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Journal of King Saud University – Science

2025 37 (2) 2972024

Research Article

Potential spread of *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) in Türkiye under changing climate: Implications for management

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A R T I C L E I N F O

Keywords:
Biosecurity
Climate change
MaxEnt
Modeling
Potential spread

A B S T R A C T

Spodoptera frugiperda Smith (EPPO code LAPHFR) is a polyphagous pest infesting various crops in numerous regions of the world. Nevertheless, it has been reported from Türkiye recently; therefore, modeling its potential spread could help to halt further spread by monitoring and biosecurity efforts. Habitat suitability of LAPHFR was modeled by the Maximum entropy Entropy Model (MaxEnt) under current (1970-2000) and future (2021-2040, 2041-2060, 2061-2080, 2081-2100) climatic conditions in Türkiye. The model was trained and tested with 6667 global occurrence records and 12 environmental variables. The model with linear class feature and regularization multiplier of 1 was found to be optimum; therefore, all simulations were performed under these settings. The results revealed that the model predicted the habitat suitability of LAPHFR with high precision (AUC = 0.80). The bio12 (annual precipitation), followed by bio1 (annual mean temperature) and bio11 (mean temperature of coldest quarter), had the highest contributions towards model training, whereas bio1, bio10 (mean temperature of warmest quarter), and bio12 were the most influential predictors essential for the distribution of LAPHFR. Highly suitable areas for LAPHFR under the current climate, which will contract in the future. Overall, LAPHFR had high spread potential to the Black Sea and southeastern Anatolia regions in the country. The model predicted that LAPHFR has extensive spread potential to the other regions from where it has not been reported yet in the country. Therefore, urgent management and biosecurity efforts are needed in the areas having high habitat suitability for LAPHFR in the country.

1. Introduction

The fall armyworm (*Spodoptera frugiperda* Smith) is a major agricultural pest, which has extended its distribution range to various countries in the world beyond the Americas (Kenis *et al.*, 2023). It poses a substantial threat to food security and the livelihoods of millions of smallholder farmers cultivating maize (Harrison *et al.*, 2022; Koffi *et al.*, 2021). Although maize is regarded as a primary host for fall armyworm (LAPHFR hereafter), it can feed >350 plant species (Montezano *et al.*, 2018). The larvae seriously harm leaves, causing significant yield reductions. For instance, yield decreases ranging from 21% to 80% have been reported from sub-Saharan Africa, which corresponds to yearly economic losses between \$2.48 billion and \$6.19 billion for the maize crop (Koffi *et al.*, 2021). In summary, LAPHFR poses a significant problem for agriculture worldwide, especially in developing areas where food security is already questionable. Mitigating its effects necessitates synchronized initiatives in research, management strategies, and agricultural education to alleviate its effects on crops and livelihoods.

The LAPHFR was first reported from Africa in 2016, from where it spread to 44 Southern African countries by 2018 (De Groote *et al.*, 2020). The yield losses caused by LAPHFR in twelve major African maize-producing countries ranged from \$2.5 billion to \$6.3 billion (Kenis *et al.*, 2023). It has now been reported from ∼70 other countries in the world. Nevertheless, LAPHFR rapidly spreads after its first introduction into new geographic regions. For example, four months after its first report from Yunnan, China, it was reported in 13 Chinese provinces (Jing *et al.*, 2020).

The LAPHFR was first reported from Türkiye during 2022 in maize with an infestation rate of 14% to 18%. The pest was recorded from all surveyed fields in the Adana province (Pehlivan and Atakan, 2022). The larvae were found to feed on leaf tissue, burrow into the developing point, damage the necrotic core, and perforate leaves. The larvae-induced damage ranged between 14% and 15% in the surveyed maize fields. Afterwards, LAPHFR was reported from Sanliurfa province during 2023, where 20-60% infestation was recorded on the examined plants (Tonğa, 2023). Both provinces have extensive maize cultivation, and the destructive nature of LAPHFR could cause severe problems in the future. Nevertheless, climatic conditions (Sensoy, 2014) of Türkiye is extremely suitable for LAPHFR, which would allow the pest to produce several generations throughout the year. Hence, predicting and prioritizing the areas suitable for the potential spread of LAPHFR are inevitable in Türkiye.

The LAPHFR is expected to extend its geographic range under climate change (Jiang *et al.*, 2022; Ramasamy *et al.*, 2022; Zacarias, 2020). The colder regions would become suitable for LAPHFR in the face of a changing climate. Models have predicted that coastal areas of southern Europe are the potential invasion hotspot for LAPHFR. Nevertheless, Mediterranean regions are predicted to be a transient

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Received: 06 November, 2024 **Accepted:** 16 May, 2025 **Published:** 31 May 2025

DOI: 10.25259/JKSUS_297_2024

habitat for LAPHFR (Gilioli *et al.*, 2023). Türkiye has diverse climatic regions, which would provide the ideal conditions for the invasion and proliferation of LAPHFR (Sensoy, 2014). Food security and agricultural productivity are expected to be severely affected by climate change. Nevertheless, it is expected that climate change would alter the distribution of LAPHFR. Agriculture may face serious difficulties because of LAPHFR's possible range expansion, especially in colder climates where farmers may not have previously coped with this pest. Increased crop damage and economic losses might result from the introduction of LAPHFR; hence, it is imperative that efficient management plans be created specifically for these recently impacted regions. Predicting the potential spread of LAPHFR in newly recorded regions and implementing biosecurity efforts based on the predictions could help to halt the spread of LAPHFR.

Species distribution models (SDMs) are recognized for their use in predicting the future spread of target species across different geographic regions (Zurell *et al.*, 2020). These models predict a species' potential spread over several spatiotemporal scales by combining environmental and species occurrence data (Guisan and Thuiller, 2005). The SDMs are used to forecast the possible spread of target species under predicted climate changes (Liu *et al.*, 2022). The potential spread maps help to identify the areas at risk, prioritize management efforts, and implement management strategies. The Maximum Entropy (MaxEnt) model is a prevalent method for forecasting changes in the distribution of certain species due to global warming. The MaxEnt model forecasts distribution by using current occurrence data with ecological, socioeconomic, topographical, and environmental characteristics (Phillips *et al.*, 2006). Several studies have predicted the global spread of LAPHFR due to climate change using the MaxEnt model (Jiang *et al.*, 2022; Zacarias, 2020). However, the potential spread of LAPHFR has never been estimated in Türkiye.

The habitat suitability of LAPHFR in Türkiye was predicted in this study using an optimized MaxEnt model under current and future conditions. The results would help to prioritize the areas for high spread risk and inform the concerned authorities to take appropriate action to halt its future spread. The major contribution of the study is the use of the MaxEnt model to predict the potential spread of LAPHFR in Türkiye under current and future environmental conditions. The study presents a unique use of the model to predict LAPHFR habitat suitability in Türkiye, where the pest was identified recently. Furthermore, the study addresses a significant gap by forecasting the pest's spread in Türkiye and examining the possible impacts of climate change on its spread. This study is one of the first investigations focusing on the diverse environment of Türkiye and the potential spread of LAPHFR across the country's many regions, despite existing research on its global distribution.

2. Material and Methods

2.1 Species distribution data

The occurrence records of LAPHFR were collected from various databases, including Global Biodiversity Information Facility (GBIF) (https://www.gbif.org/) (GBIF, 2024), Web of Science (WOS) (https://webofscience.com), ScienceDirect (https://www.sciencedirect.com/), Scopus (https://www.scopus.com/home.uri), Google Scholar (https://scholar.google.com/), Dergipark (https://dergipark.org.tr/tr/), ULAKBİM Keşif (https://www.ulakbim.gov.tr/yeniweb/ulakkesif/), TR Dizin (https://trdizin.gov.tr/), and the YÖK Thesis Center (https://tez.yok.gov.tr/UlusalTezMerkezi/). These databases resulted in 12,895 occurrence records, which were reduced to 6,667 after taxonomic refining and the elimination of duplicates. Consequently, the global occurrence dataset consisted of 6,667 occurrence records, which were used to train and test the model.

2.2 Environmental data

The WorldClim database was used to download environmental data (19 bio variables, i.e., bio1 = annual mean temperature, bio2 = mean diurnal range, bio3 = isothermality, bio4 = temperature seasonality, bio5 = max temperature of warmest month, bio6 = min temperature

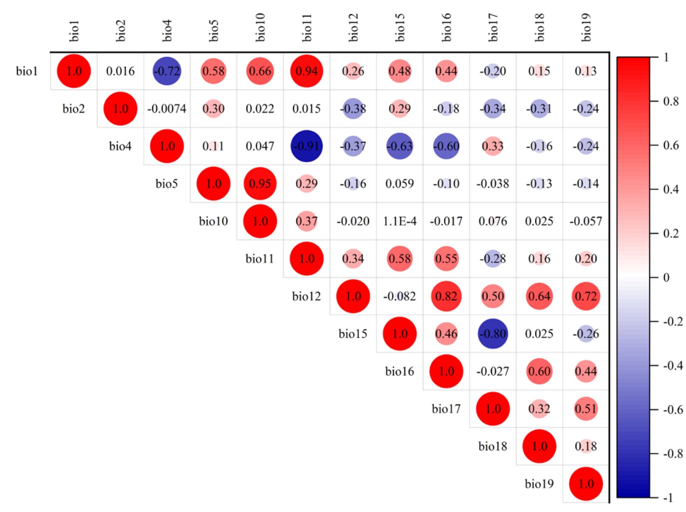

Fig. 1. Pearson correlation among the environmental variables used to predict the habitat suitability of *Spodoptera frugiperda* in Türkiye.

of coldest month, bio7 = temperature annual range, bio8 = mean temperature of wettest quarter, bio9 = mean temperature of driest quarter, bio10 = mean temperature of warmest quarter, bio11 = mean temperature of coldest quarter, bio12 = annual precipitation, bio13 = precipitation of wettest month, bio14 = precipitation of driest month, bio15 = precipitation seasonality, bio16 = precipitation of wettest quarter, bio17 = precipitation of driest quarter, bio18 = precipitation of warmest quarter, bio19 = precipitation of coldest quarter) (Fick and Hijmans, 2017) for current (1979-2000) and future (2021-2040, 2041-2060, 2061-2080, and 2081-2100) climatic conditions. The data generated at a fine resolution; 30 arc seconds were downloaded and used in the modeling procedure. The future data of two climate change scenarios, i.e., SSP1-2.6 and SSP5-8.5, were used to predict the current and future habitat suitability of LAPHFR. SSP1-2.6 is a sustainable, low-emission pathway characterized by significant reductions in greenhouse gas emissions through global collaboration. This scenario aims to restrict global warming to between 1.5°C and 2°C over pre-industrial levels till the end of 21st century. SSP5-8.5, characterized by elevated energy consumption and continued reliance on fossil fuels, is a high-emission trajectory that would significantly increase global greenhouse gas emissions. This scenario assumes that the world is undergoing rapid economic growth, characterized by a significant reliance on traditional energy sources, insufficient climate regulations, and extensive fossil fuel use. This scenario is thus associated with a much higher level of global warming, anticipated to exceed 4°C by the century's end, resulting in adverse impacts on human populations, agriculture, and ecosystems. The data for 19 environmental variables were extracted for 6667 occurrence records by using the 'raster' package in R (R Core Team, 2023). Data extraction was accompanied by a Pearson correlation analysis, which screened out variables having a correlation coefficient greater than 0.70 (Fig. 1). A total of 12 variables, i.e., bio1, bio2, bio4, bio5, bio10, bio11, bio12, bio15, bio16, bio17, bio18, and bio19 were used for model training and testing under current and future climatic conditions.

2.3 Model development

The MaxEnt model (Phillips *et al.*, 2006) uses five different feature classes, i.e., linear (L), quadratic (Q), product (P), threshold (T), and hinge (H). The MaxEnt model is a vital tool in ecology and conservation biology because of its many feature classes, which increase its capacity to depict intricate ecological relationships and provide better predictions about species distributions. Therefore, six different combinations of these classes with five different regularization multipliers (1-5) were tested to optimize the model. A total of 30 models were developed using 'enmevaluate' package in R (R Core Team, 2023). The robustness of various feature classes and regularization multiplier combinations is assessed by the displayed delta. AICc values. The model with a smaller

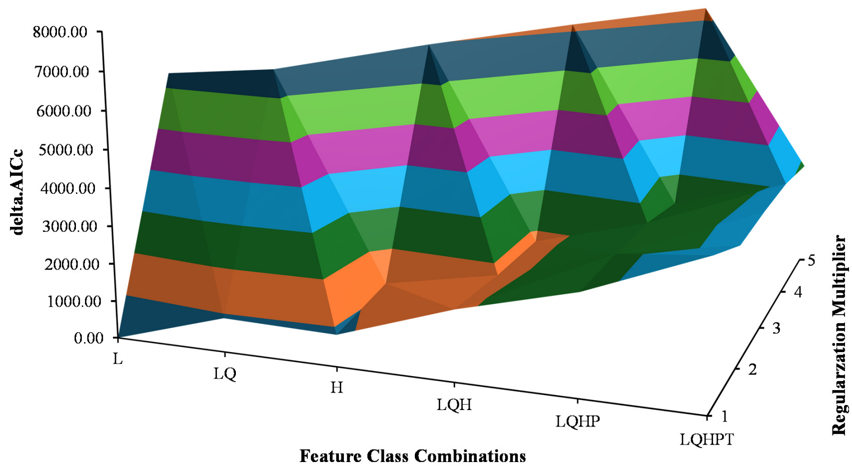

Fig. 2. The delta.AICc values of different feature class and regularization multiplier combinations used to optimize the MaxEnt model for predicting habitat suitability of *Spodoptera frugiperda* in Türkiye.

delta.AICc had less complexity; thus, preferred for biodiversity research. The results indicated that the L feature class with a regularization multiplier of 1 had the lowest delta.AICc value (Fig. 2). Consequently, these parameters were used for the training and evaluation of the model. The model was evaluated using 30% of the data, while 70% was allocated for training. The additional parameters included five replications, five thousand iterations, and equivalent training specificity and sensitivity. The area under the receiver operating characteristic curve (AUC) was employed to assess the model's predictive accuracy. Uzun and Örücü (2020) suggest that AUC values approaching 1 signify enhanced predictive potential, whereas values below 0.5 are deemed to possess inadequate predictive power. Jackknife analysis was used to assess the impact of environmental factors on model training and the significance of their permutations. Projections for Türkiye were derived using a model that has been calibrated on a global level.

2.4 Habitat suitability and area

The ability of an environment to sustain a species' development, reproduction, and survival is known as habitat suitability. The MaxEnt model provides a habitat suitability index ranging from 0 to 1, where 0 denotes extremely low habitat suitability and 1 indicated very high suitability. The habitat suitability index was categorized as unsuitable (0.0 – 0.20), moderately suitable (0.2 – 0.40), and suitable (>0.40). The area corresponding to each category for the current and future climate was computed in the raster calculation tool of ArcGIS (ESRI (Environmental Systems Resource Institute), 2012). Habitat suitability change corresponding to the current climate was computed and expressed as a percentage.

3. Results

3.1 Model evaluation

The predictive accuracy of the model was assessed using AUC value. A high-performing model with excellent discriminative capabilities between suitable and unsuitable environments is indicated by an AUC closer to 1. The model's AUC score was 0.80, showing accurate predictions of LAPHFR's habitat suitability (Fig. 3). The AUC score indicates that MaxEnt model is a reliable tool for forecasting the distribution of LAPHF) in Türkiye. The model is sufficiently reliable in predicting both suitable and unsuitable areas.

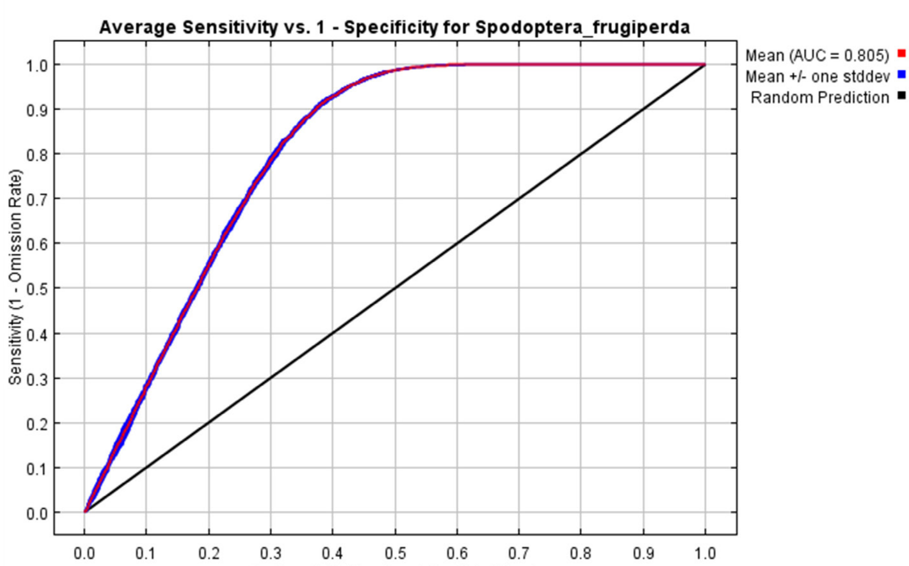

Fig. 3. The AUC curve of the optimized MaxEnt model used to predict the habitat suitability of *Spodoptera frugiperda* in Türkiye.

Table 1.
Contribution of the environmental variables towards model training and their permutation importance.

Environment variable	Contribution (%)	Permutation importance (%)
bio1	17.04	28.11
bio2	3.46	3.29
bio4	1.28	3.46
bio5	2.22	7.24
bio10	0.27	18.29
bio11	8.98	8.58
bio12	57.39	11.13
bio15	0.16	1.13
bio16	3.10	6.48
bio17	3.43	6.06
bio18	0.27	0.38
bio19	2.35	5.78

bio1 (annual mean temperature), bio2 (mean diurnal range), bio4 (temperature seasonality), bio5 (max temperature of warmest month), bio10 (mean temperature of warmest quarter), bio11 (mean temperature of coldest quarter), bio12 (annual precipitation), bio15 (precipitation seasonality), bio16 (precipitation of wettest quarter), bio17 (precipitation of driest quarter), bio18 (precipitation of warmest quarter), and bio19 (precipitation of coldest quarter)

3.2 Contribution of environmental variables

The bio12 followed by bio1 and bio11 had the highest contributions towards model training, whereas bio1, bio10, and bio12 had the highest permutation importance (Table 1). Permutation Importance quantifies the significance of each variable by evaluating the extent to which the model's performance deteriorates when that variable is randomly permuted. Greater permutation importance indicates that the variable has a stronger influence on the model's accuracy. The bio1 (annual mean temperature), bio10 (mean temperature of the warmest quarter), and bio12 (annual precipitation) had the highest permutation importance, suggesting that temperature and precipitation are crucial factors that determine whether an area is suitable for LAPHFR.

3.3 Habitat suitability

Optimized model predicted highly suitable areas in different regions of the country (Fig. 4). Although the species has been reported from Adana and Şanlıurfa provinces currently, the whole Black Sea and southeastern Anatolia regions were predicted to be highly suitable for LAPHFR under the current climate. Nevertheless, some parts of the eastern Mediterranean region were also predicted to be suitable for the species. A total of 90,000 km^2 area was predicted suitable for LAPHFR in the country. The southern and southeastern regions of the country, particularly the coastal zones of the Mediterranean and Aegean regions, are predicted to have highly suitable areas for LAPHFR under the current climate. Elevated temperatures and sufficient moisture levels in these areas provide an ideal habitat for the introduction and spread of the species. The provinces of Hatay, Mersin, Adana, and Antalya are classified as high-risk.

Figs. 5-8 indicate the changes in habitat suitability throughout several future intervals (2021–2040, 2041–2060, 2061–2080, 2081-2100) under SSP1-2.6 and SSP5-8.5 scenarios. The model projected a decline in suitable habitat for LAPHFR under both climate change scenarios, despite an increase in the high-emission scenario from 2021 to 2040. Both the low-emission and high-emission scenarios indicated that the Black Sea and southeastern Anatolia areas are ideal hotspots for LAPHFR in the future.

The model predicted a limited increase in suitable habitats under the SSP1-2.6 scenario during 2021-2040. Nevertheless, substantial habitat extension was predicted in western Anatolia, including İzmir and Denizli, coupled with enhanced suitability in southeastern areas such as Şanlıurfa and Diyarbakır under the SSP5-8.5 scenario during the same period. Coastal regions remain predominant as high-risk locations, with little alteration in central and northern regions under the SSP1-2.6 scenario during 2041-2060. Conversely, significant habitat expansion is expected into northern Türkiye, particularly in areas next to the Black Sea, such as Samsun and Trabzon, under the SSP5-8.5 scenario. This transition indicates increasing temperatures, allowing the species to invade formerly inhospitable, colder regions. Almost the entire country, including the mountainous eastern areas of Erzurum and Van, is predicted to be vulnerable to invasion under the SSP5-8.5 scenario during 2081-2100. A severe condition with broad danger across all ecological zones is expected in this scenario.

The suitable habitat will be contracted by 21.74-62.06% under the low emission scenario and 50.35-66.39% under the high emission

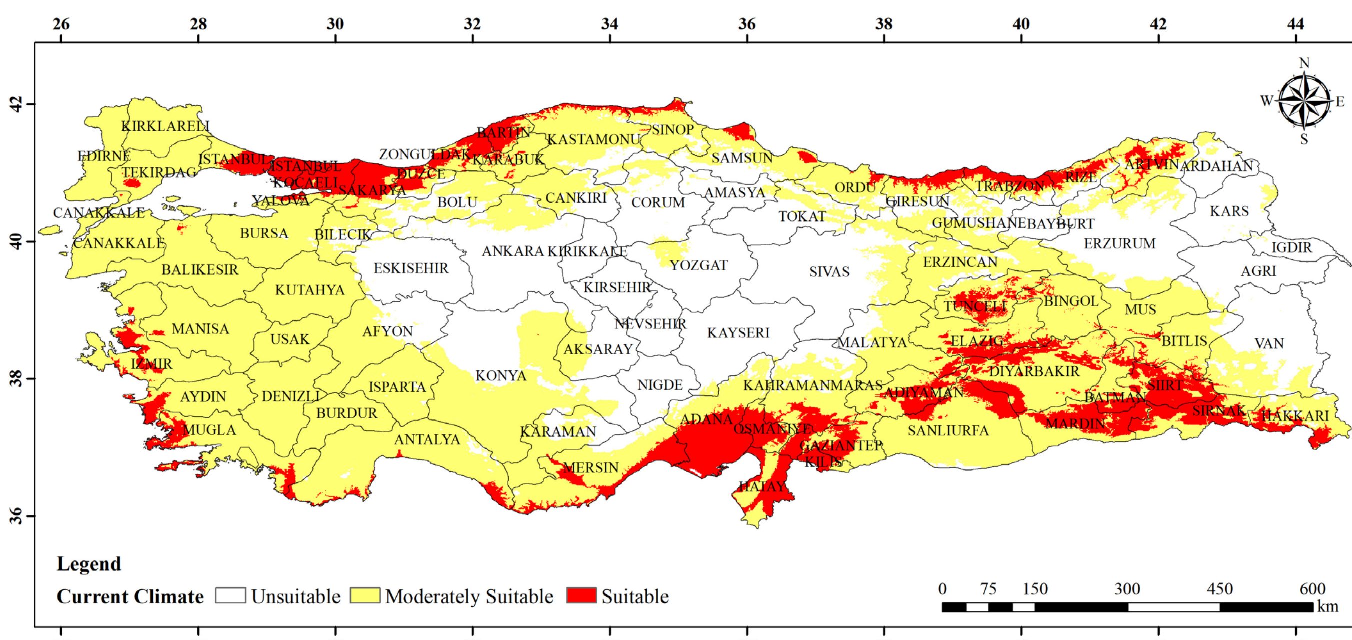

Fig. 4. Habitat suitability of *Spodoptera frugiperda* in Türkiye under current climatic conditions predicted by optimized MaxEnt model.

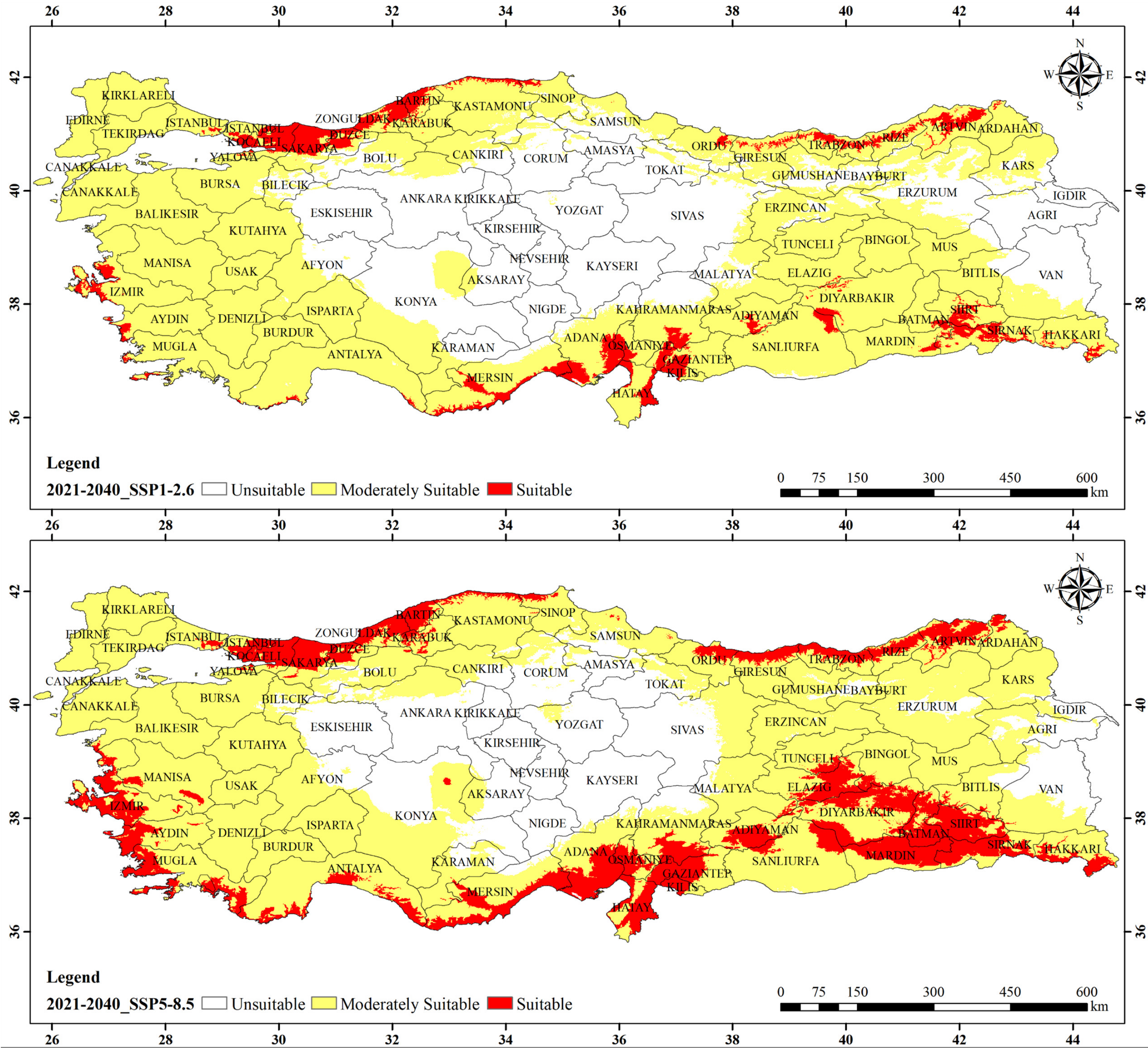

Fig. 5. Habitat suitability of *Spodoptera frugiperda* in Türkiye during 2021-2040 under SSP1-2.6 and SSP5-8.5 climate change scenarios predicted by optimized MaxEnt model.

scenario (except for a 22.59% expansion during 2021-2040) (Fig. 9). Likewise, in both future climate change scenarios, unsuitable areas will shrink as well. Nevertheless, moderately suitable areas will witness a continuous increase. The expansion of high-risk areas is especially higher under SSP5-8.5, with southern, central, and northern Türkiye becoming more susceptible. Inland areas will be at increasing danger, especially in the high-emission scenario, whereas coastal provinces will probably continue to be pest hotspots. Overall, the results denote that climate change will contract the highly suitable and unsuitable areas; however, moderately suitable areas will increase in the future.

4. Discussion

The LAPHFR is a polyphagous agricultural pest capable of inflicting considerable harm to maize and other crops (Day *et al.*, 2017; Kenis *et al.*, 2023; Liu *et al.*, 2019; Tonğa, 2023). The habitat suitability of LAPHFR was predicted in this study by using the MaxEnt model. The model had a high AUC, indicating high predictive accuracy. The Jackknife analysis indicated that bio11, bio12, and bio1 were the most important environmental variables that will affect the distribution of LAPHFR in Türkiye. The distribution and population dynamics of LAPHFR are significantly altered by temperature and precipitation. The moisture levels necessary for the survival of host plant species are affected by precipitation, which ultimately mediates the distribution of LAPHFR. The results revealed that the areas with high annual precipitation in Türkiye were highly suitable for LAPHFR. Ample moisture in these areas will facilitate the host plants' growth and larval development. Similarly, average annual temperature has a major impact on the LAPHFR life cycle. Temperatures between 26 to 30°C are optimum for development and reproduction; however, temperatures lower or higher than this range may be harmful. It is critical to maintain appropriate thermal conditions for pest growth, since studies show that

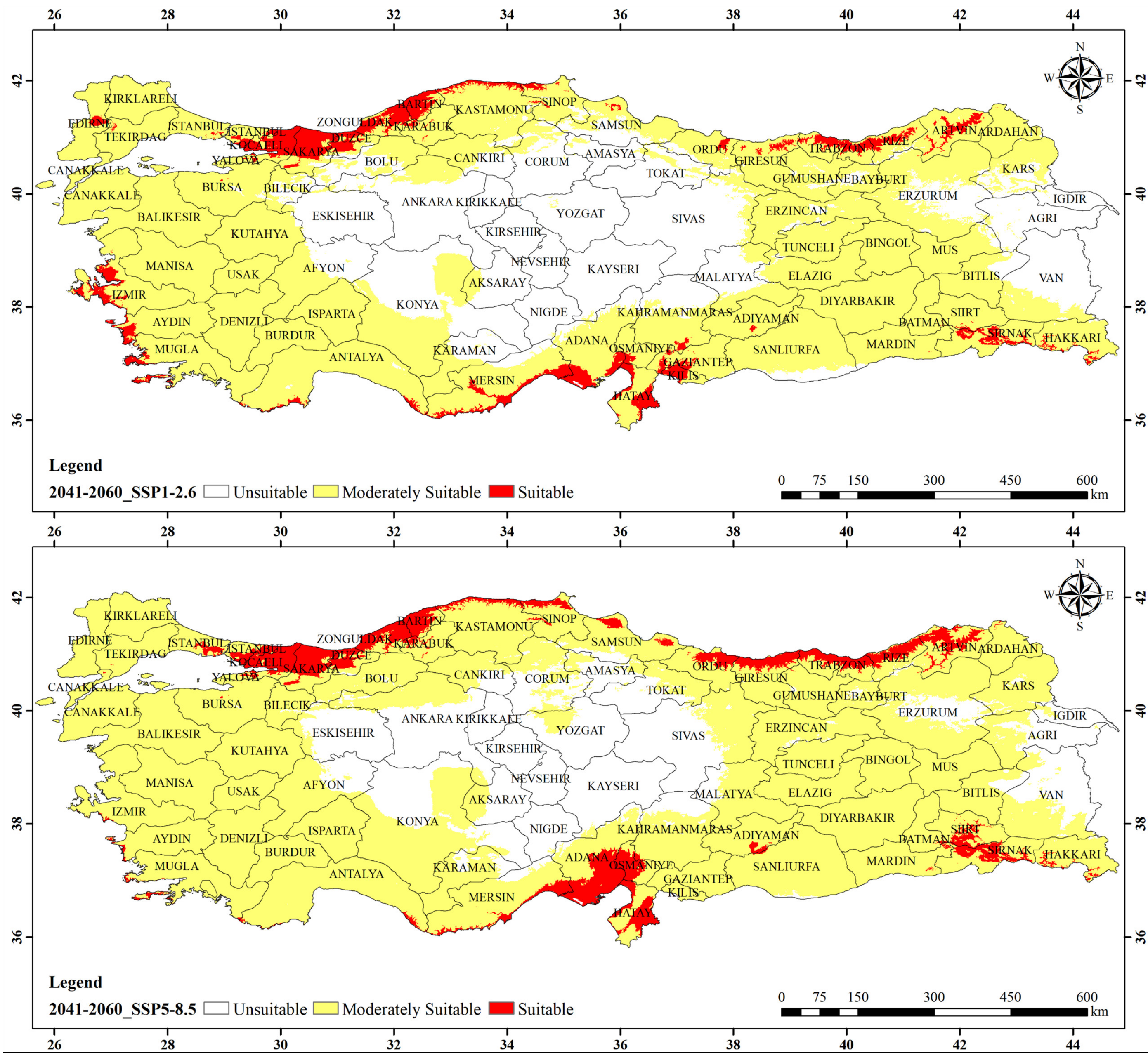

Fig. 6. Habitat suitability of *Spodoptera frugiperda* in Türkiye during 2041-2060 under SSP1-2.6 and SSP5-8.5 climate change scenarios predicted by optimized MaxEnt model.

temperatures below 12°C impede development (Barfield and Ashley, 1987). These results support those of Early *et al.* (2018), showing that the climate has a direct impact on larval growth, overall survival, and reproduction rates. Because LAPHFR can adapt to a wide range of habitats, it poses a risk to agricultural systems as climatic patterns continue to change. Moreover, the life cycle of LAPHFR is accelerated by warmer temperatures because the larvae mature more rapidly and reproduce more often. Hence, it has an increased reproductive rate due to climate change, which in turn increases the likelihood that it will spread and cause harm to crops (Du Plessis *et al.*, 2020; Malekera *et al.*, 2022).

The model projections indicated that the Black Sea and southeastern Anatolia are optimal for the proliferation of LAPHFR in Türkiye. Nevertheless, there are suitable niches in the eastern Mediterranean. These results are supported by the occurrence of LAPHFR in Adana (Pehlivan and Atakan, 2022) and Şanlıurfa (Tonğa, 2023), indicating that this species can perceive and endure diverse climatic conditions. The model predicted that around 90,000 km^2 of the country is conducive to LAPHFR, indicating substantial spread and invasion potential. The earlier studies have reported enormous spread potential of the pest in various regions of the world and adaptation to diverse environmental circumstances (Barfield and Ashley, 1987; Early *et al.*, 2018; Gilioli *et al.*, 2023; Jiang *et al.*, 2022; Zacarias, 2020). The results underscore the immediate need for monitoring and control measures to prevent the possible spread of LAPHFR in Türkiye.

It was predicted that a temporary increase in suitable habitat would occur from 2021 to 2040 under the high-emission scenario (SSP5-8.5). The increased development and reproduction rates brought about by the warmer weather are the primary causes of this expansion (Du Plessis *et al.*, 2020; Malekera *et al.*, 2022). Despite short-term habitat expansion,

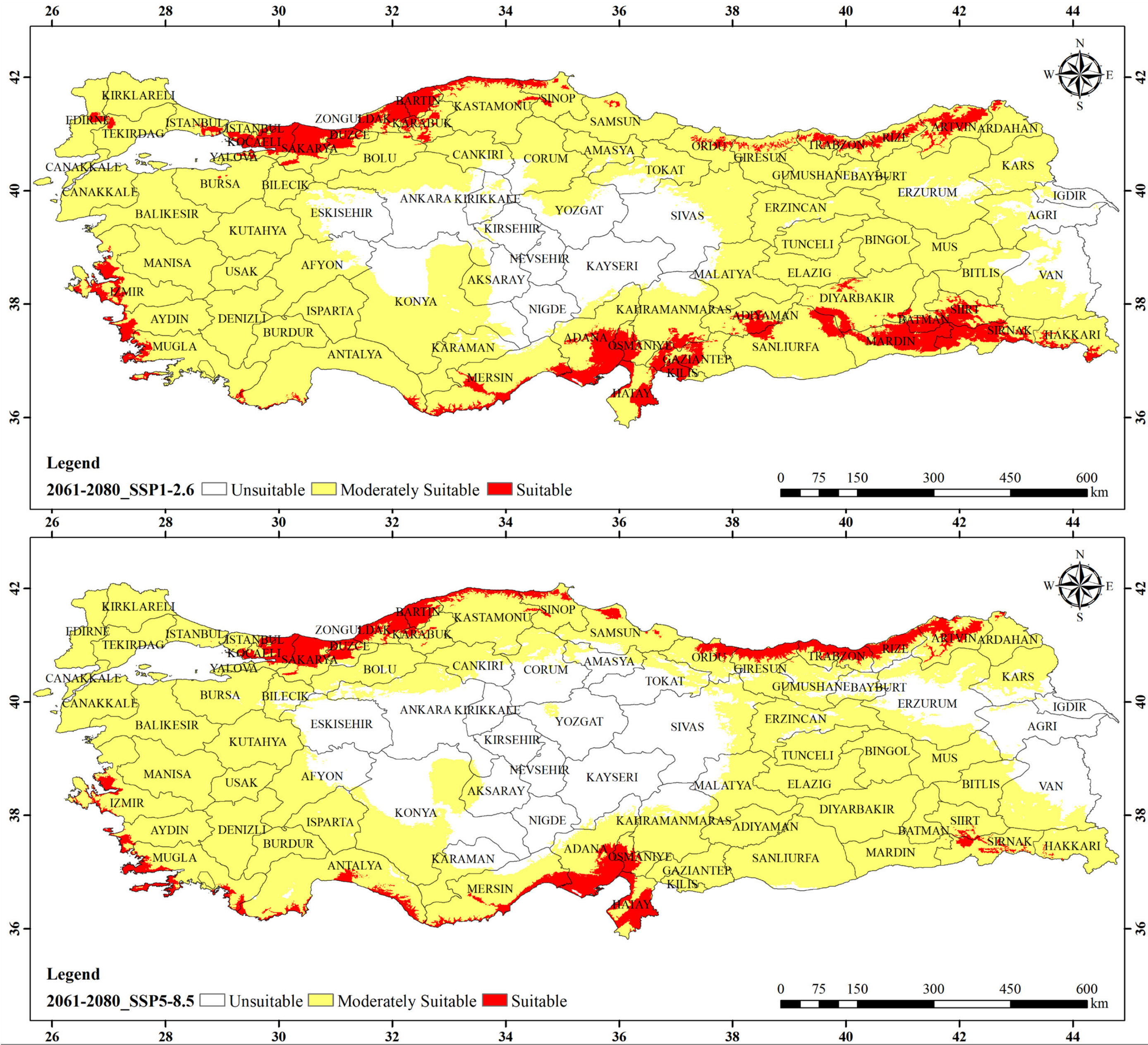

Fig. 7. Habitat suitability of *Spodoptera frugiperda* in Türkiye during 2061-2080 under SSP1-2.6 and SSP5-8.5 climate change scenarios predicted by optimized MaxEnt model.

the model predicted a long-term contraction in suitable habitats. In the low-emission scenario (SSP1-2.6), suitable habitats may decline by 21.74% to 62.06%, and in the high-emission scenario (SSP5-8.5), from 50.35% to 66.39%. This shrinking indicates that LAPHFR may experience fewer optimum zones because of environmental changes brought on by climate change. The contraction may be attributed to increased temperature beyond the upper limit of LAPHFR and the decreased precipitation (Gumus *et al.*, 2023; Ustaoğlu *et al.*, 2023).

The future spread of LAPHFR under climate change depends on intricate connections among habitat appropriateness, temperature variations, and adaptation. Despite a potential short-term habitat expansion, future projections suggest a decline in suitable habitats, necessitating that farmers in affected regions implement steps to protect their crops. Comprehending these processes is essential for formulating successful pest management strategies, particularly considering the problems posed by climate change.

The spread of LAPHFR to geographic regions like Türkiye, characterized by elevated temperatures and adequate rainfall, may have considerable consequences for agriculture. Climate change is generating new suitable habitats, which may experience increased agricultural damage, especially to crops such as maize, resulting in economic losses. Comparable areas must alter pest management practices to address the increased reproductive rates and extended distributions of LAPHFR, including climate change forecasts into their planning. Biosecurity protocols, including early detection mechanisms and international collaboration, are crucial to prevent the spreading of the pest. Moreover, prioritizing climate-resilient crops and integrated pest management (IPM) helps alleviate the effects of pests in these vulnerable regions.

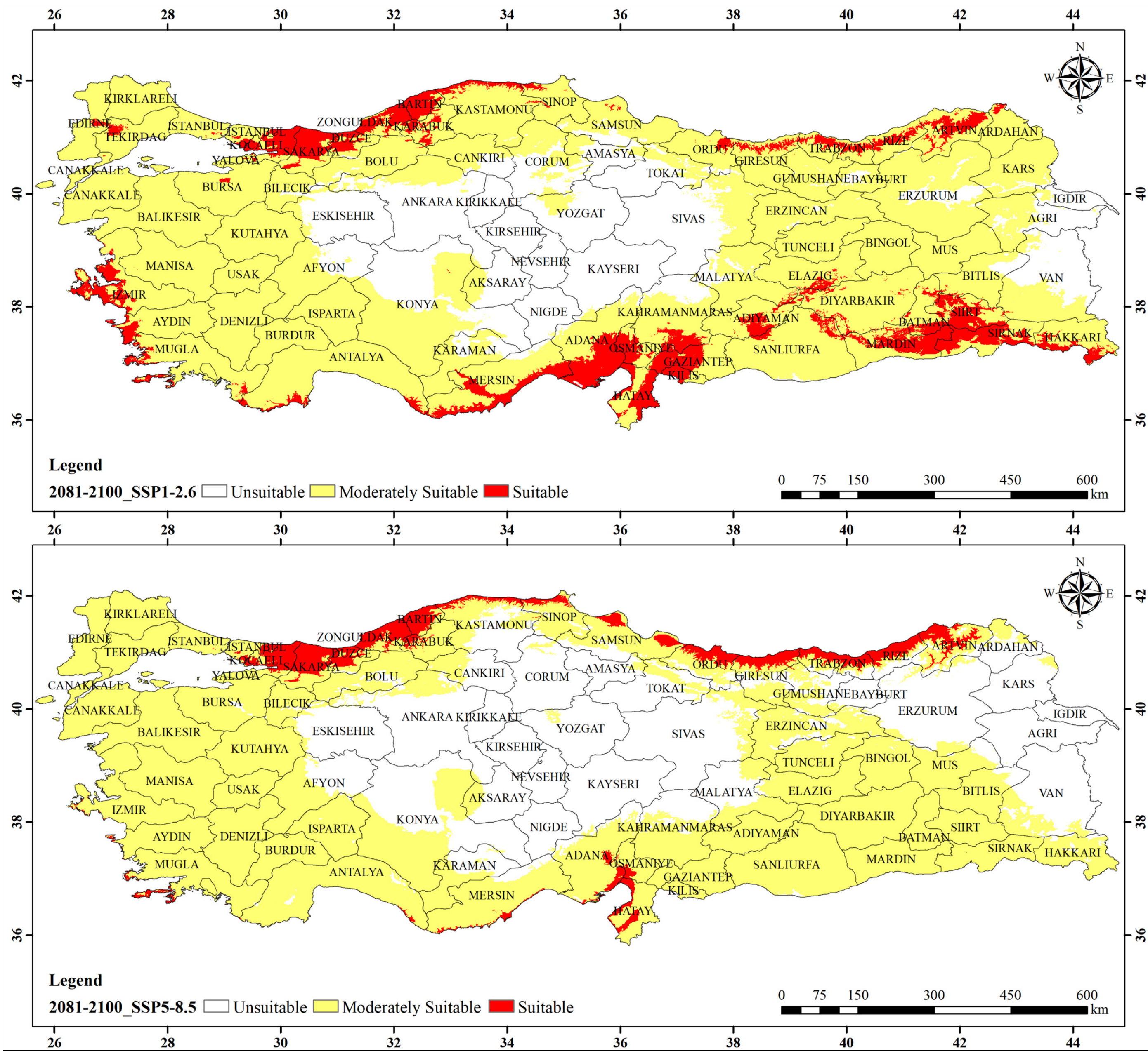

Fig. 8. Habitat suitability of *Spodoptera frugiperda* in Türkiye during 2081-21000 under SSP1-2.6 and SSP5-8.5 climate change scenarios predicted by optimized MaxEnt model.

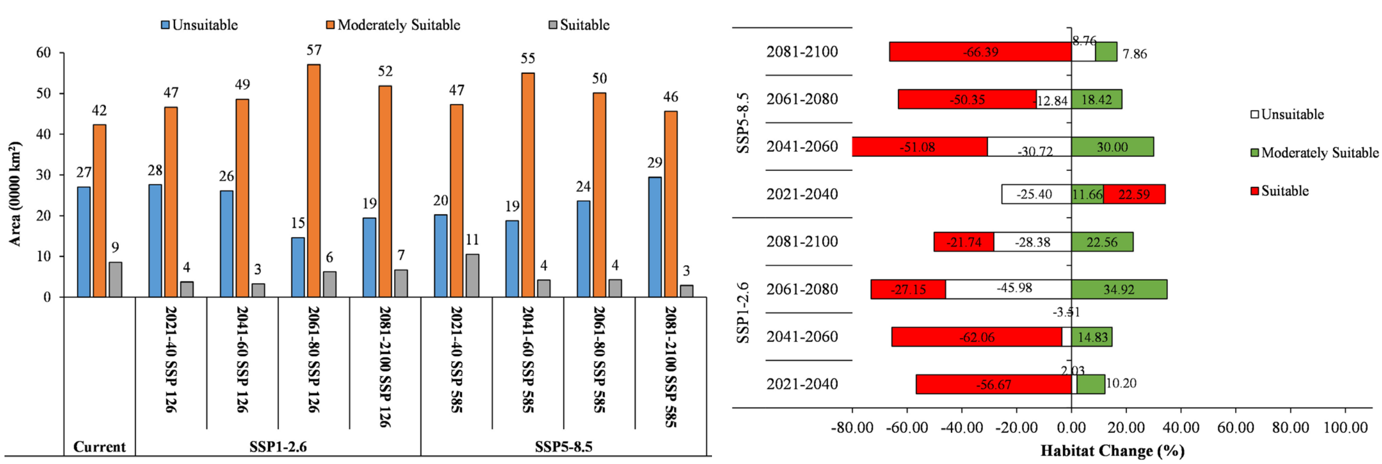

Fig. 9. Area of different habitat suitability categories *Spodoptera frugiperda* in Türkiye and habitat changes under changing climate.

5. Conclusion

The optimized MaxEnt model predicted the habitat suitability of LAPHFR in Türkiye with high accuracy. Annual precipitation (bio12), annual mean temperature (bio1), and the mean temperature of the coldest quarter (bio11) will affect the distribution of LAPHFR. The model suggests the Black Sea and southeastern Anatolia are under high invasion risks of LAPHFR. Highly suitable habitats will expand during 2021-2040 under high-emission scenarios, followed by a subsequent contraction in highly suitable habitats. Highly suitable regions will contract by 21.74-62.06% under a changing climate. It is essential to concentrate on enhancing surveillance and early detection systems in high-risk regions, implementing integrated pest control tactics that consider area ecological factors, and emphasizing climate mitigation initiatives to diminish the probability of significant habitat growth in high-emission scenarios to reduce the future invasion risk.

CRediT authorship contribution statement

Tarkan Ayaz: Contributed towards conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing original draft preparation, and writing, review and editing.

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.

Declaration of Generative AI and AI-assisted technologies in the writing process

The author confirm that there was no use of Artificial Intelligence (AI)-Assisted Technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

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