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ORIGINAL RESEARCH ARTICLE

Expected prevalence of the facultative parasitoid *Megaselia scalaris* of honey bees in Africa and the Mediterranean region under climate change conditions

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Abstract

The biological invasion with new pests and pest status are highly impacted by future climate change conditions. There are a number of parasitic flies that can infect honey bees causing some economic damages. The information related to the geographical distribution of such parasitic pests is very limited under current and future climate conditions. The facultative parasitoid *Megaselia scalaris* is the focus of this study. Ecological modeling approach was used to model current and potential future distribution of this fly in Africa and the Mediterranean region. Occurrence records from five countries, six temperature variables, future models for 2050 and 2070, and maximum entropy algorithm in Maxent were used during the analysis. The highest contribution in the model was to annual mean temperature, mean diurnal range, minimum temperature of the coldest month, and the mean temperature of the warmest quarter representing 92.4% of the total percentage. The performance of the model was perfect according to the evaluation analysis. The study maps showed the suitability of current conditions for the prevalence of this fly in various regions in Africa and Europe. Maps for all time points confirmed the occurrence of this pest in North Africa especially Northern parts from Egypt to Morocco, Sub-Saharan Africa, and countries in South Europe. The implications of such prevalence of *M. scalaris* on beekeeping were discussed.

Keywords Modeling · Maxent · Beekeeping · Pest · Honey bees

Background

The fly *Megaselia scalaris* (Order: *Diptera* and Family: *Phoridae*) is among the insects with medical importance for human and animals (Harrison and Gardner 1991; Benecke and Lessig 2001; Anderson and Huitson 2004; Costa et al. 2007a, b; Fischer 2007; Disney 2008; Nazni et al. 2011) as well as is considered as a pest to stored products (Karunaweera et al. 2002). Also, this fly is used in laboratory experiments as a model insect (Dama 2014). This fly has shown parasitic activity on pollinators and honey bees (Core et al. 2012; Ricchiuti et al. 2016; Cham et al. 2018). A group of flies belong to Family Phoridae other than *M. scalaris* has been detected in honey bee workers including Apocephalus borealis (Core et al. 2012; Mohammed 2018) and *Megaselia rufipes* (Dutto and Ferrazzi 2014). Another sister group of flies from Family Sarcophagidae including *Senotainia tricuspis* can cause damages to honey bee colonies (Morse and Flottum 1997; Felicioli et al. 2000).The infection with these flies is expected to contribute in causing decline of bee colonies especially under high infestation levels.

M. scalaris has been detected in honey bee workers as facultative parasites (Ricchiuti et al. 2016; Cham et al. 2018). The larvae as other flies from Phoridae can feed on honey bee tissues and hemolymph reducing the longevity of bees, leading at the end to reducing colony strength. The exact effects of this fly on honey bee behavior and orientation to colonies are not well known. A similar fly, *A. borealis* showed effects on flight ability of bees and caused abnormal attraction to light (Core et al. 2012). *M. scalaris* is expected to occur in various locations in the world but the actual occurrence records are limited to some countries including some regions in Africa and Europe (Menail et al. 2016; Ricchiuti et al. 2016; Cham et al. 2018). The possible changes in the pest status and ability of this fly to invade new

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regions under climatic change conditions are not known. In fact, such changes are expected to lead wide effects on beekeeping and associated pests and diseases of honey bees (Le Conte and Navajas 2008; Abou-Shaara 2016).

Understanding future changes in pest status is primarily linked with changes in temperature (Le Conte and Navajas 2008; Yoruk and Sahinler 2013; Abou-Shaara 2016; Jamal et al. 2021). So, specific temperature variables can be analyzed to present better expectations about future changes in prevalence of bee pests (Jamal et al. 2021) in combination with specific software for ecological modeling including MaxEnt (Wei et al. 2018; Hosni et al. 2020; Polidori and Sánchez-Fernández 2020; Jamal et al. 2021). The present study aimed to highlight the prevalence of *M. scalaris* as a pest to the valuable insect (honey bees) in the Mediterranean region and Africa under current and future climatic conditions. Also, the potential damages from this pest to beekeeping are discussed.

Materials and methods

1. Occurrence records in Europe and Africa

The available records of *Megaselia scalaris* in Africa and Europe are generally limited. The available data from GBIF Occurrence Download (Global Biological Information Facility, GBIF.org, December 2020, https://doi.org/10.15468/dl.bev3a8) beside previous publications were utilized to achieve the modeling. So, records from two European countries (Italy and France) and three African countries (Algeria, Cameroon, and Madagascar) were used in the study. Each country was represented by 20 records to keep the balance between the investigated countries. All the records were initially checked for their accurateness using Google Earth prior to the run of the model.

2. Temperature variables for current conditions

The most comprehensive source for environmental variables is WorldClim website (www.worldclim.org). This online source was used in many prediction studies (Abou-Shaara 2016; Hosni et al. 2020; Jamal et al. 2021). So, specific temperature datasets were downloaded from WorldClim (v2.1, January 2020) and used in the analysis (Jamal et al. 2021). These datasets and their abbreviations are:

1) Annual mean temperature (bio 1).
2) Mean diurnal range (bio 2), calculated as mean of max monthly temp—min monthly temp.
3) Maximum temperature of the warmest month (bio 5).
4) Minimum temperature of the coldest month (bio 6).
5) Mean temperature of the warmest quarter (bio 10).
6) Mean temperature of coldest quarter (bio 11).

The abbreviations used are the original abbreviations by WorldClim. The other temperature datasets with abnormal data or distribution were not included in the study (Escobar et al. 2014; Samy et al. 2016; Alkishe et al. 2017). All these variables had a spatial resolution of 5 km^2, which improves the accuracy of the analysis. The percentages of contribution of each variable used in the study were calculated in combination with response curves to highlight the role of temperature in the occurrence of *M. scalaris.*

3. Temperature variables for future conditions

Future climate model from the Beijing Climate Center (BCC-CSM2-MR) (Eyring et al. 2016) was used in the analysis to predict future distribution of *M. scalaris* in South Europe and Africa. This model presents two expectation time points (2050 and 2070) with two limits of Shared Socio-economic Pathways (SSP126 and SSP585) in accordance with the Intergovernmental Panel on Climate Change (the 6th article) for the six temperature variables selected in the study. So, four future maps were obtained from the model: two maps for 2050 and another two maps for 2070. The maps can help in better predicting of the future distribution of *M. scalaris* under climate change conditions.

4. Ecological modeling

The ecological modeling using maximum entropy modeling for current and future conditions was achieved by Maxent v 3.4.1 (Phillips et al. 2020). The model used 25% of the records for testing the model and 75% for training the model. The Maxent distribution in the used model was determined using 10,075 points. The maps from the model were presented using cumulative as the output format. So, a colour legend considering values from 20 to 100 as very high and from 12.5 to 20 as high, 0 to 12.5 as low and 0 as very low was added beside each map to explain the results. Typically, the highest values especially more than 20 indicate the highest occurrence according to Maxent tutorial (Phillips 2017).

5. Performance of the ecological model

Some options were selected during the modeling using Maxent to evaluate the performance of the ecological model (Phillips 2017; Jamal et al. 2021). These options included the jackknife tests for test and training data, area under the curvy (AUC), and omission rates on training and test data. These values were discussed to justify the quality of the analysis.

Results

1. Contribution percentages of temperature datasets in the model

The six variables contributed in the model by 1.2 to 30.4%. Typically, these percentages from the highest to the lowest values were 30.4, 30.2, 18.5, 13.3, 6.5, and 1.2% for bio1, bio2, bio6, bio10, bio11, and bio5, respectively. Thus, the highest contributions were to annual mean temperature, mean diurnal range, minimum temperature of the coldest month, and the mean temperature of the warmest quarter representing 92.4% of the total percentage. The response curves of these four variables are presented in Fig. 1. It is clear that temperatures from 13–15 °C, 6–7 °C, 2/19 °C, and 17–19 °C for bio1, bio2, bio6 and bio10, respectively are suitable for the occurrence of *M. scalaris*. The lowest contributions were to mean temperature of the coldest quarter and maximum temperature of the warmest month representing only 7.7% of the total percentage.

2. Modeling current distribution of *Megaselia scalaris*

The distribution in Africa based on the current conditions shows the suitability of some areas in the Sub-Saharan Africa and in the northern parts of Egypt, Libya, Tunisia, Morocco, and Algeria for *M. scalaris* (Fig. 2). The desert areas in North Africa are not anticipated to be suitable for this fly. Also, the map shows that the ability of this fly to adapt with conditions in Africa is limited in specific areas although the huge area of Africa. Mostly the coastal regions around the continent are the key regions for the prevalence of *M. scalaris.* This model clearly shows the suitability of all coastal areas in the Mediterranean region for the occurrence of *M. scalaris.* The highest infection in Europe is expected to occur in Portugal, Spain, France and Italy. Beekeeping in these regions either in south Europe or in the scattered areas in Africa is expected to suffer from the parasitism by *M. scalaris.*

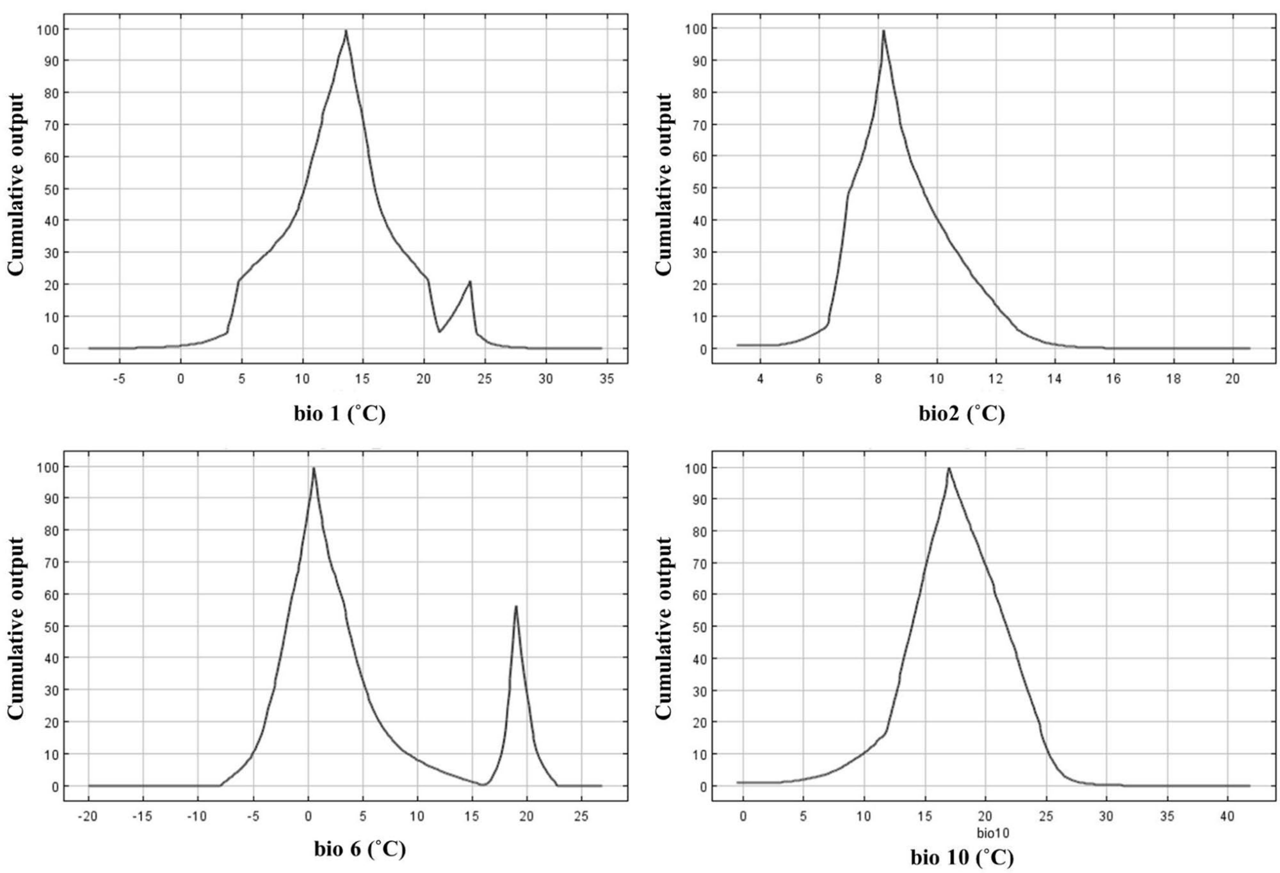


Fig. 1 Response curves representing the cumulative output and temperature degrees (°C) for four temperature variables. These variables are; bio1: annual mean temperature, bio2: mean diurnal range, bio6: minimum temperature of the coldest month, and bio 10: mean temperature of the warmest quarter

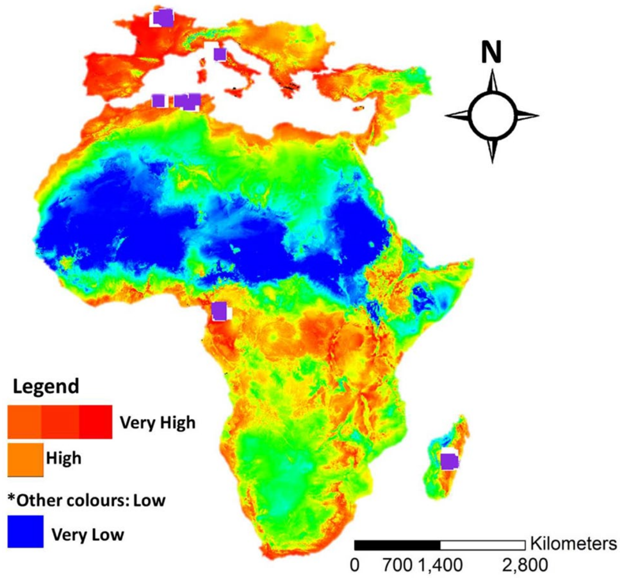


Fig. 2 The potential prevalence of *Megaselia scalaris* in Africa and Sothern parts of Europe under current climatic conditions. The training and test records in the five countries (France, Italy, Algeria, Cameroon, and Madagascar) are marked with white and violet squares, respectively

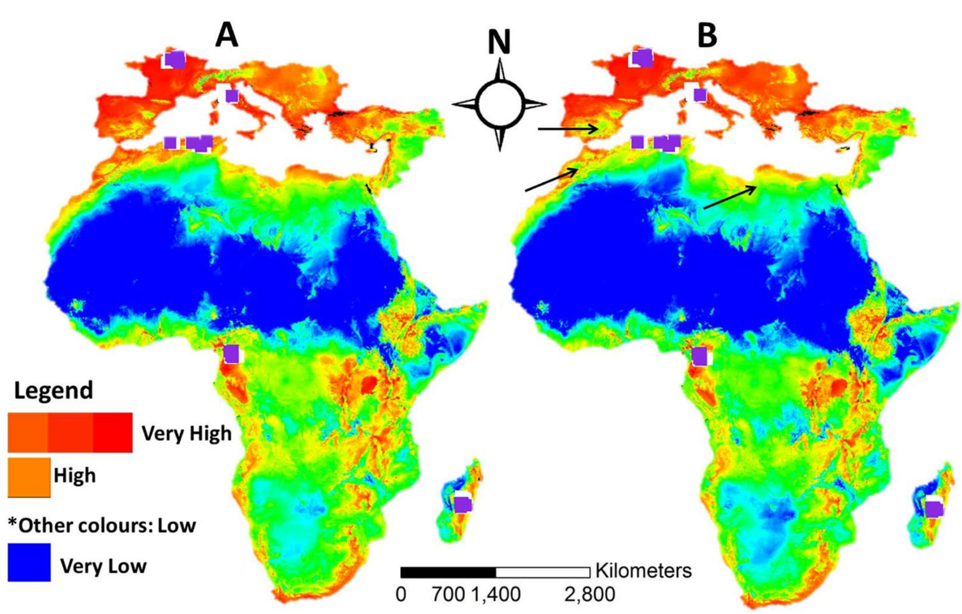
3. Modeling future distribution of *Megaselia scalaris*

It seems that future conditions during 2050 and 2070 at the low limit of SSP126 will not be different greatly than current distribution of this pest (Figs. 3a and 4a). So, the pest status in Southern European countries and in Africa will be the same as current conditions. Still the Northern parts of Africa especially coastal regions will be the most suitable for the occurrence of this pest. Also, Sub-Saharan Africa contained some suitable areas for *M. scalaris*. It is also clear that deserts and highlands in Africa and South Europe will not be suitable for *M. scalaris.* The most infected areas are located in the western parts of Africa (especially Morocco) and some European countries (Italy, Portugal, Spain, and France). The high limits of SSP 585 for 2050 and 2070 (Figs. 3b and 4b) show clear variations than current conditions and the low limit of SSP126 for the two time points. These variations concentrate on the low prevalence in North Africa especially in Egypt, Libya, Morocco, and some parts of Portugal and Spain. The map Fig. 4b additionally shows the low prevalence of *M. scalaris* in some parts of Cameroon than current situation. Indeed, all maps support the occurrence of this pest in most Arabian countries in Africa including northern parts of Egypt. Also, the high prevalence in South Europe and some parts in Sub-Saharan Africa are supported by all maps and cross the two time points. The threats for beekeeping from this pest are likely to be continues over a long period through 2050 and 2070. This reflects the dangerous effects of this pest on beekeeping especially in apiaries located at the most suitable regions for *M. scalaris.*

4. Model performance

The evaluation tests based on analysis of omission (Fig. 5) and jackknife test (Fig. 6) were used to justify the performance of the used model. The omission on test and training samples used in the Maxent model was not far than the predicted omission as a function of the cumulative threshold (Fig. 5a). The receiver operating

Fig. 3 The potential prevalence of *Megaselia scalaris* in Africa and Sothern parts of Europe under future climatic conditions (2050) with two limits SSP 126 **a** and SSP 585 **b**. Black arrows denote to changes in map B than A



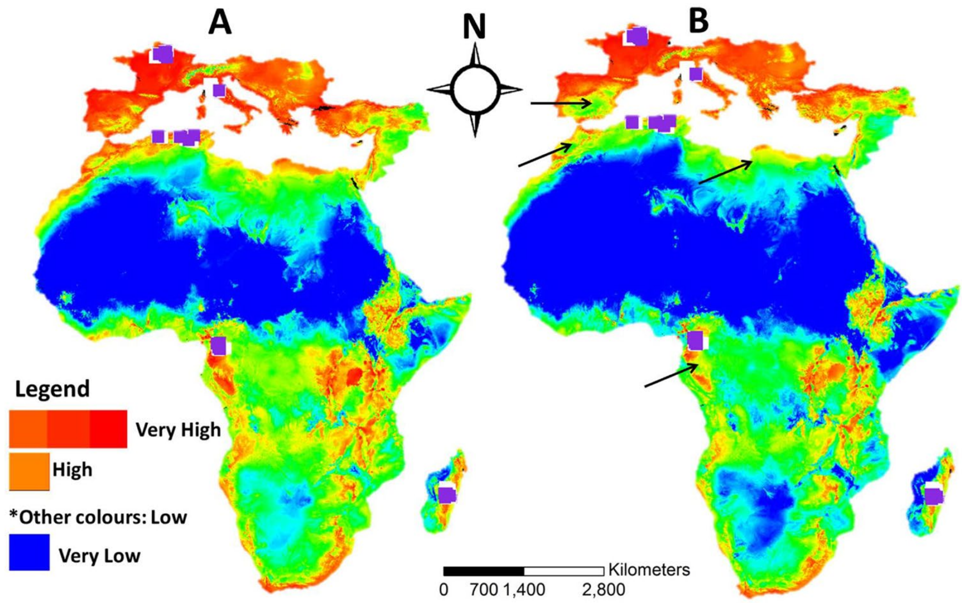


Fig. 4 The potential prevalence of *Megaselia scalaris* in Africa and Sothern parts of Europe under future climatic conditions (2070) with two limits SSP 126 **a** and SSP 585 **b**. Black arrows denote to changes in map **b** than **a**

characteristic (Fig. 5b) show the high values of area under curvy with 0.965 and 0.962 for test and training data, respectively.

The jackknife test is shown in Fig. 6 for the six temperature variables used in the model. The regularized training gain (Fig. 6a) shows the highest importance of variable 2 (mean diurnal range) with the highest gain when used separately. The area under the curvy (Fig. 6b) shows high value for all variables more than 0.82. Also, the test gain (Fig. 6c) shows high value than 0.80 for all variables.

Discussion

1. Contribution percentages of temperature datasets in the model.

Temperature plays a key role in the development of *M. scalaris* (Disney 1994). The highest temperature is better for the development of immature stages than low one (Dama 2014; Thomas et al. 2016). So, it is expected that the development rate of *M. scalaris* is slower in cooler conditions than hotter

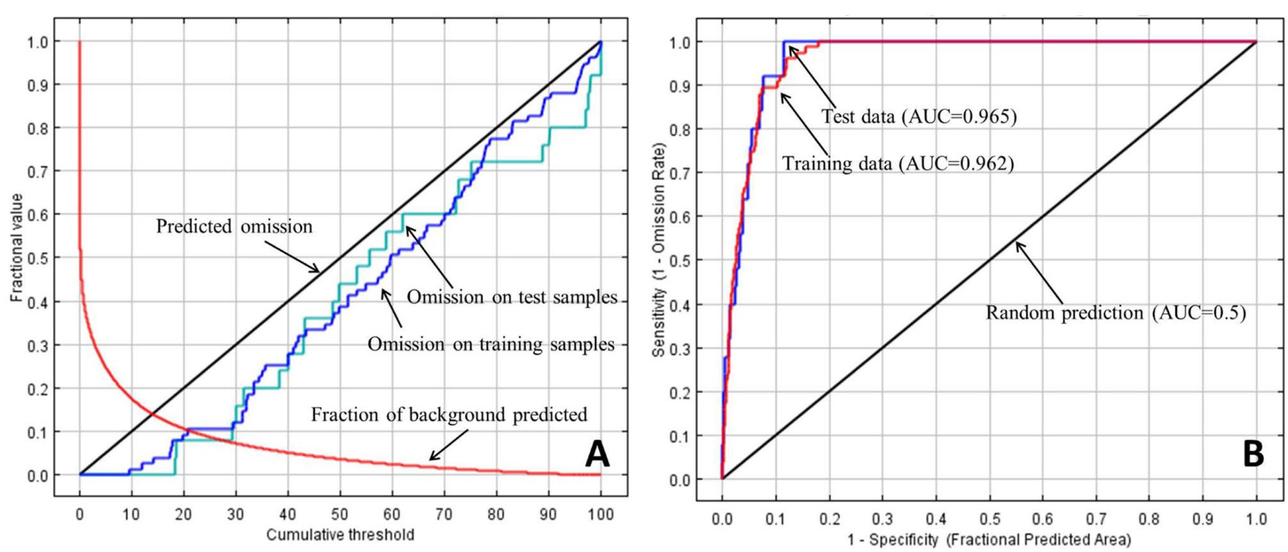


Fig. 5 Analysis of omission and predicted area **a** and the receiver operating characteristic (Sensitivity versus 1-Specificity) **b** for *Megaselia scalaris*. AUC: area under curvy

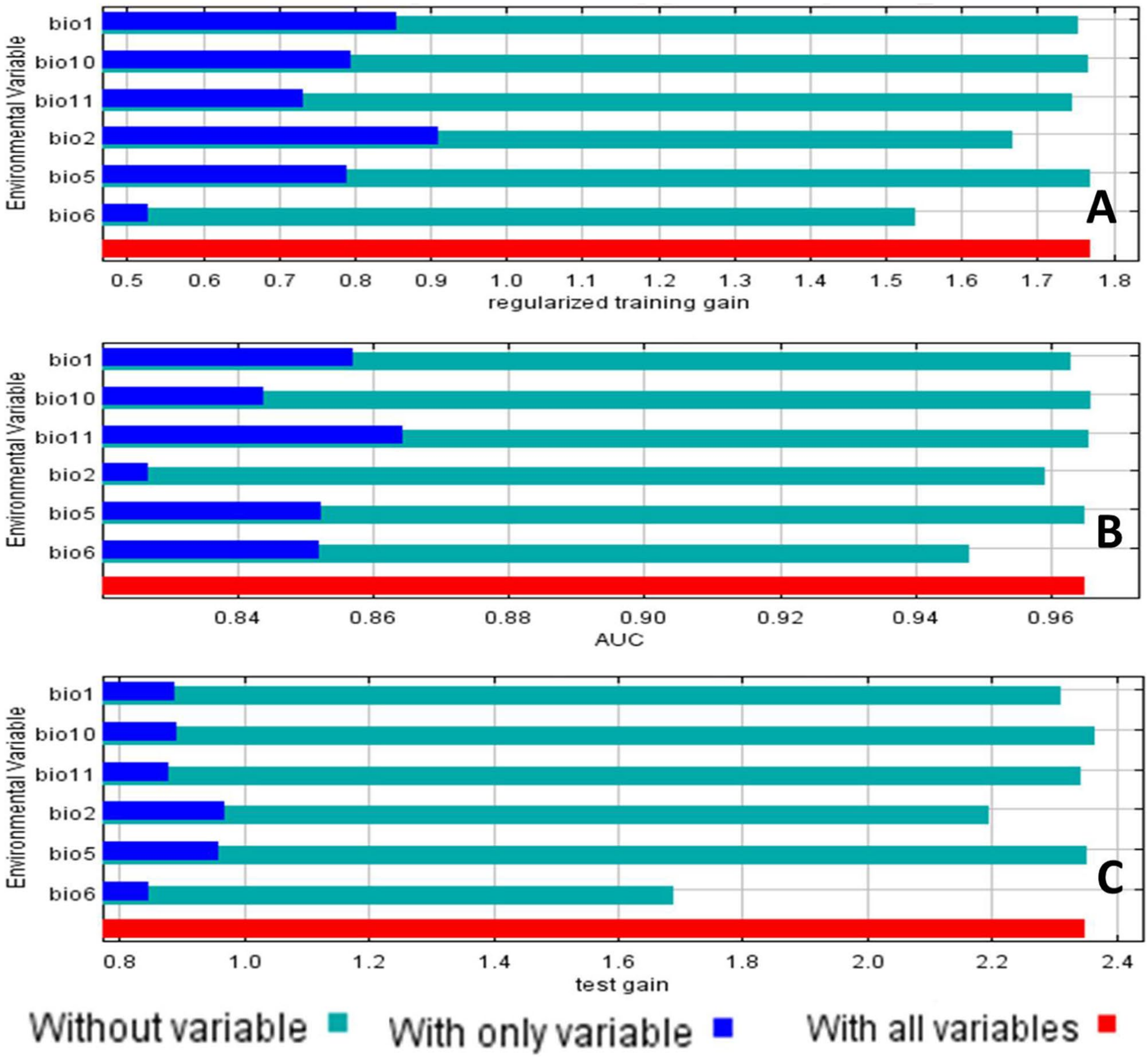


Fig.6 The jackknife test for the six temperature variables used in the analysis: regularized training gain **a**, area under curvy (AUC) **b**, and test gain **c**. bio1: Annual mean temperature, bio2: Mean diurnal range, bio5: Maximum temperature of warmest month, bio6: Minimum temperature of coldest month, bio10: Mean temperature of warmest quarter, and bio11: Mean temperature of coldest quarter

ones. Also, it is expected that summer is the perfect period for the prevalence of this fly especially under European conditions. According to this expectation, a study in Italy showed prevalence of this fly during period from July to September (Ricchiuti et al. 2016), representing summer. The development rates of this fly under European conditions and Northern parts of Africa are expected to be lower than Cameroon and Madagascar due to the variations in air temperature throughout the year. Indeed, temperature variables considering all months tended to be towards high temperature over 6 °C. The highest contributions of annual mean temperature and mean diurnal range supports the important role of temperature in the occurrence of *M. scalaris.*

2. Modeling current distribution of *Megaselia scalaris*

The model map based on the variables of the current conditions was not far than the actual situation of this pest. The map highlighted the presence of *M. scalaris* in France, Italy, Algeria, Cameroon, and Madagascar. These countries represent the test and training records used in the model analysis. Also, the occurrence at these countries is confirmed from previous publications (Menail et al. 2016; Ricchiuti et al. 2016; Cham et al. 2018). In addition to these countries, Portugal and Spain beside some parts of Greece and Turkey were considered as highly suitability locations for this pest.

Also, northern parts of Africa including Egypt, Libya, Tunisia and Morocco showed high suitability for the prevalence and establishment of *M. scalaris.* Thus, the current conditions are highly suitable for the distribution of *M. scalaris* in this wide area causing damages to bee colonies. Actually, limited areas in Sub-Saharan Africa showed suitability for this pest. In fact, reports about this pest in Africa are very low. The limited occurrence can be explained in light of the used temperature variables considering that coastal regions as the most suitable for this pest. Accordingly, a study by Ricchiuti et al (2016) showed the preference of *M. scalaris* to coastal areas (high infection in apiaries near to coasts) than other places. The maps showed that dry conditions and highlands with very low temperature are out of the suitability range of this pest.

3. Modeling future distribution of *Megaselia scalaris*

Ecological modeling for future condition during 2050 and 2070 showed high similarities in the distribution of *M. scalaris* to current conditions. This proves that climate changes will not greatly affect the status of this pest and will not hinder its ability to occupy South Europe, North Africa and Sub-Saharan Arica. Therefore, beekeeping will be impacted by this pest at areas with high suitability for it. The only scenario for the low prevalence of this pest was presented by the high limit of SSP 585 during 2050 and 2070. The maps of this limit showed some restrictions in the distribution of *M. scalaris* in Cameroon, Northern parts of Egypt and Morocco, and some parts of Portugal and Spain. Such limitations in the distribution of the pest can be attributed to climate changes especially the increase of air temperatures at these areas. The study showed the less suitability of deserts with dry conditions to the prevalence of *M. scalaris.* This specific finding is in line with other studies on parasitic flies of honey bees: *Senotainia tricuspis* showed less preference to dry conditions than areas with wet weather (Haddad et al. 2015).

In fact, beekeeping has special importance in the investigated countries for the agricultural sector including Egypt and other North Africa countries (Al-Ghamdi et al. 2016). Also, these countries are fully suitable for beekeeping except areas in deserts or mountains where extreme environmental conditions are existed (*e.g.* Abou-Shaara 2015). So, the prevalence of this pest in these countries especially in apiaries is expected to cause damages to bee colonies. Beside the direct movement of this pest from location to another (active prevalence), the passive prevalence can also occurs by the transportation of infected bee packages and equipment. Such method for the prevalence of bee pests was highlighted with other bee pests (Neumann and Elzen 2004; Mutinelli 2011; Gordon et al. 2014). In fact, the information about the damages of bee colonies by *M. scalaris* is still limited and incomplete. So, studies on this point are still required and highly recommended. Other bee parasites from Diptera showed damages to bee colonies especially in case of high infestation levels such as the infestation with *Senotainia tricuspis* (Mathis 1975; Bedini et al. 2006). The co-infection of bee colonies with a group of parasites is expected to cause high damages to be colonies; especially, some parasitic flies including *S. tricuspis* occur in the study locations (Bermejo et al. 1996; Hatoom 1996; Kara and Pape 2002; Bedini et al. 2006; Al-Chzawi et al. 2009; Pires et al. 2011; Haddad et al. 2015). Monitoring and control methods for *M. scalaris* should be developed, for example developing chromotropic traps (Piazza and Marinelli 2000), plant essential oils (Abd El-Gawad and Rabab 2018), light traps and utilizing biological control agents (Abou-Shaara and Staron 2019).

4. Model performance.

The high performance of the model was inferred from the closure between the omission on test and training samples inside and the predicted omission in the other side (Jamal et al. 2021). Also, the values of area under curvy (AUC) were higher than 0.75 for test and training data and typically with values of 0.965 and 0.962, respectively. This highly supports the good fit of the model as shown from previous studies (Mulieri and Patitucci 2019; Hosni et al. 2020; Jamal et al. 2021). In addition to that the jackknife test for all variables showed high AUC more than 0.82.

Conclusion

The ecological modeling for the potential occurrence of *Megaselia scalaris* in Africa and South Europe under current and future conditions during 2050 and 2070 using two limits of Shared Socio-economic Pathways (126 and 585) was performed in the present study. The model showed high performance according to the used tests including omission rates and jackknife test for the used variables. Two variables: annual mean temperature, mean diurnal range contributed highly in the model. All the outputs confirmed the potential prevalence of this pest in northern parts of Africa from Egypt to the far west, and in some areas in the Sub-Saharan Africa. Also, some European countries are expected to be hot spots for the prevalence of this pest. All deserts and highlands are not expected to be invaded by this pest. So, beekeeping at such areas is expected to suffer from this pest. The potential effects of *M. scalaris* on beekeeping require additional attention from specialists to develop perfect monitoring and control strategies.

Abbreviations *M. scalaris*: *Megaselia scalaris*; GBIF: Global Biological Information Facility; bio 1: Annual mean temperature; bio 2: Mean diurnal range; bio 5: Maximum temperature of the warmest month; bio 6: Minimum temperature of the coldest month; bio 10: Mean temperature of the warmest quarter; bio 11: Mean temperature of coldest quarter; SSP: Shared Socio-economic Pathways; AUC: Area under the curvy

Authors' contributions H.A. and A.D. designed, performed, wrote and revised the manuscript. The authors contributed equally in the study. Also, the authors read and approved the final manuscript.

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Availability of data and materials All data generated or analyzed during this study are included in the text and the corresponding author has no objection to the availability of data and materials.

Declarations

Competing interests Both authors declare that they have no conflict of interest.

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