the areas where the predictor variables exist.

To evaluate the predictive performance of the model, we utilized the Area under receiver operating characteristic Curve (AUC) approach (Fielding and Bell, 1997). The AUC was plotted to represent the performance of the model in terms of a true-positive rate and a false-positive rate at different classification thresholds. The AUC value varies between 0 and 1, with an AUC of 0.5 corresponding to the efficiency of a random guess.

Habitat suitability values that were calculated with the Maxent model range from 0 to 1. For interpretation purposes, the suitability values were classified into four classes: Low (0–0.25), Moderate suitability (0.25–0.5), High suitability (0.5–0.75) and Very High Suitability (0.75–1).

2.3. Climate data

Since the probability of species occurrence depends on climatic conditions, climate data were used to calibrate the model and to produce predictions of the species occurrence. The climate data used to calibrate the Maxent model was provided by the Worldclim project database (https://worldclim.org, Fick and Hijmans, 2017), which can be accessed via the "raster" package in R and includes standardized climate data with relatively high resolution worldwide. Specifically, we used the Worldclim historical data 1970–2000 at a resolution of 0.04° (approximately 4 km) for daily precipitation, minimum and maximum temperature. The Worldclim database only included the historical period of 1970–2000, therefore we used this period of climate data to calibrate and validate the model.

The focus area of this study covered Slovenia, which is situated at the intersection of four major geographic regions – the Alps, the Dinarides, the Pannonian plain and the Mediterranean. Due to its complex terrain, we aimed at using the most accurate climatic data to predict the probability of the chosen species occurrence for Slovenia. In this regard, we utilized the data provided by the Slovenian Environment Agency for creating predictions of potential distribution in Slovenia. The historical time series of daily precipitation, minimum and maximum temperature covered the period 1981–2010 over Slovenia in a regular grid, with a resolution of 0.125° (approximately 12 km). The data were originally obtained from weather station data and interpolated to the territory of the entire country using spatial interpolation methods by the Slovenian Environment Agency (ARSO, 2023g).

The future climate simulations provided by the Slovenian Environment Agency are the result of regional climate models of the EURO-CORDEX project at a 0.11° resolution. The model projections data have been bias-corrected, i.e. corrected according to the measurements in Slovenia in the period 1981–2010. For this study, we used climate model projections of daily precipitation (ARSO, 2023e, ARSO, 2023f), minimum (ARSO, 2023c, ARSO, 2023d) and maximum temperature (ARSO, 2023a, ARSO, 2023b) in the period 1981–2100 for the RCP4.5 and RCP8.5 emission scenarios over Slovenia in a regular grid, with a resolution of 0.125° (approximately 12 km). Representative Concentration Pathways (RCP) are climate change scenarios of projected future greenhouse gas concentrations and are closely tied to the Shared Socioeconomic Pathways (SSPs). The SSP scenarios include a range of baseline scenarios spanning up to 8.5 W/m^2 of radiative forcing by 2100 – a very low forcing level (SSP1-2.6, corresponding to RCP2.6), a medium stabilisation scenario (SSP2-4.5, corresponding to RCP4.5) and a very high baseline emission scenarios (SSP5-8.5 corresponding to RCP8.5) (Abram et al., 2019).

In addition to the historical period (1981–2010), we have analysed climate model simulations that cover two time periods, namely the present (2011–2040) and the future (2041–2070). The historical period of 1981–2010 serves as the base period as it includes the most accurate climate data available for a given location. Moreover, the use of accurate historical data allows the model to be tested for its ability to reproduce known climate conditions, improving the reliability of the model in predicting future scenarios.

An ensemble of six regional climate model simulations was used for the scope of the analysis (Table 1). To present the uncertainty of the model results, the model ensemble' minimum, maximum and median value were calculated, the latter serving as the representative value of the model results. In the scope of the results, only the RCP4.5 scenario results will be presented, although main differences with the RCP8.5 will be pointed out, if applicable. Considering current policies and the state of the measures reported to limit global warming, RCP4.5 is currently the most likely RCP scenario (Climate Action Tracker, 2023).

From the original climate variables of daily precipitation, minimum and maximum temperature, several climate variables are derived which were used to analyse the distribution of the species. The variables are denoted as bioclimatic variables and are derived from the monthly temperature and rainfall values in order to generate more biologically meaningful variables (Hijmans et al. 2005).

2.4. Maize crop data

With the intention of representing some of the data in more detail, we performed an analysis on maize fields density. Since maize is one of FAW's preferred host plants, as well as the most important crop in Slovenia, a more detailed analysis of the grid cells with the highest maize fields density was performed. The same 12 km grid resolution of climate data was also used to aggregate data for maize fields in Slovenia for the year 2022. Data on fields where maize was planted that year, was acquired from the national Agency for Agricultural Markets and Rural Development (AKTRP, 2022). Then the area of maize fields that fit into each grid cell was summed up so that we were able to rank grid cells for area of maize fields and determine which grid cells had the greatest potential to be affected, should FAW find its way into Slovenia.

3. Results

3.1. Model evaluation and variable importance

The calculated values of AUC were high for all 5 sub-models for FAW, indicating that predictions are significantly better than random (Table 2). As a consequence, the average AUC was also high (0.954), as was the AUC of the model calibrated with the full set of occurrences (0.956). The full dataset AUC was similarly high for *E. laphygmae* (0.961), *C. marginiventris* (0.888), *T. Remus* (0.825) and *T. pretiosum* (0.892).

According to the model results, the climate variables with the highest

Table 1
Downscaled regional climate models (RCMs) of the EURO-CORDEX project included in the analysis, global climate models (GCMs) that set the boundary conditions for the RCMs.

GCM	RCM	Institution contributor of the RCM
CNRM-CERFACS-CNRM-CM5	CLMcom-CCLM4-8–17	CLM Community with contributions by BTU, DWD, ETHZ, UCD,WEGC
ICHEC-EC-EARTH	DMI-HIRHAM5	Danish Meteorological Institute
IPSL-IPSL-CM5A-MR	IPSL-INERIS-WRF331F	Laboratoire des Sciences du Climat et de l'Environnement, IPSL, CEA/CNRS/UVSQ
MOHC-HadGEM2-ES	KNMI-RACMO22E	Royal Netherlands Meteorological Institute, Ministry of Infrastructure and the Environment
MPI-M−MPI−ESM−LR	CLMcom-CCLM4-8–17	CLM Community with contributions by BTU, DWD, ETHZ, UCD,WEGC
MPI-M−MPI−ESM−LR	SMHI-RCA4	Rossby Centre, Swedish Meteorological and Hydrological Institute, Norrkoping Sweden

Table 2
Results of Area under receiver operating characteristic Curve (AUC) for FAW and other species produced with the Maxent model. The average AUC of the folds is also presented.

Species name	Consecutive fold	AUC	Average AUC	Full dataset AUC
S. frugiperda	1	0.956		0.956
	2	0.952		
	3	0.953	0.954	
	4	0.956		
	5	0.953		
C. marginiventris	1	0.867	0.758	0.888
	2	0.603		
	3	0.826		
	4	0.630		
	5	0.867		
T. remus	1	0.865	0.789	0.825
	2	0.841		
	3	0.859		
	4	0.552		
	5	0.828		
E. laphygmae	1	0.939	0.955	0.961
	2	0.976		
	3	0.972		
	4	0.987		
	5	0.902		
T. pretiosum	1	0.799	0.804	0.892
	2	0.741		
	3	0.738		
	4	0.914		
	5	0.829		

contribution to the occurrence of FAW were annual precipitation (bio12), annual mean temperature (bio1), precipitation of the driest quarter of the year (bio17) and precipitation of the warmest quarter of the year (bio18). FAW thrives in environments with relatively large amounts of annual precipitation, relatively high annual mean temperature, moderate amounts of precipitation in the driest quarter of the year and relatively low amounts of precipitation in the warmest quarter of the year (Figure A.2).

On the other hand, the variable with the highest contribution to the occurrence of parasitoids *C. marginiventris* and *T. remus* was minimum temperature of the coldest month (bio6), with precipitation of the wettest quarter (bio16) coming second for *C. marginiventris* and precipitation of the coldest quarter (bio19) coming second-most important for *T. remus*. For *T. pretiosum* and *E. laphygmae*, precipitation of the coldest quarter (bio19) is the most important, whereas temperature annual range (bio7), precipitation of the driest quarter (bio17) (*T. pretiosum*) and precipitation of the wettest quarter (bio16) (*E. laphygmae*) follow. The variable contribution plot for these species is also shown in the Appendix in Figure A.3.

3.2. Probability of occurrence of FAW and its parasitoid natural enemies under historical climate

Using the 1981–2010 climate dataset, we predicted the highest probability for FAW occurrence in the eastern and SW part of Slovenia which represent the warmest and driest parts of Slovenia (Fig. 1). The predicted probability of occurrence of *C. marginiventris* and *T. remus* in the past climate was relatively high for the majority of Slovenia excluding the NE part in the case of *C. marginiventris* and especially the SE and NW part in the case of *T. Remus*. Similar results were obtained for the habitat suitability for *T. pretiosum*¸ with the highest suitability predicted for the eastern and SW part of Slovenia. Habitat suitability for *E. laphygmae* was predicted the highest for the central, southern and NW part of Slovenia, almost directly overlapping the area with low current suitability for the FAW.

3.3. Probability of occurrence of FAW and its parasitoids under current and future climate scenarios

In the Fig. 2, the median suitability across the 5 sub-models is presented. However, it is important to have in mind the uncertainty of the model results, represented by the minimum and maximum model calculated probability, which is presented in the Appendix (Figure A.4). In the present and near-future climate characterized by the period 2011–2040, the climate suitability of Slovenia for FAW (Fig. 2a) is not significantly different in comparison to the period 1981–2010 (Fig. 1a). Results are similar for the middle of the century (Fig. 2b), when the suitability for FAW occurrence will slightly increase in the areas with existent suitability in the present climate, this being the eastern and SW part of Slovenia. In the regions of Slovenia with low current suitability for the FAW, the potential distribution under either of the climate scenarios is not expected to increase significantly around the middle of the century (Fig. 2b). On the other hand, the regions with the highest maize field areas coincide with moderate climate suitability for the FAW (marked yellow) thus making the main maize-growing regions of Slovenia in 2041–2070 vulnerable regardless of the RCP scenario (Fig. 2b, scenario RCP8.5 results are not presented). Considering the maximum model values for 2041–2070, the SW part of the country shows an especially high climate suitability (shown in red) for FAW under the RCP4.5 (Figure A.4d).

Model projections of climate suitability for Slovenia for the four parasitoid species in the current and near future climate of 2011–2040 are shown in Fig. 3. Again, median model values are shown, with the minimum and maximum results presented in the Appendix (Figure A.5). In the near future, the climate suitability of Slovenia is expected to be moderate to very high for the species *C. marginiventris* (Fig. 3a) and *E. laphygmae* (Fig. 3b) in comparison to 1981–2010, leaving only the north-eastern part of Slovenia with relatively low suitability for the two species (marked blue and green).

The median model results show an increased climate suitability for *T. remus* in comparison to the reference period 1981–2010*,* with an emphasis on the eastern, SW and central part of the country (Fig. 3c). Interestingly, the suitability of climate for *T. pretiosum* is slightly increased for some parts of Slovenia, but decreased for the mountainous north-western part of the country (Fig. 3d).

Our model results for the climate suitability of Slovenia for the four parasitoid species in 2041–2070 are shown in Fig. 4. The assessment of climate suitability for the analysed species during the period 2041–2070 reveals variability across different scenarios and geographical regions within Slovenia. For *C. marginiventris* under RCP4.5, there is no greater indication of improvement in the climate suitability (Fig. 4a). The prospective climate suitability under RCP4.5 is very high across the majority of Slovenia for *E. laphygmae* (Fig. 4b) and *T. remus* (Fig. 4c). For *E. laphygmae*, this excludes the north-eastern part of Slovenia, whereas for *T. remus*, this represents the majority of Slovenia, apart from the mountainous NW part and the central southern part of the country.

Similar to the findings for the current climate in Slovenia, Fig. 4d illustrates that the eastern and SW regions exhibit the highest climate suitability for *T. pretiosum* in the period 2041–2070. In contrast, the suitability in the mountainous regions, the S and in the central part of Slovenia is slightly decreased for this particular species. Interestingly, when comparing the results of all periods studied, it can be seen that the climate suitability for *T. pretiosum* in the western half of the country gradually decreases throughout the 90-year period. In the eastern half of the country, the suitability for *T. pretiosum* initially decreases in the period 2011–2040 (Fig. 3d), but then increases again in the period 2041–2070 (Fig. 4d) compared to 1981–2010.

For all of the analysed species, the trend in modelled suitability appears relatively consistent across both RCP scenarios, although the climate is anticipated to be slightly more suitable for *C. marginiventris, E. laphygmae, T. remus* and *T. pretiosum* in the years 2041–2070 under RCP8.5 compared to RCP4.5.

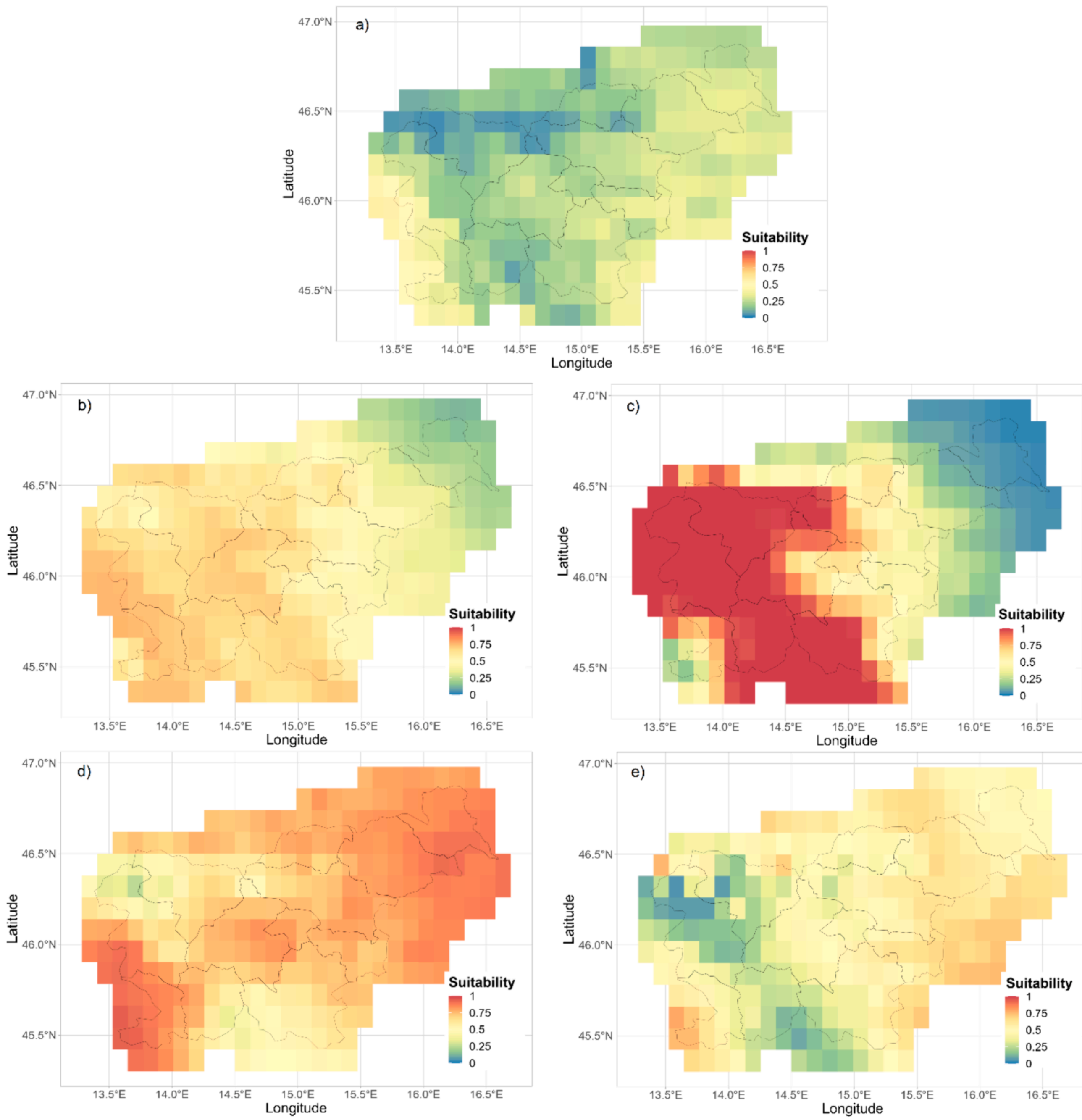

Fig. 1. Predicted habitat suitability, under the 1981–2010 climatic dataset, for (A) FAW, and its parasitoids (B) *Cotesia marginiventris*, (C) *Eiphosoma laphygmae*, (D) *Telenomus remus* and (E) *Trichogramma pretiosum*.

4. Discussion

FAW poses great threat to global production of not only maize, but also cotton, forage grasses, sugar cane, rice and so on (Montezano et al., 2018, Overton et al., 2021). For Slovenia, the crop most at risk is maize. The majority of research quantifying yield losses and the relationship between FAW pest pressure and yield globally has also focused on maize (Cruz et al., 2012; Horikoshi et al., 2021; Varshney et al., 2021). Maize production in Slovenia is a very important sector, using up around 40 % of the arable land in Slovenia and yielding up to 1,800,000 t in the last years (Travnikar et al., 2023). Because of a predominantly two-crop rotation, where maize is often planted for two or even more years in a row, eradication of the pest upon its invasion might be difficult, but more importantly, the existence of many intensive farms in Slovenia that rely heavily on silage maize as feed for animals, might be threatened. Timely discovery and eradication are therefore crucial, as an extensive action plan, prepared for the case of invasion by state institutions, showcases (MKGP, 2024).

Biodiversity-based measures such as biological control represent relatively safe, economically-accessible, and environmentally friendly alternatives to pesticide use and stand as the most promising solutions for cereal growers worldwide. Lately, numerous studies are showing a strong and rapidly growing scientific basis for implementing biological control methods against FAW (Abbas et al., 2022; Ahissou et al., 2021; ; Kenis et al., 2023; Varshney et al., 2021; Wyckhuys et al., 2024).

Knowing which organisms to use for biological control is crucial. The results of our model projections provide useful information on the climatic suitability for four FAW natural enemies to establish in Slovenia,

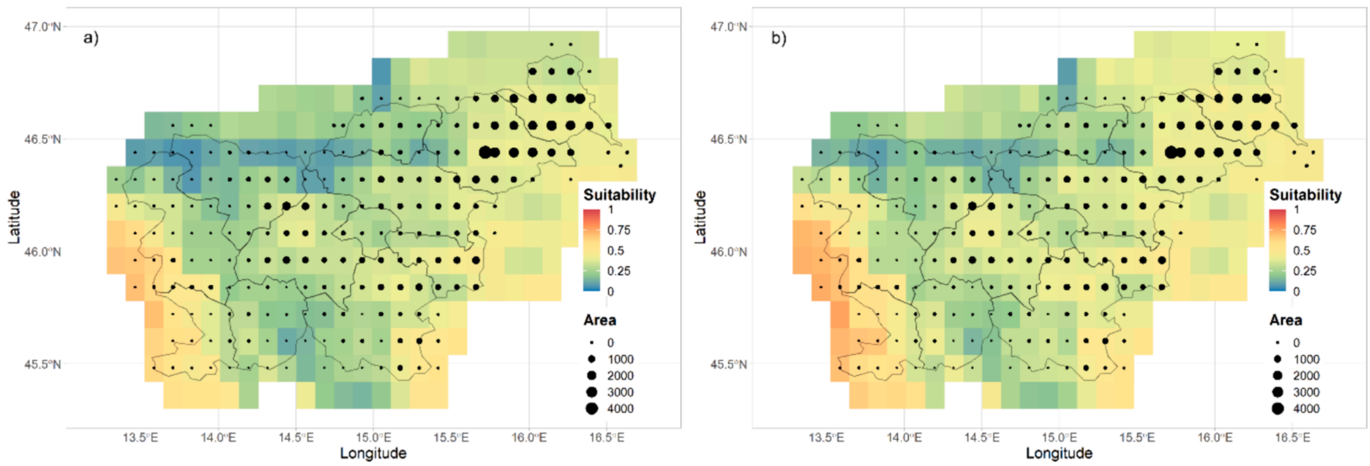

Fig. 2. Predicted habitat suitability for the FAW under 2011–2040 climate (A) and 2041–2070 climate (B), multi-model median results are presented for scenario RCP4.5. Information on maize field area (in ha) in 2022 is presented by black points.

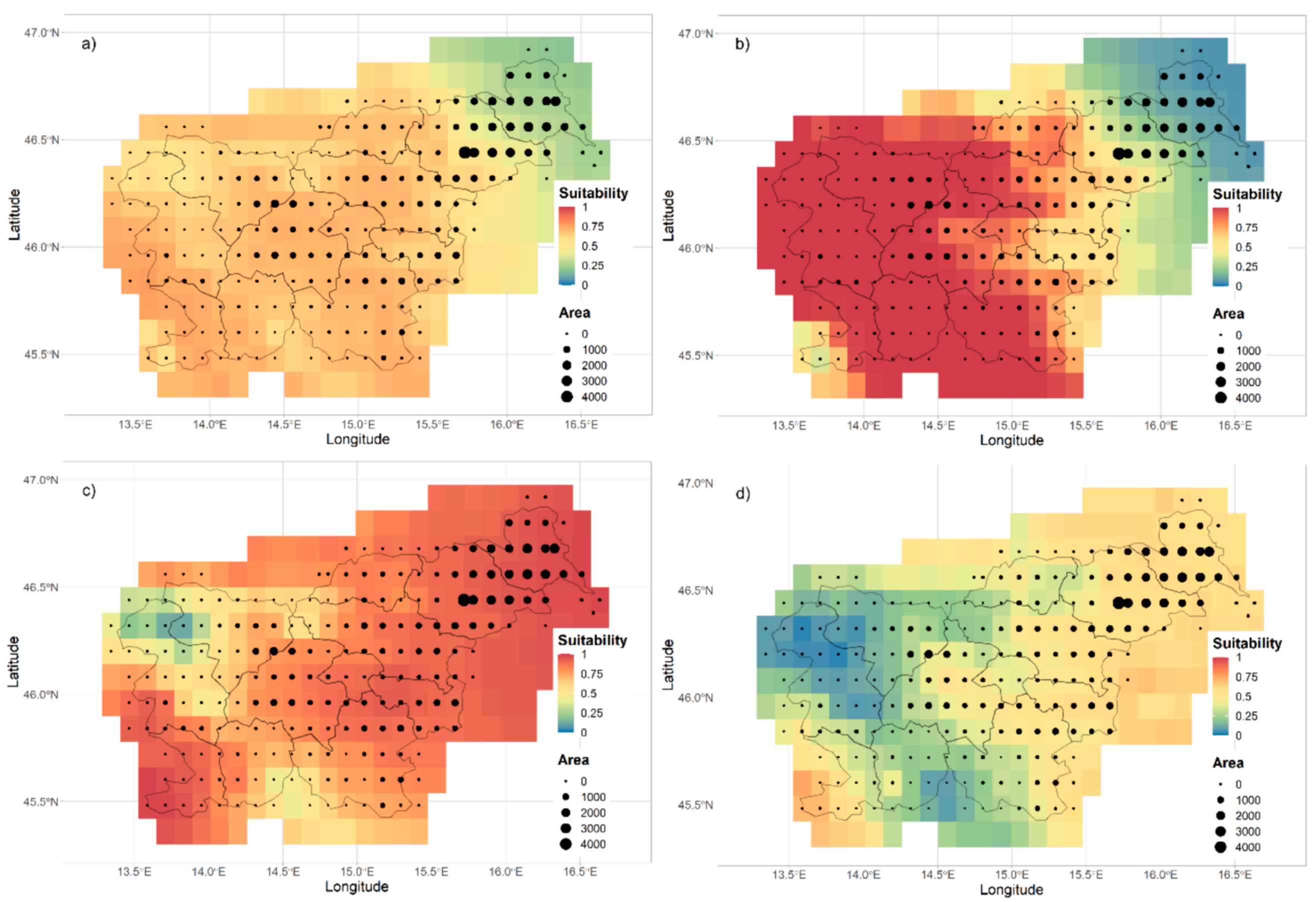

Fig. 3. Predicted habitat suitability for the analysed parasitoids under 2011–2040 climate, multi-model median is shown for *C. marginiventris* (A), *E. laphygmae* (B), *T. remus* (C) and *T. pretiosum* (D) for scenario RCP4.5. Information on maize field area (in ha) in 2022 is presented by black points.

and therefore, highlight their potential for consideration in a pre-emptive biocontrol assessment. We have shown that the climate suitability of Slovenia for FAW will increase throughout the century, with the most vulnerable parts of eastern and southwestern Slovenia already having a moderately high probability of FAW occurrence in the present climate of 1981–2010 (about 0.5). This suitability would most likely increase if the data on greenhouses was included in the calculations, as environmental conditions in those are even more favourable and would allow for overwintering of the pest in case of colder winters. By combining the predicted suitability of the Slovenian climate for FAW with information on maize field data, we were also able to show that the regions with the largest areas with maize cultivation coincide with a moderate to high climate suitability for FAW, putting the main maize-growing areas of Slovenia at significant risk.

Similar to the results of the study by Tepa-Yotto et al. (2021), our results show that the climate suitability of the region will increase for all four selected FAW parasitoids with climate change under the RCP4.5 scenario, with this effect being even more pronounced under the RCP8.5

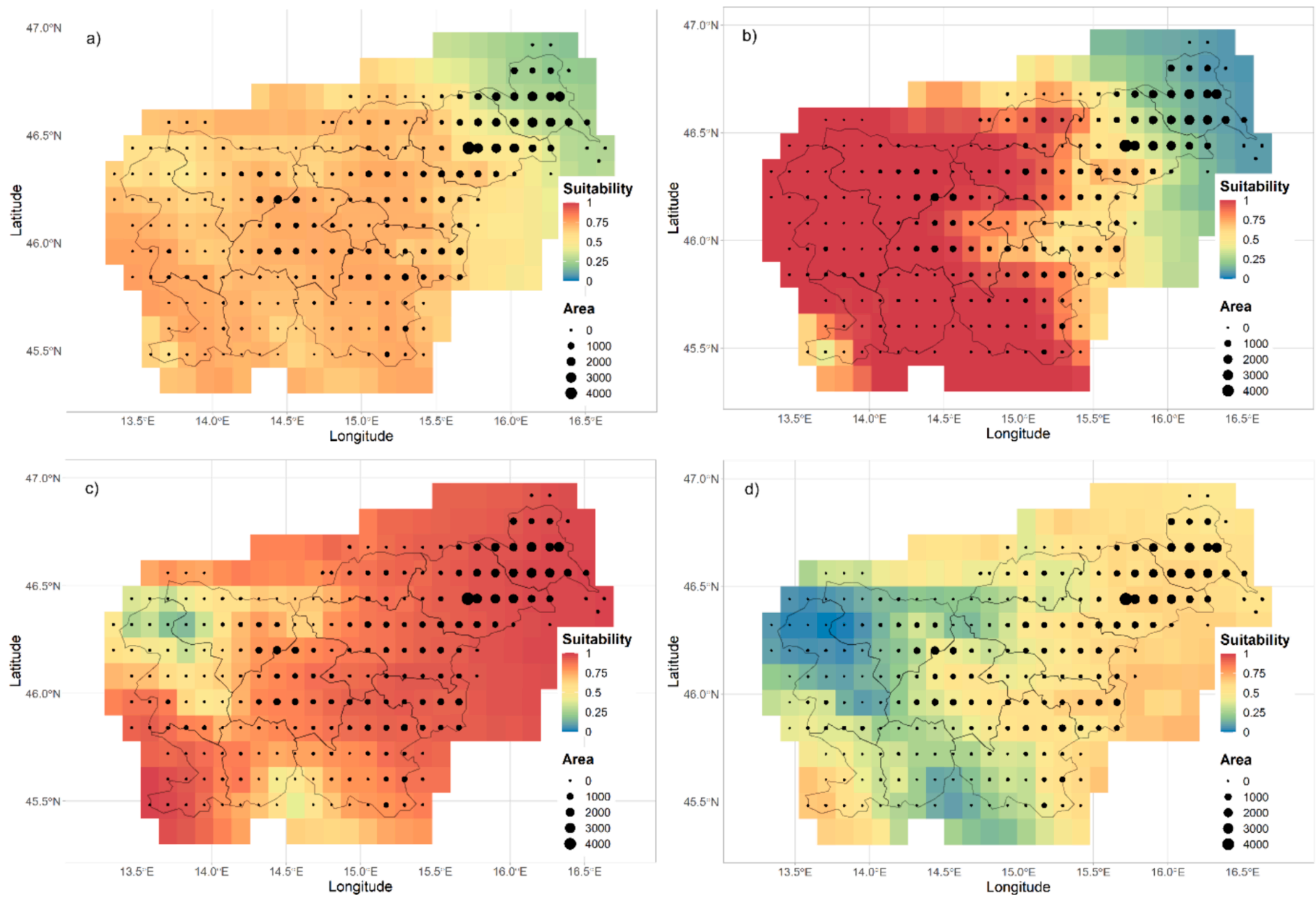

Fig. 4. Predicted habitat suitability for the analysed parasitoids under 2041–2070 climate, multi-model median is shown for *C. marginiventris* (A), *E. laphygmae* (B), *T. remus* (C) and *T. pretiosum* (D) for scenario RCP4.5. Information on maize field area (in ha) in 2022 is presented by black points.

scenario. Our results suggest that the future climate of Slovenia shows the highest probabilities for parasitoids *T. remus* and *E. laphygmae*, with the habitat suitability of *T. remus* coinciding with the main regions of maize production. This result identifies *T. remus* as the most suitable natural enemy that would thrive in the regions of Slovenia under highest threat of FAW, which is interesting, as the study by Tepa-Yotto et al. (2021) found the probability of *T. remus* to be only moderate. This difference is likely a result of a higher resolution of data used in our study, and based on this we believe our results to be more trustworthy. Although with slightly lower predicted climate suitability compared to *T. remus*, *T. pretiosum* could similarly represent a possible natural enemy to FAW. Especially later throughout the 21st century, the climate suitability of the region for *T. pretiosum* in the maize-growing parts of the country is relatively high (suitability around 0.5). Nonetheless, the results of Maxent models for small sample sizes, such as the four parasitoids in our case, should be interpreted with caution. When occurrence records are drawn from too small a geographic area, Maxent can give very large values when extrapolating to conditions outside the range present in the study area (Phillips et al., 2006).

The assessment of climate suitability for the analysed species also showed some geographic variability across Slovenia. The predicted climate suitability was notably high (>0.75) for *E. laphygmae* across the majority of Slovenia, however, its calculated niche was directly overlapping the regions with the lowest suitability for FAW. Therefore, based on climatic suitability, *E. laphygmae* would not serve as the best option for the implementation of biological control measures. For *C. marginiventris*, the predicted climate suitability was relatively low for the greater part of Slovenia, with an indication of improvement between the past climate (1981–2010) and the period around the middle of the century (2041–2070). Based on the assumptions made in the introduction about the proposed combined release of an egg and larval parasitoid (Tepa-yotto et al., 2021), these last two findings are less encouraging, as the two natural enemy species with the highest probability are both egg parasitoids. This would mean that the candidate biological control agents would only target the FAW for a short time period (egg development range from 7 days at 18 °C to just 2 at 32 °C). With an introduction of a larval parasitoid species, this period could increase by 10 (32 °C) to 37 (18 °C) days, significantly increasing the time window where FAW could be targeted. Knowing this, and relying on the climate change to result in the more favourable conditions over the next 50 years, *C. marginiventris*, a larval parasitoid, might also be a good candidate to consider despite the slightly lower climate suitability.

Based on the pre-emptive biological control framework, proposed by Avila et al. (2023), FAW would definitely fall into the category of a high-risk pest, as it is an important pest in its native range and in the newly invaded areas globally. Its threat was recognized by authorities in Slovenia, as well as at the European level, and regulations were introduced to minimize the risk of transfer (MKGP, 2024, EPPO, 2023). Results of our modeling effort support the concerns that Slovenia is at risk, though caution is required when considering the results of ecological niche models, regardless of the model used. As noted by Phillips et al. (2006), predicted ranges usually exceed the actual distribution of the species, whether or not a model covers the full niche requirements of a species. Several factors, including geographic barriers to dispersal, biotic interactions, and human-induced environmental changes, contribute to the fact that not all regions that fulfil a species' niche requirements are occupied. In addition, climate projections are used to represent plausible future conditions in relation to the different global warming scenarios, with RCP4.5 representing the current realistic scenario (Climate Action Tracker, 2023) and RCP8.5 representing the current pessimistic scenario. Since the future climate is not known with certainty, different model projections were used in this study to account for the uncertainty of future conditions. Still, rapid spread of the pest worldwide seems to validate the model predictions. FAW has not yet been detected in Slovenia, but just in the last year there were two accounts of invasion to Greece (EPPO, 2023), which, considering that the moths can travel over large distances, is not very far away. Climate change impacts also suggest that in the near future, conditions for FAW in Slovenia will most likely improve. Luckily, the same improvement in conditions will likely also benefit the natural enemies.

FAW has been studied extensively in the past, so risk assessments have been developed on both the EU and the national level, documenting information on pathways of interception, biology, hosts etc. (MKGP, 2024, EPPO, 2023). Eradication efforts have been attempted in invaded countries, albeit with limited success. Chemical control remains a predominant strategy, often supplemented by cultural practices such as crop rotation and planting non-host crops (Sparks and Nauen, 2015). However, the effectiveness of chemical pesticides is hampered by the pest's rapid development of resistance (Banerjee et al., 2017). Biological control methods, including the use of natural enemies, have shown promising results in managing FAW populations abroad, therefore it is crucially important that similar studies are undertaken in order to increase preparedness and act quickly when an invasion occurs, as Avila et al. (2023) suggest.

Notably less information is available on the actual real-world distribution overlap between FAW and the four selected parasitoids. There is a significant lack of information especially for *E. laphygmae*, but its suitability was also undermined by the model results. Based on that, our suggestion for future control measures in Slovenia would be a combined classical biocontrol effort with both *T. remus* and *T. pretiosum*. For example, a series of studies in Brazil showed that release of the egg parasitoids *T. remus* and *T. pretiosum* has the potential to reduce field populations (Tay et al., 2023, van Lenteren, 2012; van Lenteren et al., 2018). Additionally, information has been gathered about the number of released individuals (Figueiredo et al., 2002; Pomari et al., 2013), the dispersal capacity (Pomari-Fernandes et al., 2018), and costs (Vieira et al., 2017) to allow the development of a *T. remus* release program, as well as a release program of *T. pretiosum* (Tay et al., 2023). In order to bridge the knowledge gaps, collaboration between researchers, policymakers, agricultural stakeholders, and international organizations in developing integrated pest management strategies for FAW will be of utmost importance. The negative side effects of introduction of non-native natural enemies for biological control purposes should be considered before any releases are planned. Slovenia has leaned heavily on the safe side in this regard in the past, and in order to facilitate both a safe and prompt action, further studies, including laboratory experiments should be undertaken.

5. Conclusions

In conclusion, this study underscores the urgent need for proactive measures to mitigate the threats posed by the fall armyworm (FAW, *Spodoptera frugiperda*) to agricultural systems, particularly in regions like Slovenia where maize production plays a significant role. The findings highlight the increasing climate suitability for FAW in Slovenia, indicating a heightened risk of invasion and subsequent economic losses. Introduction of non-native species as required for classical biological control is not possible in Slovenia without a thorough risk assessment, due to the current legislation. Exemptions are theoretically allowed, but have to be justified by the ministry responsible for agriculture and approved by the ministry responsible for environment. The pre-emptive assessment framework proposed by Avila et al. (2023) would enhance preparedness in biological control by speeding-up the decision-making process for the introduction of biocontrol agents, so they can be approved in the anticipated arrival of the target pest. This would greatly contribute to control FAW and reduce its associated damage in the early stages of the invasion process. In order to inform the decision makers about the risks and possible solutions connected to FAW invasion in Slovenia, a climate suitability analysis was performed for four possible natural enemies of the FAW. The results of the study highlighted *Telenomus remus* as the most climatically suitable, with the climate suitability for this parasitoid increasing throughout the 21st century regardless of the climate scenario considered. On the other hand, promising results were also found for *Trichogramma pretiosum*, as its current and future ecological niche matched well with the maize crop field data of Slovenia. In the case of *Eiphosoma laphygmae* and *Cotesia marginiventris*, their climate suitability was predicted as relatively high but only for some parts of Slovenia, which are not in as high of a danger of FAW as the regions with highest maize field areas. The effectiveness of such control measures hinges on a thorough understanding of the ecological niche and distribution overlap between FAW and selected parasitoids, underscoring the importance of further research in this field. Collaboration between various stakeholders, including researchers, policymakers and agricultural professionals, will be essential for developing and implementing integrated pest management strategies tailored to Slovenia's specific context. Moreover, careful consideration of the potential negative impacts associated with the introduction of non-native natural enemies is crucial to avoid unintended ecological consequences. By leveraging scientific knowledge, fostering collaboration, and implementing proactive pest management measures, Slovenia can bolster its resilience against FAW and safeguard its agricultural productivity in the face of evolving environmental challenges. This study serves as a foundational step towards informing evidence-based decision-making and guiding future research efforts aimed at addressing the complex challenges posed by invasive pests like FAW. Ultimately, by taking proactive and collaborative action, Slovenia can enhance its capacity to effectively minimize the threat of FAW and mitigate the risks posed to its agricultural sector, ensuring food security and sustainability for future generations.

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CRediT authorship contribution statement

Zala Žnidaršič: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Tjaša Pogačar:** Supervision. **Stanislav Trdan:** Supervision, Conceptualization. **Miha Curk:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A1. Raw species occurrence data of the GBIF database and occurrence data with duplicates removed (Accessed 23 February 2024).

Occurrences	Occurrences without duplicates	Scientific name
11.655	6149	*Spodoptera frugiperda* (J. E. Smith, 1797)
297	27	*Cotesia marginiventris* (Cresson, 1865)
258	43	*Trichogramma pretiosum* (Riley, 1879)
193	28	*Eiphosoma laphygmae* (Costa Lima, 1953)
172	34	*Telenomus remus* (Nixon, 1937)

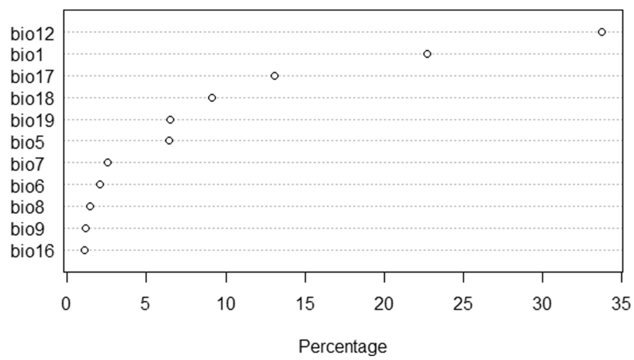

Fig. A1. Predictor variable contribution for the FAW Maxent model calibrated with the full set of occurrences.

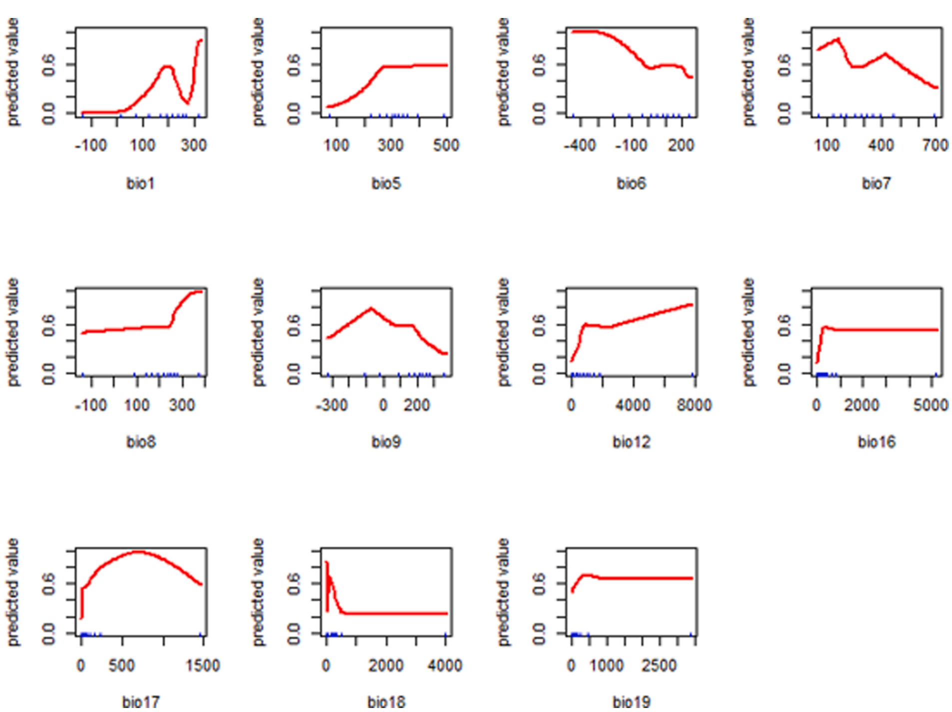

Fig. A2. Variable response curves for the FAW Maxent model calibrated with the full set of occurrences.

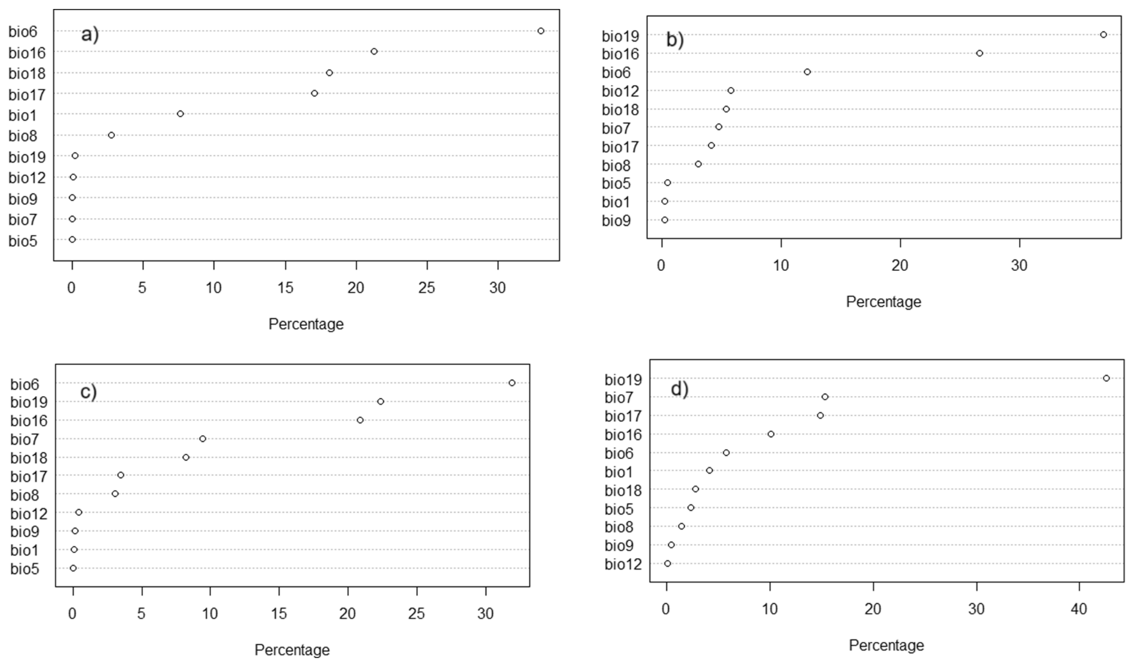

Fig. A3. Predictor variable contribution for the Maxent models of the four parasitoids *C. marginiventris* (A), *E. laphygmae* (B), *T. remus* (C), *T. pretiosum* (D) calibrated with the full set of occurrences.

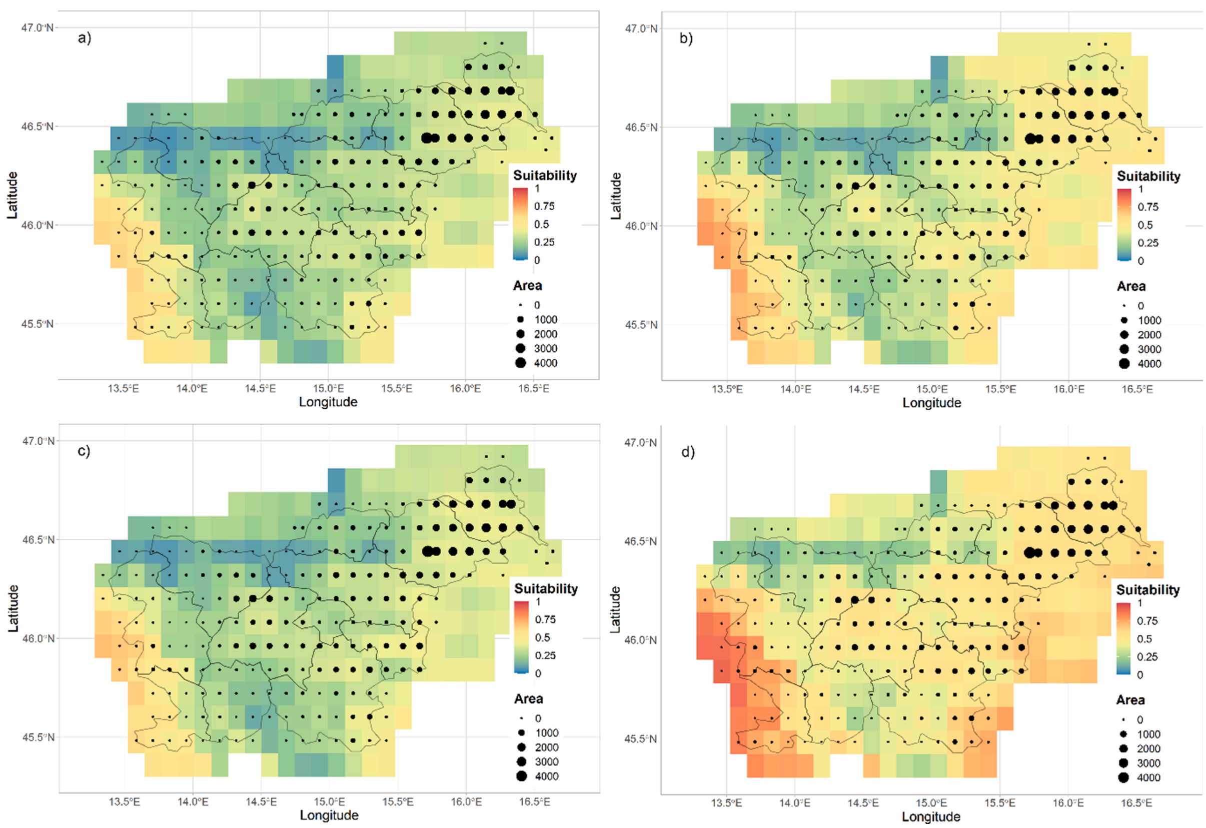

Fig. A4. Predicted minimum and maximum habitat suitability for the FAW under 2011–2040 climate (A, B) and under 2041–2070 climate (C, D) for scenario RCP4.5. Information on maize field area (in ha) in 2022 is presented by black points.

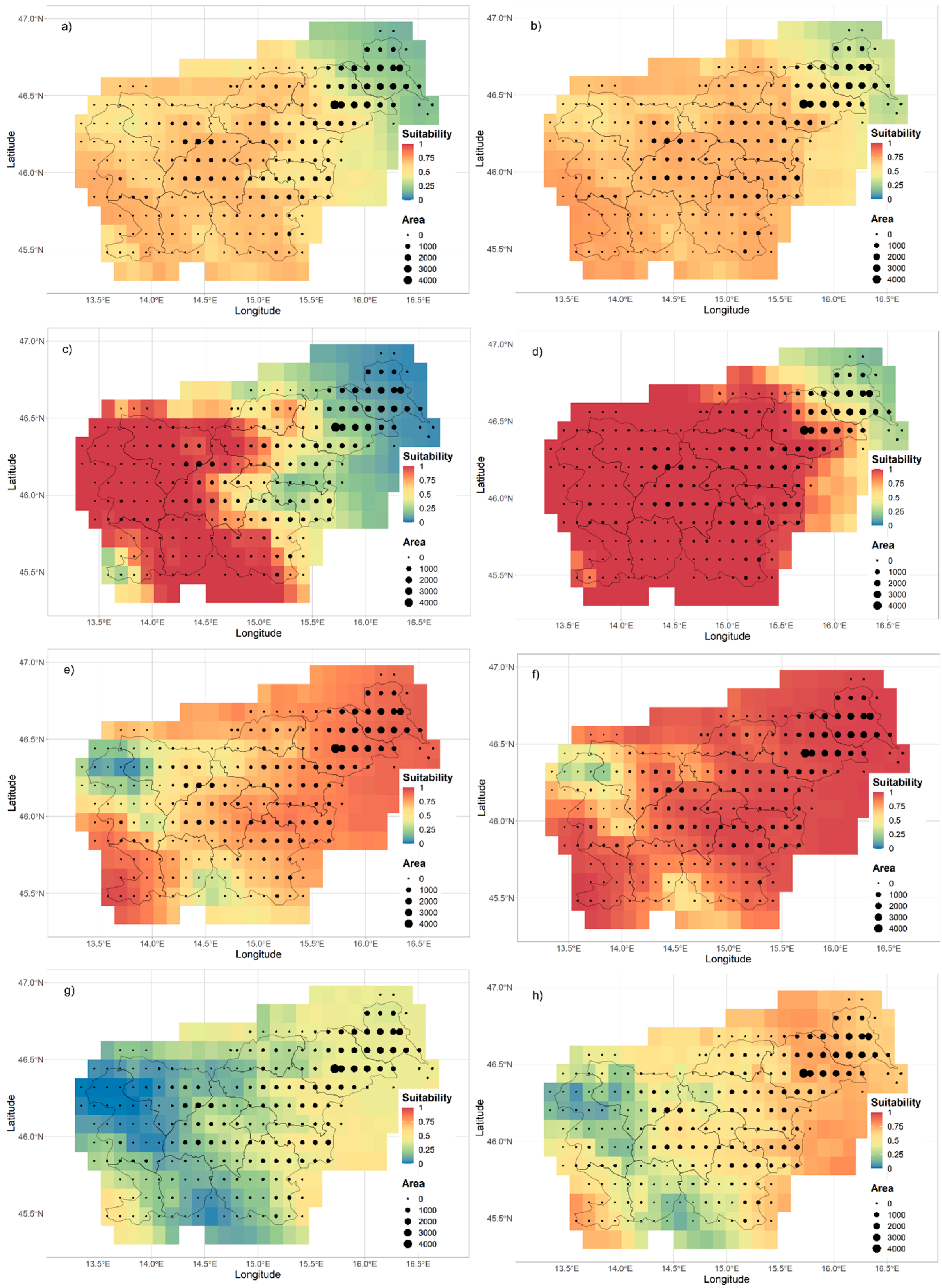

Fig. A5. Predicted minimum and maximum habitat suitability for the four parasitoids *C. marginiventris* (A, B), *E. laphygmae* (C, D), *T. remus* (E, F), *T. pretiosum* (G, H) under 2011–2040 climate for scenario RCP4.5. Information on maize field area (in ha) in 2022 is presented by black points.

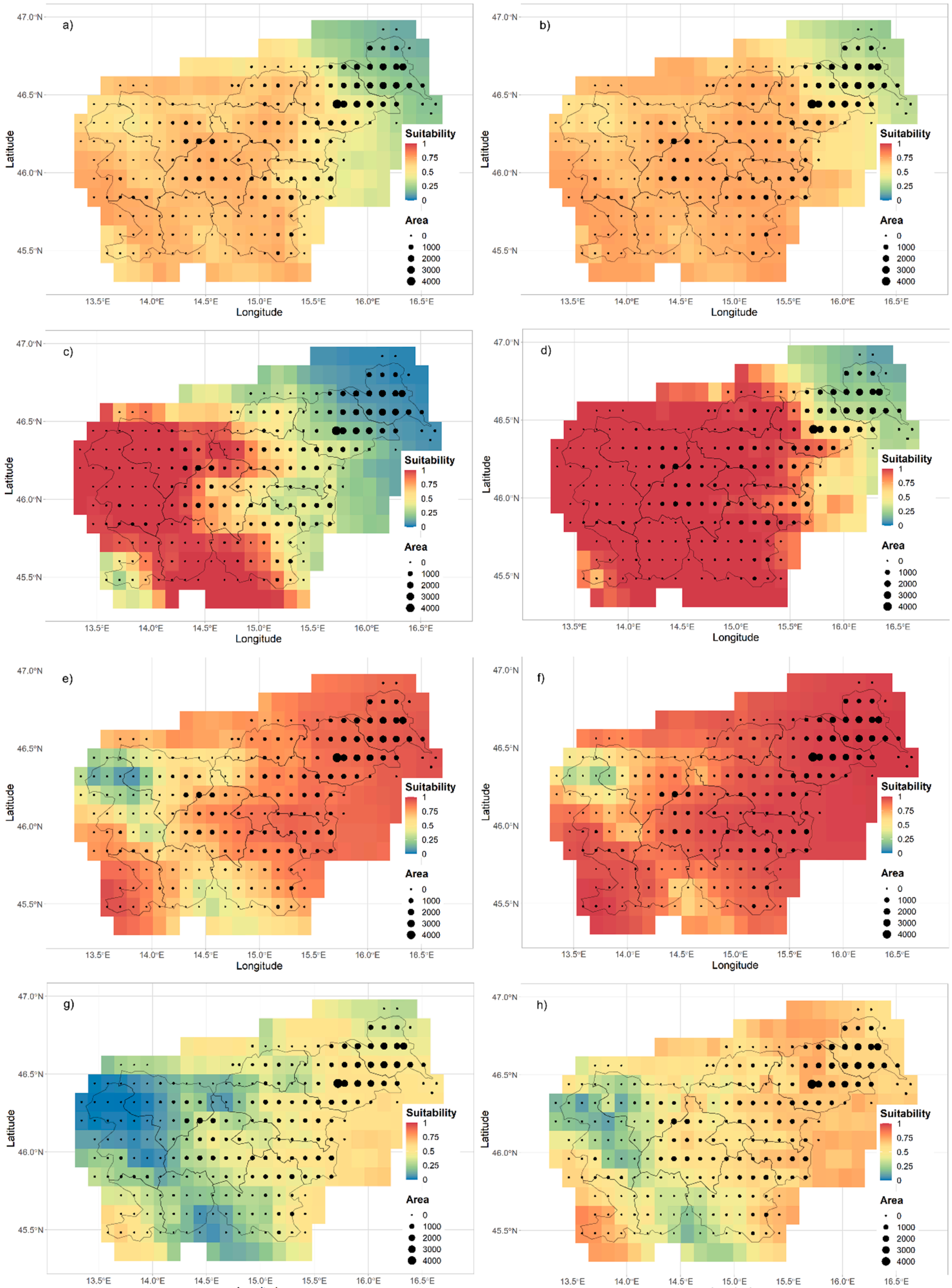

Fig. A6. Predicted minimum and maximum habitat suitabilityfor the four parasitoids *C. marginiventris* (A, B), *E. laphygmae* (C, D), *T. remus* (E, F), *T. pretiosum* (G, H) under 2041–2070 climate for scenario RCP4.5. Information on maize field area (in ha) in 2022 is presented by black points.

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