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Using Maximum Entropy Algorithm to Analyze Current and Future Distribution of the Asian hornet, *Vespa velutina*, in Europe and North Africa Under Climate Change Conditions

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ABSTRACT

The Asian hornet, *Vespa velutina*, has invaded Europe during the last few years. This hornet is a dangerous pest to honey bee colonies and can cause significant economic damages. In this study, current and future distributions of this pest in Europe and North Africa were analyzed using maximum entropy algorithm. Different environmental factors were used in the Maxent model to predict the suitability of the study area for this pest. Two future models with two Shared Socio-economic Pathways (126 and 585) were used to estimate the future distribution of *V. velutina* in 2050. The Maxent model for *V. velutina* showed high performance based on the analysis of omission/commission rates and the area under curve. Jackknife test showed the high importance of temperature variables in *V. velutina* distribution. The model maps indicated the potential invasion of this pest to other areas in Europe and North Africa including deserts in Libya and Egypt. Negative consequences of such invasion on beekeeping and environmental balance are expected.

Key words: Honey bees, GIS, Maxent, pest, velutina.

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INTRODUCTION

Climate is changed rapidly and future climate conditions may negatively impact on honey bees, *Apis mellifera* L., and can be considered as a major future threat (Yörük & Sahinler, 2013). Indeed, the increase in temperature is the common phenomena of climate change. Such change in temperature can adversely affect activities of honey bees and beekeeping in side (Le Conte & Navajas, 2008; Abou-Shaara, 2016; Abou-Shaara, Owayss, Ibrahim, & Basuny, 2017) and the distribution of bee diseases and pests in the other side (Le Conte & Navajas, 2008) in addition to plant pollination and activity of pollinators (Hegland, Nielsen, Lazaro, Bjerknes, & Totland, 2009; Scaven & Rafferty, 2013; Rader et al, 2013). Bearing in mind that honey bees are crucial pollinators for many crops worldwide (Allen-Wardell et al, 1998; Abou-Shaara, 2014). In fact, honey bees have numerous numbers of pests which are distributed geographically (Le Conte & Navajas, 2008; Abou-Shaara & Staron, 2019). Some of them has recently succeeded to invade new regions other than their original locations including the Asian hornets, *Vespa velutina* (Lepeletier, 1836) (Hymenoptera: Vespidae) which were recorded in some Western European countries (López, González, & Goldarazena, 2011; Grosso-Silva & Maia, 2012; Monceau et al, 2014) and become established.

The predatory hornets from genus *Vespa* (Fam. Vespidae) include about 22 species (Archer, 2012). The common hornet in North Africa and the Mediterranean region is the oriental hornets, *Vespa orientalis* (Linnaeus, 1771) (Archer, 1998). This hornet was recorded accidentally in Madagascar (Carpenter and Kojima, 1997) and Mexico (Dvořák, 2006) without wide establishment. It causes damages to bee colonies which require developing methods for its control (Shaaban et al, 2015). Its activity is correlated with temperature and relative humidity (Taha, 2014) and generally extended from spring until autumn (Khodairy & Awad, 2013; Islam, Iftikhar, & Mahmood, 2015). Recently, the Asian hornet, *V. velutina* which occurs from Afghanistan to eastern China, and Indonesia (Carpenter & Kojima, 1997) has invaded France (Haxaire, Bouguet, & Tamisier, 2006), Spain (López et al, 2011), Portugal (Grosso-Silva & Maia, 2012), Italy (Demichelis et al, 2014), and Belgium (Monceau et al, 2013). This hornet is a predator to honey bees (Abrol, 1994; Abrol, 2006; Tan et al, 2007), and could cause damages to bee colonies in a similar way to the Oriental hornets. Also, the life cycle of this hornet is similar to the Oriental hornets including the presence of overwintering periods for queens which end up in early spring (Monceau et al, 2012). The presence of these two species at the same geographical range can be considered as a high risk to bee colonies and beekeeping as well as to the biodiversity in the invaded regions.

The social nature of these hornets as well as the dispersal range of queens in search for place for hibernation which is expected to be wide (Monceau et al, 2013) support their ability to invade additional countries in Europe and North Africa. Moreover, the short distances between Europe and North Africa in side and climate change in the other side greatly support the expansion of this hornet. This point has not been deeply studied. In fact, beekeeping is considered among the essential agricultural activities in North Africa especially Egypt due to the vital role of bees in plant pollination

(Abou-Shaara, 2015; Al Naggar, Codling, Giesy, & Safer, 2018). Also, some Arabian countries import bee packages from Egypt especially Gulf countries (Al-Ghamdi & Nuru, 2013; Al-Ghamdi, Alsharhi, & Abou-Shaara, 2016). The Oriental hornets are the main Vespidae predator to honey bees in North Africa which requires efforts from beekeepers to control them (Archer, 2012; Khodairy & Awad, 2013; Taha, 2014; Abou-Shaara, 2017). The potential invasion of the Asian hornets to North Africa can hinder beekeeping development and cause severe economic losses.

Predicting the geographical distribution of species is commonly achieved using climatic suitability models (Guisan & Thuiller, 2005). Different tools can be employed to predict species distribution in the future, and MaxEnt is one of these tools (Wei, Wang, Hou, Wang, & Wu, 2018; Jamal et al, 2021). The analysis depends on occurrence data of the species and assumed environmental variables (Hosni, Nasser, Al-Ashaal, Rady, & Kenawy et al, 2020; Jamal et al, 2021). Most models depend basically on analyzing environmental variables especially those aims to assess effects of climate change. Other variables like land cover and vegetation index could improve the models but they are not available for future conditions. This prevents their use in studying the influences of climate change on species distribution (Hosni et al, 2020). Therefore, in this study environmental variables were utilized to understand current and future distribution of the Asian hornets in Europe and North Africa, with discussing the consequences of the potential invasion of these hornets on beekeeping and environment.

MATERIALS AND METHODS

Occurrence locations

Some Asian countries are the original geographical locations of the Asian hornet, *Vespa velutina* (abbreviated as AH). However, this hornet species has invaded some countries in West Europe and showed high adaptability to its new environment. To understand the current and future distribution of AH in Europe and North Africa, only occurrence records from Europe (the new environment) were used in this study. Also, the geographical area of the study was limited to cover some European countries beside North Africa. The available records of the AH from the Global Biological Information Facility (GBIF.org, 2020) were mainly used. So, 295 confirmed locations were included in this study after excluding locations without coordinates or with uncertain distribution or with repeated coordinates.

Climate data

Five climate variables based on temperature and relative humidity with a spatial resolution of about 5 km^2 available from worldclim.org (Fick & Hijmans, 2017) were used in the analysis. These variables were: annual mean temperature (bio1), mean diurnal range (bio2), temperature seasonality (bio4), annual precipitation (bio12), and precipitation seasonality (bio15). These specific datasets were selected based on some initial analyses to select the most important variables (Hosni et al, 2020; Abou-Shaara et al, 2021).

Bioclimatic data available from WorldClim v2.1 released in January 2020 for the period from 1970 to 2000 were used to analyze the current global climate. The downscaled future climate data from the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al, 2016) from two climate models: the Meteorological Research Institute (MRI-ESM2-0; Institution ID: MRI) and the Beijing Climate Center Climate System Model (BCC-CSM2-MR; Institution ID: BCC) from two Shared Socio-economic Pathways (SSP126 and SSP585) were used to analyze future climate for 2050 (average from 2041-2060). The Shared Socio-economic Pathways (SSPs) are used by the Intergovernmental Panel on Climate Change (IPCC) in the IPCC AR6 instead of Representative Concentration Pathways (RCPs) in the IPCC AR5.

Modeling of current and future geographic distribution

The maximum entropy modeling utilizing Maxent v 3.4.1 (Phillips et al, 2020) was used to estimate current and future distribution of AH in Europe and North Africa. The model used 222 presence records for training and 73 for testing (25% random test points). Algorithm terminated after 500 iterations (17 seconds), 10218 points used to determine the Maxent distribution, and the regularization values: linear/quadratic/product: 0.050, categorical: 0.250, threshold: 1.000, hinge: 0.500.

For future conditions, the average from the two climate models MRI-ESM2-0 and BCC-CSM2-MR was presented using ssp126 (the low limit), ssp585 (the high limit), and the overall average for the two SSPs. This can present precise prediction about future distribution of AH. The output format was cumulative. The model images for current and future conditions were reclassified using ArcGIS 10.5 into four suitability degrees: rare (0-0.01), moderate (0.01-1), high (1-20), and very high (20-100) in line with Maxent guideline (Phillips, 2017) and previous study (Jamal et al, 2021).

Model performance

The contribution percentages of the analyzed variables in the model were calculated beside the response curve of each bioclimatic variable. The model was evaluated based on analysis of omission/commission rates. The omission rate and predicted area as a function of the cumulative threshold was analyzed. The receiver operating characteristic (ROC) were utilized to identify the area under curve (AUC) as an indication of the model performance. Also, the jackknife test of variables was presented. These parameters were selected based on previous studies (Hosni et al, 2020; Abou-Shaara & Darwish, 2021; Jamal et al, 2021).

RESULTS

Contribution percentages

Estimates of relative contributions of the five environmental variables to the Maxent model were 41.5%, 27.9%, 20.4%, 9%, and 1.2% to bio 4, bio 12, bio 1, bio 15, and bio 2, respectively. The highest contribution was to temperature seasonality, annual precipitation, and annual mean temperature. The response curves of variables with the highest contribution (Fig. 1) suggest specific favorable ranges of temperature and precipitation of AH in its new environment in West Europe.

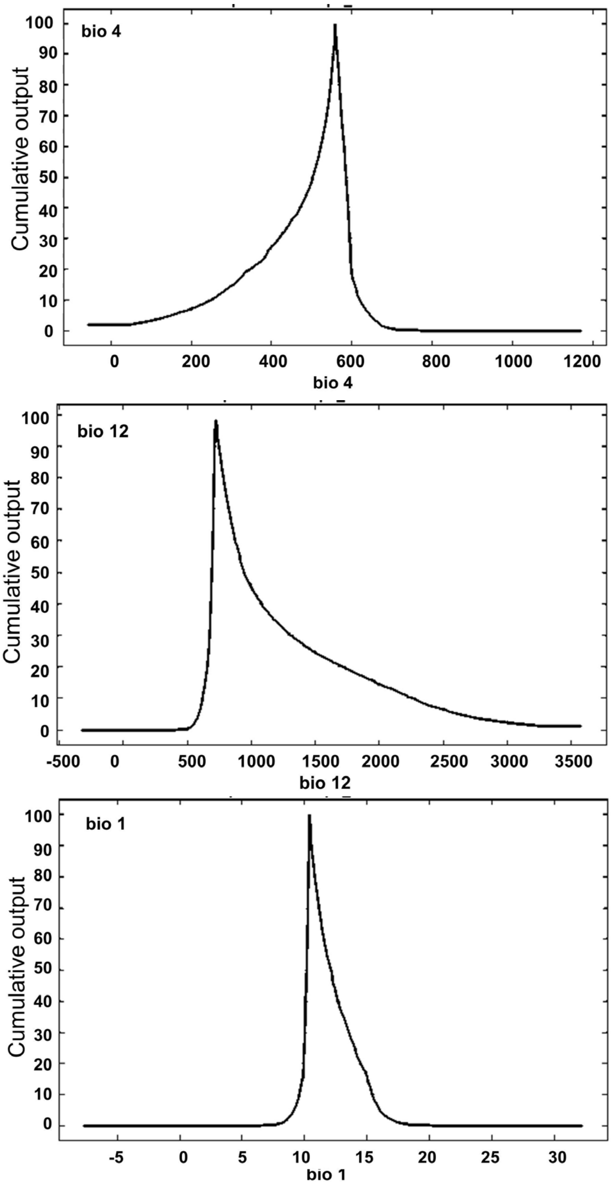

Fig. 1. Response curves of the most contributed variables in the model: temperature seasonality (bio4), annual precipitation (bio12), and annual mean temperature (bio1).

Current distribution

The current distribution (Fig. 2) reflects the real distribution of the AH in France, Spain, Belgium and Portugal as the new environment of this hornet in Europe. The South-Western parts of Europe were classified as very high suitable. Some other parts in Europe were classified as very high suitable including parts in England, Italy, and Turkey. Areas in some other European countries and in North Africa were classified as highly or moderately suitable. In general, the coastal regions in North Africa are moderately suitable for the AH. Also, some desert areas in Libya and Egypt as well as some parts close to North-East of Egypt were classified as moderately suitable. Regions with cold weather at North Europe and desert regions in North Africa were classified as rarely suitable for AH.

Future distribution

The model using the low limit of SSP126 (Fig. 3), the high limit of SSP 585 (Fig. 4), and the overall average (Fig.5) showed high similarities with the current distribution model with few exceptions as highlighted in Fig. 6. The three maps approximately showed the same future distribution except that the map based on the high limit of SSP differed slightly than the other two maps mainly in the suitability of some locations in Libya and Egypt to the AH. Approximately no changes will occur at West Europe than current distribution except that England will be more suitable for the AH.

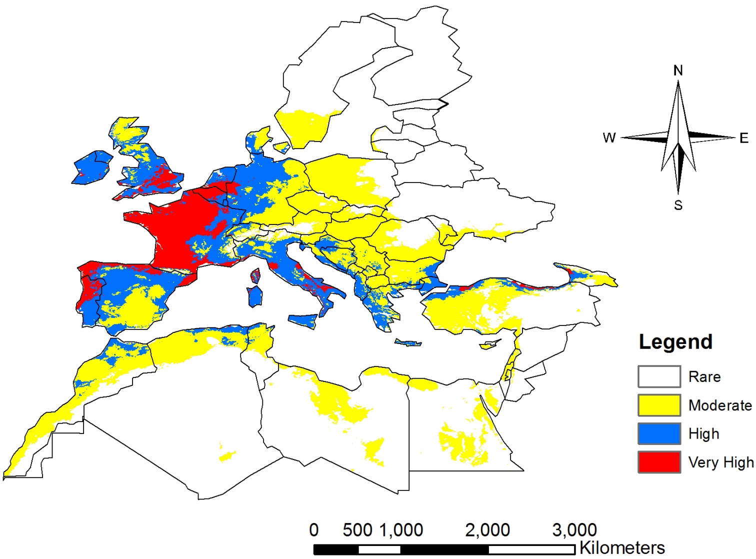

Fig. 2. Distribution of the Asian hornet under current climate conditions.

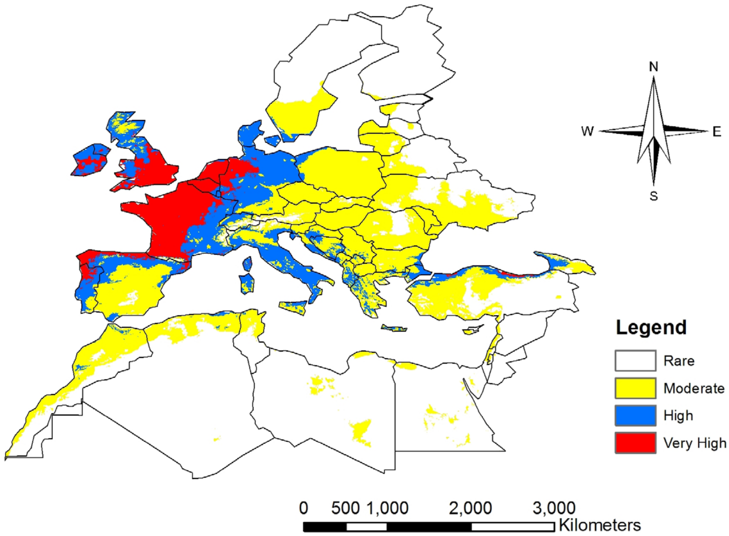

Fig. 3. Distribution of the Asian hornet under future climate conditions (SSP 126). This figure is the average of two climate models (MRI-ESM2-0 and BCC-CSM2-MR).

The locations with high suitability are not anticipated to be greatly changed than current (Fig. 6). The locations with moderate suitability in Europe will be approximately the same in the future. The coastal regions in North Africa and some locations in Libya and Egypt will be moderately suitable for the AH according to the maps based on the low limit of SSP and the overall average.

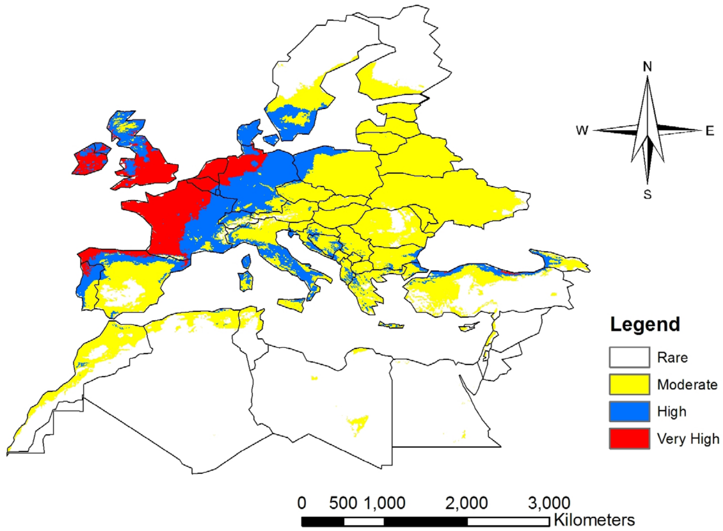

Fig. 4. Distribution of the Asian hornet under future climate conditions (SSP 585). This figure is the average of two climate models (MRI-ESM2-0 and BCC-CSM2-MR).

Model performance

The omission rate is calculated both on the training presence records and on the test records (Fig. 7). This rate is very close to the predicted omission. The receiver operating characteristic (ROC) curve for the training and the test data is shown in Fig. 8. The area under the curve (AUC) is 0.965 and 0.961± 0.006 for training and test data, respectively. Jackknife test using area under the curvy (AUC) on test data (Fig. 9) shows the high AUC of the variables over 0.7. bio 1 and 4 had the highest AUC, followed by bio 15, then bio 12, and finally bio 2.

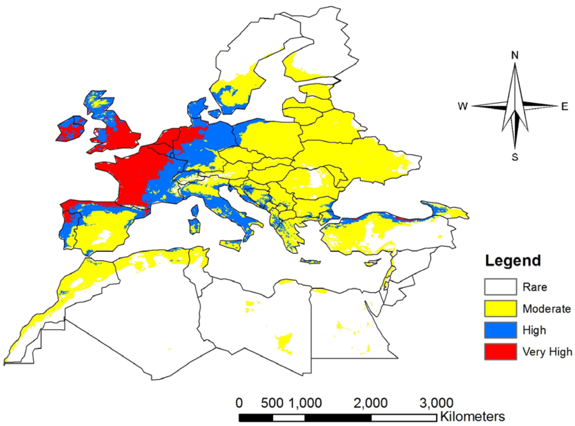

Fig. 5. Distribution of the Asian hornet under future climate conditions (SSP 126 and SSP 585). This figure is the average of two climate models (MRI-ESM2-0 and BCC-CSM2-MR).

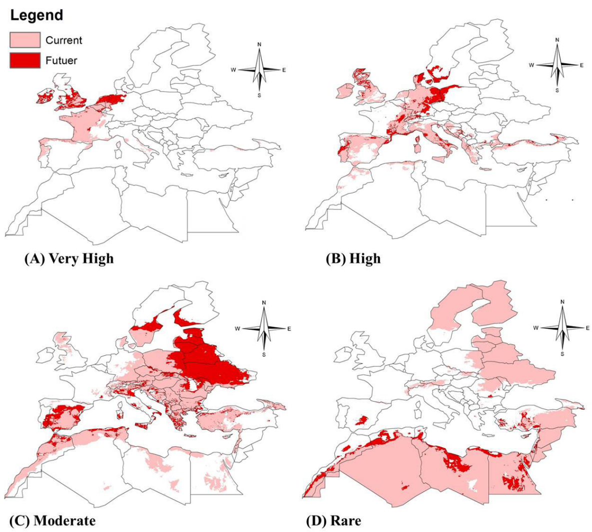

Fig. 6. Differences between current and future distribution (overall average) in each suitability class.

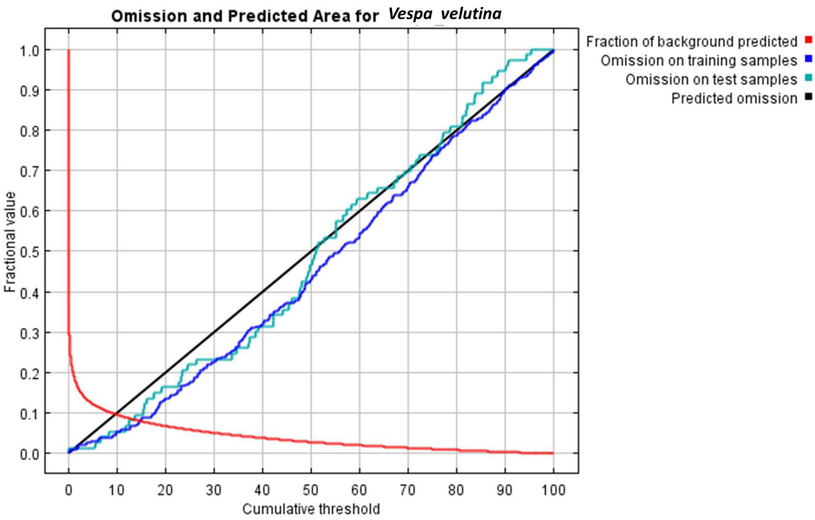

Fig. 7. The omission rate and predicted area as a function of the cumulative threshold.

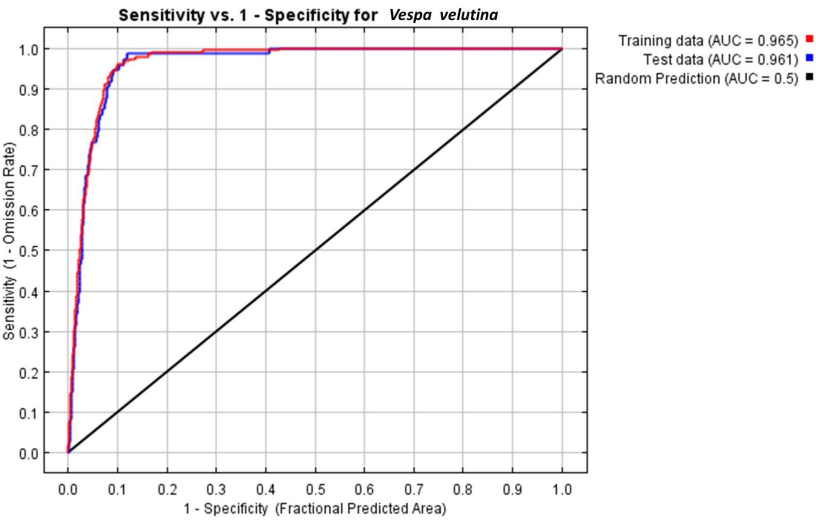

Fig. 8. The receiver operating characteristic (ROC) curve for the training and test data.

DISCUSSION

Contribution percentages

The variables with the highest contribution percentages were temperature seasonality, annual precipitation, and annual mean temperature. In fact, activities of Vespidae insects are impacted by temperature (Matsuura & Yamane, 1990; Taha, 2014).

Current distribution

Thus, two variables based on temperature (i.e. temperature seasonality and annual mean temperature) possessed 61.9% of the total. It seems that the AH becomes adapted to low/moderate temperature as showed from the response curves of highly contributed variables, which can be understood by its establishment in west Europe.

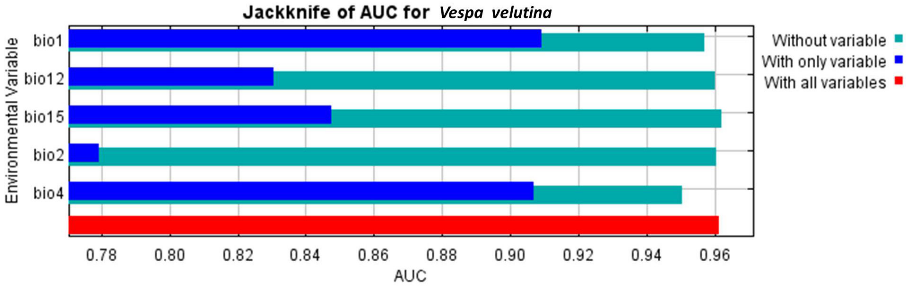

Fig. 9. Jackknife test using area under the curvy (AUC) on test data. bio1: annual mean temperature, bio2: mean diurnal range, bio4: temperature seasonality, bio12: annual precipitation, and bio15: precipitation seasonality.

The AH arrived in 2004 to Europe via South-Western France and then colonized in other countries including Spain, Portugal, and Belgium with good establishment (Haxaire et al, 2006; López et al, 2011; Grosso-Silva & Maia, 2012; Monceau et al, 2014). Notably, the current distribution obtained from the model showed high similarity with the real situation with some few exceptions. Thus, these countries were very high suitable for the AH. Accordingly, a previous study predicted the invasion success of AH in Western Europe especially in South-Western France based on data from its native range in Asia (Villemant et al, 2011). Most recently AH has been recorded in Hamburg, northern Germany (Husemann, Sterr, Maack, & Abraham, 2020). This supports the present study model as Germany among the highly suitable areas for AH. The exceptions reported in this study are the very high suitability of parts in England, Italy, and Turkey to AH. Perhaps the AH will colonize at these countries later. The geographical nature of each country may contribute in affecting the spread of AH such as the insular nature of England. In addition to this, some areas in other European countries and in North Africa were considered as highly or moderately suitable. This means that the AH can invade this countries especially environmental conditions at them are suitable for its occurrence. Moreover, the close distance between Morocco and Europe can facility the introduction of AH to North Africa.

In general, the coastal regions in North Africa are moderately suitable for the AH. This point is supported by a previous study as the occurrence of AH in Europe was characterized by specific environmental variable (high level of precipitation during the driest month of the year) which suggested the expansion of AH in the potentially invaded countries through coastal margins (Villemant et al, 2011). The invasion of AH to Africa can happen through Morocco and then through the coastal regions to invade other countries including Egypt. Also, AH can invade Egypt through the North-East part (Sinai) as some parts close to Sinai were classified as moderately suitable for the AH. Regions at North Europe with cold weather as well as most desert regions in North Africa were classified as rarely suitable for AH. It seems that the very low or high temperature at these regions caused such unsuitability for the occurrence of the AH.

Future distribution

Approximately, this is the first study to use the Shared Socio-economic Pathways (SSP) of two climatic models to predict future distribution of AH in Europe and North Africa. The old method for forecasting future conditions using Representative Concentration Pathways (RCPs) is currently outdated. The model showed high similarities with the current distribution model especially in West Europe except that England will be more suitable for the AH. No noticeable variations observed in regard to locations with high or moderate suitability for AH. Perhaps, future conditions will be in favor of AH colonization and establishment. On the contrary with the prediction that desert regions will become even drier due to climate change, which can negatively affect honey bees (Le Conte & Navajas, 2008). This study showed the potential distribution of the AH at coastal regions and some other locations in North Africa including deserts in Libya and Egypt.

Under future conditions, bee colonies were predicted to suffer from heat stress especially during summer (Abou-Shaara, 2016). The invasion of the AH to new regions will be another stress on bee colonies in addition to climate change. Especially, the AH has been reported to attack bee colonies fiercely (Shah & Shah, 1991; Tan et al, 2007; Kim, Choi, & Moon, 2006; Jung, Kim, Lee, & Baek 2008). Furthermore, honey bees at the invaded regions (e.g. in France) showed less ability to withstand the attack of AH (Rortais et al, 2010). This indicates that the damages from AH to apiaries will be high although honey bees showed some defensive behaviours against AH in Europe (Monceau et al, 2018). Another problem that the AH can compete the native hornet (*V. orientalis*) in attacking bee colonies which can cause high economic losses to beekeepers due to the loss of their colonies. In a previous study on AH and the European hornet, *Vespa crabro*, a high overlap in trophic preference was found with preference for honey bees than other insects or diets (Cini et al, 2018). Moreover, the AH can disturb the natural balance of living organisms in the invaded areas especially the prey spectrum of AH contains several insect species including some pollinators (Villemant et al, 2011).

Another key problem that the AH may transfer new diseases to bees and other Hymenoptera in the invaded areas as well as it can share some diseases with them. Especially AH and other Vespidae hornets generally are close in their genetic characteristics (Perrard et al., 2013; Takahashi, Okuyama, Minoshima, & Takahashi, 2018; Abou-Shaara & Elbanoby, 2020), and some of them can transport diseases to honey bees. For example, the oriental hornet (*Vespa orientalis*) can transfer the American Foulbrood disease to bees (Elhoseny, 2016). Moreover, Moku Virus and Israeli acute paralysis virus were detected in AH (Yañez, Zheng, Hu, Neumann, & Dietemann, 2012; Garigliany et al, 2017). Fortunately, some methods have been suggested for the control of AH (Monceau et al, 2014) include the use of traps

(Demichelis et al, 2014), utilizing biocontrol agents (Darrouzet, Gévar, & Dupont, 2015), and the selection of bees with defensive behaviors (Monceau et al, 2018). However, more trends for the effective control of the AH are still required.

Model performance

The model used in the present study showed high performance as the omission rate was very close to the predicted omission. This is supported by previous studies (Abou-Shaara et al, 2021; Abou-Shaara & Darwish 2021). Also, the area under the curve (AUC) for training and test data was 0.965 and 0.961, respectively. Moreover, the Jackknife test showed the high AUC of the variables over 0.7. These values are close to 1, indicating the perfect discrimination of the used model especially that value more than 0.75 denotes to a very good fit of the model (Mulieri & Patitucci 2019; Hosni et al, 2020; Jamal et al, 2021).

CONCLUSION

The generated maps from this study are of beekeeping importance as they estimate the possible distribution of the predator hornet (*Vespa velutina*) to honey bees in the study regions (Europe and North Africa). Also, the model maps illustrated the effects of climate change on AH distribution based on the Shared Socio-economic Pathways. According to this study, some parts in Europe and North Africa including deserts in Libya and Egypt showed moderate to high suitability for the distribution of AH under current and future climate conditions. This suggests that these regions could be invaded by AH, causing damages to beekeeping sector and harming the biodiversity. So, the study models act as an alert for these countries to avoid the possible invasion of AH. Efforts to follow the expansion of the AH in Europe and to prevent it from invading other countries should be planned by the responsible authorities. In fact, the environmental conditions in North Africa are somewhat similar to those in the Levant and the Gulf countries. So, further study to follow the potential expansion of AH to such areas is required.

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