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Modelling the probability of presence of *Aedes aegypti* and *Aedes albopictus* in Iran until 2070

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ABSTRACT

Objective: To determine the suitable ecological habitats of *Aedes* (*Ae.*) *aegypti* and *Ae. albopictus* in Iran due to climate change by the 2070s.

Methods: All data relating to the spatial distribution of *Ae. aegypti* and *Ae. albopictus* worldwide, which indicated the geographical coordinates of the collection sites of these mosquitoes, were extracted from online scientific websites and entered into an Excel file. The effect of climatic and environmental variables on these mosquitoes was evaluated using the MaxEnt model in the current and future climatic conditions in the 2030s, 2050s, and 2070s.

Results: The most suitable areas for the establishment of *Ae. aegypti* are located in the southern and northern coastal areas of Iran, based on the model outputs. The modelling result for suitable ecological niches of *Ae. albopictus* shows that in the current climatic conditions, the southern half of Iran from east to west, and parts of the northern coasts are prone to the presence of this species. In the future, some regions, such as Gilan and Golestan provinces, will have more potential to exist/establish *Ae. albopictus*. Also, according to the different climate change scenarios, suitable habitats for this species will gradually change to the northwest and west of the country. The temperature of the wettest season of the year (Bio8) and average annual temperature (Bio1) were the most effective factors in predicting the model for *Ae. aegypti* and *Ae. albopictus*, respectively.

Conclusions: It is required to focus on entomological studies using different collection methods in the vulnerable areas of Iran. The future modelling results can also be used for long-term planning to prevent the entry and establishment of these invasive *Aedes* vectors in the country.

KEYWORDS: *Aedes aegypti*; *Aedes albopictus*; Dengue fever; Chikungunya; Ecological Niche Modeling; Climate change

1. Introduction

Dengue virus and Chikungunya virus are considered emerging diseases in some geographical areas of the world, which will probably spread to many countries in the coming years. According to the reports of the World Health Organization, the global incidence of dengue has grown rapidly in recent years and the number of dengue cases increased over 8-fold over the last two decades. In 2021, dengue fever affects countries including Brazil, the Cook Islands, Colombia, Kenya, Paraguay, Peru[1]. Of 129 countries at risk of infection, 70% of the burden is in Asia[2]. In the Southwest Asia, several epidemics of dengue fever have been observed in Saudi Arabia, Afghanistan, and Pakistan[1]. Chikungunya is another important mosquito-borne viral disease

Significance

Given the importance of *Aedes aegypti* and *Aedes albopictus* as invasive species, this study aimed to determine their suitable ecological habitats in Iran considering climate change by the 2070s. This study is done for the first time in Iran, and its findings can help the *Aedes* mosquito monitoring program in terms of determining the places that should be investigated.

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that has spread rapidly and has been documented in over 60 countries in Asia, Africa, Europe, and the Americas. The outbreaks of chikungunya were reported recently in Sudan and Yemen[3,4].

Aedes (*Ae.*) *aegypti* is the proven vector of dengue and chikungunya viruses, but where it is not extant or present in low numbers, *Ae. albopictus* has been incriminated as the primary vector[5]. In recent decades, both species have expanded rapidly in the Eastern Mediterranean Region and southwest Asia[6]. The outbreak of dengue fever in China, India, and Pakistan, and its emerging epidemic in Tokyo, Japan, which has been unprecedented for the past 70 years, are all signs of changes in the geographical distribution and ecology of vectors[5]. Today, the above-mentioned vectors are established in most of Iran's neighbouring countries. In Iran, *Ae. albopictus* was first reported in Chabahar[7], Sistan and Baluchestan Province. Another vector, *i.e. Ae. aegypti* was observed in Bandar Lengeh, Hormozgan Province[6,8] yet the establishment of these species in the country has not been confirmed. Considering the invasion of *Ae. aegypti* and *Ae. albopictus* to Iran, as well as case reports of dengue fever and chikungunya, there are concerns about the establishment of these vectors and the risk of the spread of dengue fever and chikungunya in the country. Some Iranian health experts believe that a tsunami of dengue epidemics will reach Iran in the next few years[9].

The distribution of these species is mainly driven by both human movement and the presence of a suitable climate. On the other hand, the most important reasons for the distribution of *Ae. aegypti* and *Ae. albopictus* are urbanization, the international trade in used tires, and the import of lucky bamboo[1,5,10]. Climate change and global warming play an important role in changing the distribution pattern of the vectors[11]. Numerous floods due to climate change in recent years seem to be a major factor in the outbreak of dengue fever in Pakistan[12]. However, understanding the impact of climate change on the prevalence of diseases requires a tool to know the intensity, duration, and spatial dimensions. Assessing the vulnerability of society and the impact of climate change on vector-borne diseases can be carried out by the creation of vectors map in current and future climatic condition. Modelling the spatial distribution and finding the probability of the presence of vectors under climate change scenarios enable scientists to predict high-risk areas and the pattern of the distribution of the vectors. In this context, various modelling studies have been carried out on the effects of climate change on the distribution of *Ae. aegypti* and *Ae. albopictus* in China[13,14], Eastern Mediterranean Region[15], United States[16], Mexico[17], Canada[18], Pakistan[19], and Panama[20]. Due to the different ecology of each vector and the unlike effects of the environment on them, the distribution pattern of vectors will depend on the type of climatic variables. The selection of valid parameters plays an important role in creating a reliable model that can be achieved through the full knowledge of ecology and literature review. Studies have shown that various climatic factors including temperature, rainfall, and population density were the main variables to effectively predict the presence of these vectors[21,22].

A modeling study in Iran showed that the southern regions of Sistan and Baluchestan Province were at greater risk of *Ae. albopictus* as well as more urban sites connected by provincial roads[9]. Given that Iran has common land and water borders with dengue endemic countries like Pakistan, Afghanistan, and Oman, it is at risk of invasion of vectors from different regions. A comprehensive study was needed in the country to develop an appropriate management plan to prevent the establishment of vectors and to predict possible outbreaks of dengue fever and chikungunya. This study aimed to identify areas of human health risk posed by the colonization of *Ae. aegypti* and *Ae. albopictus* in Iran. Therefore, we utilized modelling to predict suitable habitats for *Ae. aegypti* and *Ae. albopictus*, as the main vectors of dengue/chikungunya in Iran.

2. Materials and methods

2.1. Data on the presence sites of Aedes aegypti and Aedes albopictus

Data related to the collection points of these mosquitoes were extracted from articles published in the field of their fauna in different countries of the world. For this purpose, reputable scientific databases such as PubMed, ISI Web of Science, Scopus, and Google Scholar for articles in English, and Magiran, SID, and Iran Medex databases for articles in Persian and dissertations were reviewed. All data relating to the spatial distribution of the two species, *Ae. aegypti* and *Ae. albopictus*, which indicated the geographical coordinates of the collection site were entered in an Excel file. The data in the Excel file was then saved in CSV format for modelling. During this process, a total of 2 780 points of presence were collected for both species. Of these, 2 369 points of presence related to *Ae. aegypti* and 1 493 points of presence belonging to *Ae. albopictus*. It should be noted that in some places both species have been caught.

2.2. Collection of environmental and climatic data

To investigate the effect of climatic variables on the main vectors of dengue and chikungunya, climatic data were obtained from the worldclim website (https://www.worldclim.org) at the spatial resolution of 2.5 minutes (about 5 km) for the historical climate data (1971-2000). The altitude layer was also obtained from this website at the same resolution.

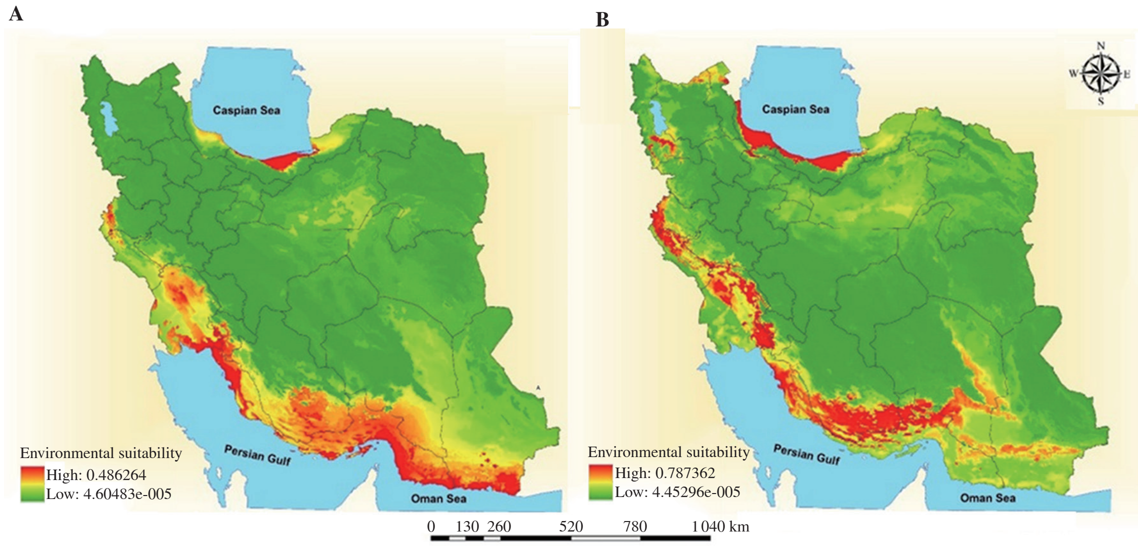

Figure 1. Environmental suitability for *Aedes aegypti* (A) and *Aedes albopictus* (B) in Iran using the historical bioclimatic variables.

2.3. Determining areas prone to the presence of Aedes aegypti and Aedes albopictus in 2030, 2050, and 2070 considering climate change

For this purpose, data on 19 bioclimatic variables with a spatial resolution of 5 km^2 based on the GCM model of BCC-CSM1-1 and three scenarios (RCP2.6, RCP4.5, and RCP8.5) for the whole world was downloaded from the worldclim website for years 2030, 2050 and 2070[23]. Bioclimatic variables with less than 0.8 correlations were identified using band collection statistics analysis in ArcMap. Finally, 8 bioclimatic and one environmental variable bio1 (annual average temperature), bio2 [average of monthly temperature (max-min], bio7 (annual temperature range), bio8 (average temperature of wettest quarter), bio14 (precipitation of driest month), bio15 (precipitation seasonality), bio16 (precipitation of wettest quarter), bio19 (precipitation of coldest quarter) and altitude were used for modeling. Information from field studies of the last two decades worldwide on these two species of mosquitoes as well as information on climatic characteristics downloaded for the coming years was used for modeling in MaxEnt software and possible changes in the spatial distribution of these two species in the current and future conditions were estimated.

In the MaxEnt model, 75% of the species presence points were used to train the model and 25% of the remaining presence points were used to evaluate the constructed model. The output map in the MaxEnt model is a map in which the cells have continuous values between zero and one, and the closer the value of a cell in this map is to one, the higher the habitat suitability of the cell for the species. To reduce the spatial autocorrelation for the data of the presence points of the vectors of dengue fever and chikungunya, the SDM toolbox in ArcMap was used and a radius of 10 km was selected. Points that were less than this radius were removed to reduce model orientation. The Jackknife test in the MaxEnt model was used to determine the most important effective variable in the model. The validity of the MaxEnt model was performed using the area under the ROC curve (AUC). The area under the curve is equal to the probability of distinguishing between the presence and absence points by a model. The AUC range is between 0.5 and 1, which represents the value of 0.5 for a completely random model and the value of 1 for a model with good predictive power. AUC of 0.7 to 0.8 shows a good model, 0.8 to 0.9 excellent, and more than 0.9 excellent predictions[24]. After modelling for the whole world, the model output was clipped in the ArcMap based on the border of Iran and the layer of Iranian provinces was placed on the resulting map to determine the extent of habitat suitability for each vector in different provinces.

3. Results

3.1. Modelling the environmental suitability using historical bioclimatic variables

Figure 1 shows the areas with the best ecological niches for *Ae. aegypti* and *Ae. albopictus* under the current climate. As shown in this figure, Sistan and Baluchestan, Hormozgan, Kerman, Bushehr, Fars, Kohgiluyeh and Boyer-Ahmad, Khuzestan, Ilam, Kermanshah, Lorestan, Golestan, Mazandaran, and Gilan provinces have more suitable habitats for *Ae. aegypti* (Figure 1A). Also, suitable habitats for *Ae. albopictus* are located in Sistan and Baluchestan, Hormozgan, Kerman, Bushehr, Fars, Kohgiluyeh and Boyer-Ahmad, Khuzestan, Ilam, Lorestan, Kermanshah, West Azerbaijan, East Azerbaijan, Qazvin, Gilan, Mazandaran, and Golestan provinces (Figure 1B).

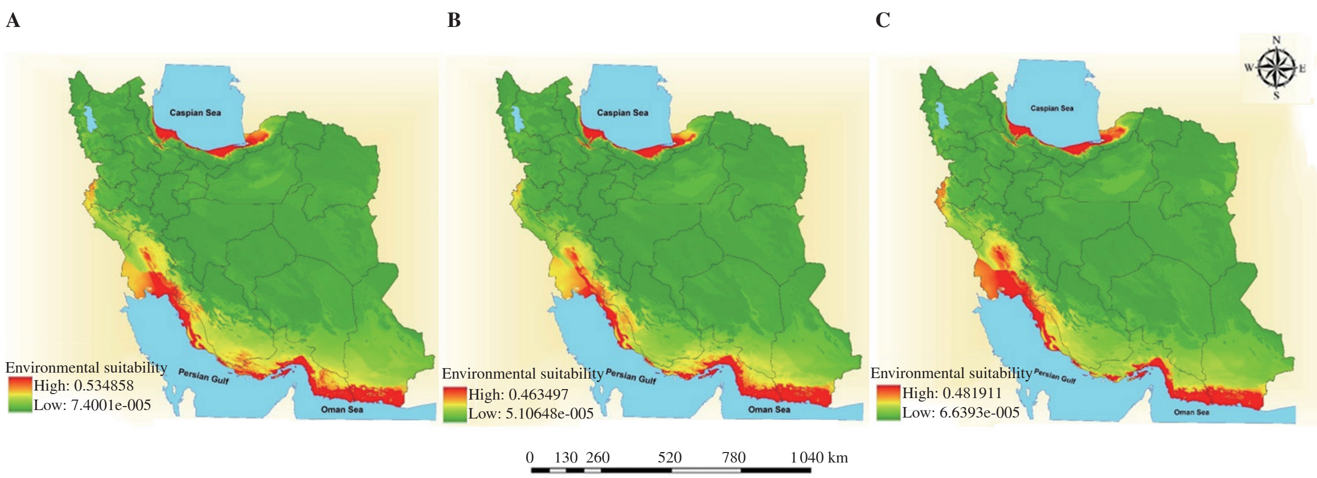

Figure 2. Environmental suitability for *Aedes aegypti* in Iran in 2030s under different climate change scenarios (A: RCP2.6, B: RCP4.5, C: RCP8.5).

At this stage of the modelling, for both species the area under the curve (AUC) was higher than 0.9 (0.920 for *Ae. aegypti* and 0.940 for *Ae. albopictus*), which indicates a very good model prediction. The Jackknife test also showed that the temperature of the wettest season of the year (Bio8) was the most effective factor in predicting the model for *Ae. aegypti*, while the variable of average annual temperature (Bio1) was the most effective factor in predicting the model for *Ae. albopictus*.

3.2. Modelling the main vectors of dengue fever and chikungunya in the 2030s

3.2.1. Habitat suitability for Aedes aegypti

Figure 2A shows the habitat suitability for *Ae. aegypti* in the 2030s according to RCP 2.6 scenario. As can be seen, the coastline of the south and north of the country provides the most suitable habitats for this species. The range of these habitats will be extended from the south of the country to the border parts of Kermanshah Province. Compared to the current climatic conditions (Figure 1A), the favorable habitats of this mosquito will decrease in the south of the country, but in the north of Iran, it shows an increasing trend. The environmental variable with the greatest impact on the model, such as the current climatic conditions, was the temperature of the wettest season of the year (Bio8). Given that the AUC is 0.903, the model provides a very good prediction.

Under the RCP4.5 scenario, the south and north coasts of the country provide the most suitable habitats for this species (Figure 2B). Habitat suitability will increase from a maximum of 46% in RCP2.6 to 53% in RCP4.5. This means that the conditions in some areas will be more suitable for the establishment of *Ae. aegypti*. However, the suitable areas for the growth and development of this species in terms of environmental conditions, compared to the current climate conditions (Figure 1A) in the south of the country will decrease and increase in the north of Iran. The environmental variable with the most impact on the model was bio7, or the difference between the maximum temperature of the hottest month of the year and the minimum temperature of the coldest month of the year. Given that the AUC is 0.904, the model provides a very good prediction.

In the RCP8.5 scenario, the south and north coasts of the country provide the most suitable habitats for this species. Habitat suitability will increase from a maximum of 46% in RCP2.6 to 48% in RCP8.5 (Figure 2C). This means that the conditions in some areas will be more suitable for the establishment of *Ae. aegypti*. Also, the western part of Kermanshah Province and the northern part of Khuzestan Province will be more prone to the presence of this species compared to other studied scenarios in the 2030s. The environmental variable with the greatest impact on the model was the bio8 (temperature of the wettest month of the year). Given that the AUC is 0.904, the model provides a very good forecast.

3.2.2. Habitat suitability for Aedes albopictus

According to RCP2.6, the south and north coasts of the country, large areas of the northwest and west of the country provide the most suitable habitats for this species. Comparing the current climate conditions (Figure 1B) with RCP2.6, habitat suitability will decrease from a maximum of 78% in the current situation to 75% in RCP2.6. However, new areas in the north and northwest of the country will be prone to the presence and establishment of this vector (Figure 3A). The environmental variable with the greatest impact on the model was bio1 or average annual temperature. Given that the AUC is 0.923, the model provides a very good prediction.

According to RCP4.5, the south and north coasts of the country, as well as large areas of the northwest and west of Iran will provide the most suitable habitats for this species. Comparing the current climate conditions (Figure 1B), habitat suitability will decrease

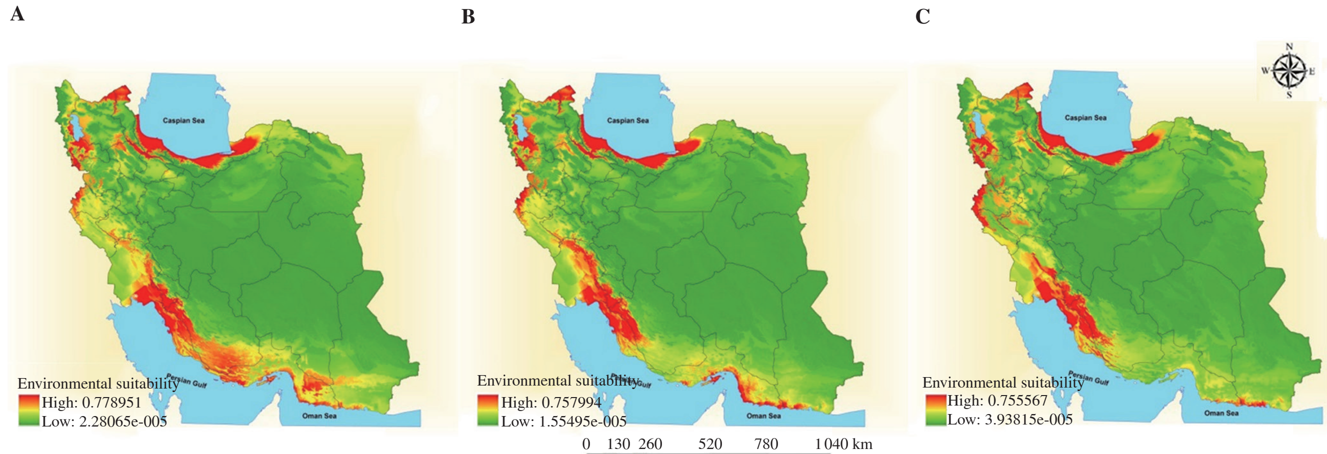

Figure 3. Environmental suitability for *Aedes albopictus* in Iran in 2030s under different climate change scenarios (A: RCP2.6, B: RCP4.5, C: RCP8.5).

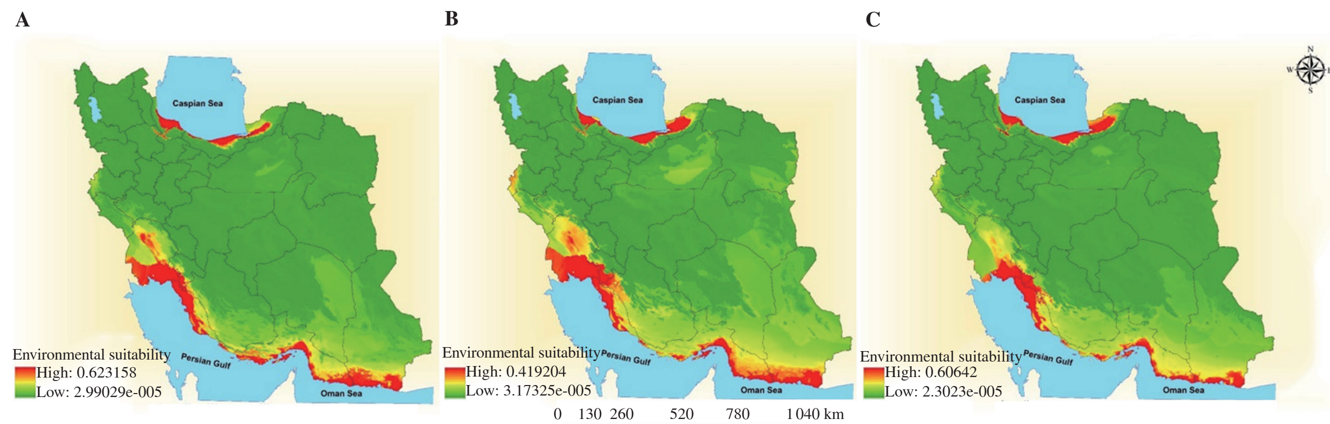

Figure 4. Environmental suitability for *Aedes aegypti* in Iran in 2050s under different climate change scenarios (A: RCP2.6, B: RCP4.5, C: RCP8.5).

from a maximum of 78% in the current situation to 77% in RCP4.5. However, new areas in the north and northwest of the country will be prone to the presence and establishment of this vector and it seems that there are more favourable habitats for this species in the western half of the country (Figure 3B). The environmental variable with the greatest impact on the model was the average annual temperature (Bio1). Given that the AUC is 0.923, the model provides a very good prediction.

With RCP8.5, only a limited part of Sistan and Baluchestan and Hormozgan provinces will be suitable for the establishment of this species, but its probability of presence in the north, northwest, and western strip of the country will increase. Comparing the current climate conditions (Figure 1B) with RCP8.5, habitat suitability will decrease from a maximum of 78% in the current situation to 75% in this scenario. However, new areas in the north and northwest of the country will be prone to the presence and establishment of this vector, and, it seems that there are more favorable habitats for this species in the western half of the country (Figure 3C). The environmental variable with the greatest impact on the model was the average annual temperature (Bio1). Given that the AUC is 0.923, the model provides a very good prediction.

3.3. Modelling the main vectors of dengue fever and chikungunya in the 2050s

3.3.1. Habitat suitability for Aedes aegypti

Figure 4 shows the habitat suitability for *Ae. aegypti* in the 2050s according to RCP2.6. As can be seen, compared to the current climatic conditions, habitat suitability will be concentrated on the south and north coasts of the country. Comparing the current climate conditions (Figure 1A) with RCP2.6, habitat suitability will increase from a maximum of 48% in the current situation to 62% in RCP2.6. In this scenario, the probability of the presence of *Ae. aegypti* in Ilam and Kermanshah provinces is reduced, but in Gilan, Golestan, and the northern parts of Qazvin provinces, it will increase (Figure 4A). The environmental variable with the greatest impact on the model was the temperature of the wettest month of the year (Bio8). Given that the AUC is 0.902, the model provides a very good prediction.

With the RCP4.5 scenario, compared to the current climatic conditions, habitat suitability will be concentrated on the south and north coasts of the country. Comparing the current climate conditions (Figure 1A) with RCP4.5, habitat suitability will decrease from a maximum of 48% in the current situation to 42% in RCP4.5.

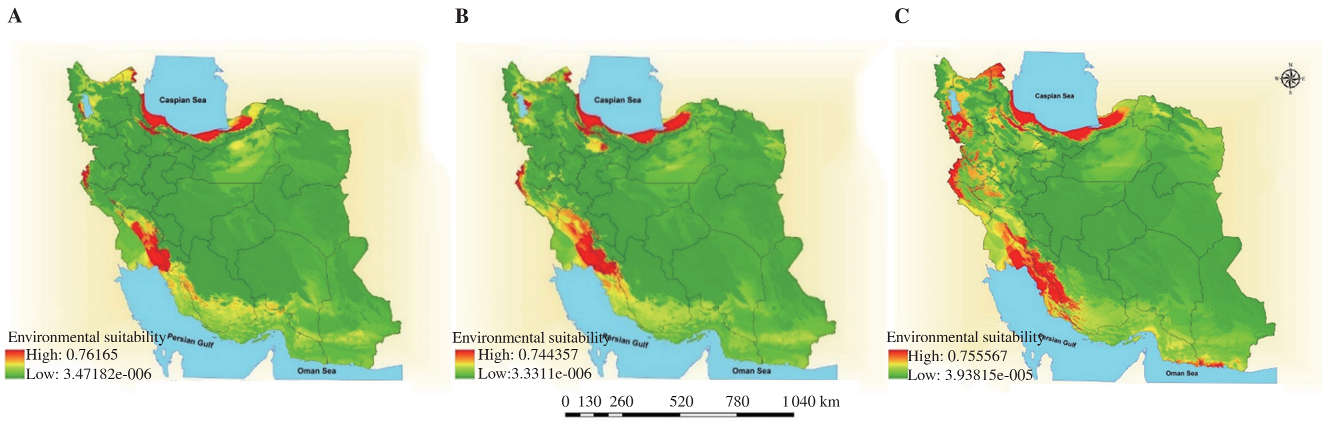

Figure 5. Environmental suitability for *Aedes albopictus* in Iran in 2050s under different climate change scenarios (A: RCP2.6, B: RCP4.5, C: RCP8.5).

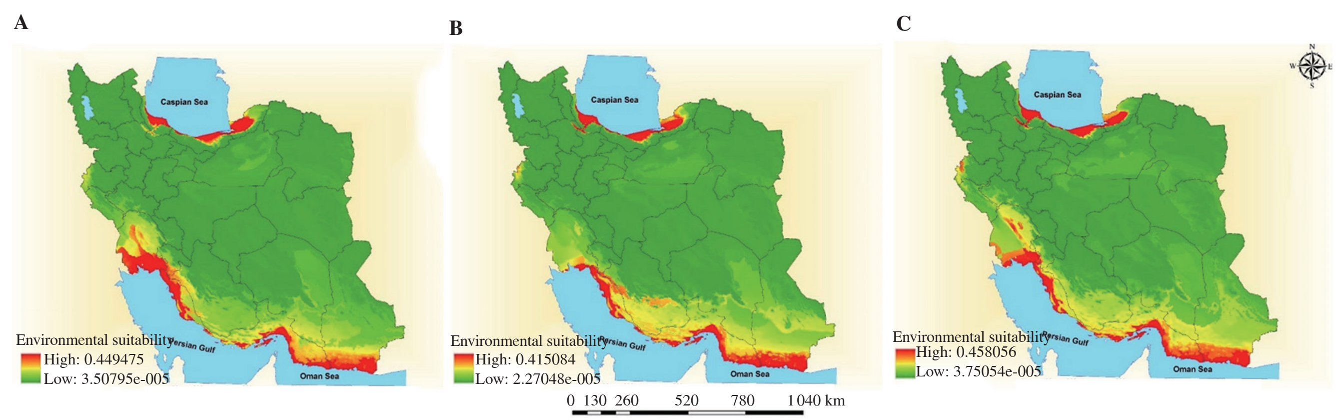

Figure 6. Environmental suitability for *Aedes aegypti* in Iran in 2070s under different climate change scenarios (A: RCP2.6, B: RCP4.5, C: RCP8.5).

In this scenario, unlike RCP2.6, the probability of the presence of *Ae. aegypti* in Ilam and Kermanshah provinces increases, and compared to the current climate, this probability will increase in Gilan, Golestan, and the northern parts of the Qazvin provinces (Figure 4B). The environmental variable with the greatest impact on the model was the temperature of the wettest month of the year (Bio8). Given that the AUC is 0.902, the model provides a very good prediction.

According to RCP8.5, as can be seen in figure 4, compared to the current climatic conditions, habitat suitability will be concentrated on the south and north coasts of the country. Comparing the current climate conditions (Figure 1A) with RCP8.5, the habitat suitability will increase from a maximum of 48% in the current situation to 60% in RCP8.5. Compared to the current climate, the probability of the presence of this mosquito species in Gilan, Golestan, and northern parts of Qazvin provinces will increase, but in Ilam, Kermanshah, southern Kerman, southern Fars, northern Hormozgan and northern Khuzestan provinces will decrease (Figure 4C). The environmental variable with the greatest impact on the model was the average annual temperature (Bio1). Given that the AUC is 0.901, the model provides a very good prediction.

3.3.2. Habitat suitability for Aedes albopictus

Figure 5A shows the habitat suitability for *Ae. albopictus* in the 2050s according to RCP2.6. As can be seen, compared to the current climatic conditions, habitat suitability will be concentrated in the north, northwest, west, and southwest areas of the country. Comparing the current climate conditions (Figure 1B) with RCP2.6, habitat suitability will decrease from a maximum of 78% in the current situation to 76% in RCP2.6. Compared to the current climate, the probability of the presence of this mosquito in Golestan, as well as northern parts of Qazvin and Zanjan provinces will increase, but in Sistan and Baluchestan, Hormozgan, Fars, Bushehr, Ilam, Lorestan, and parts of Khuzestan will decrease (Figure 5A). The environmental variable with the greatest impact on the model was the average annual temperature (Bio1). Given that the AUC is 0.926, the model provides a very good prediction.

In RCP4.5, compared to the current climatic conditions, habitat suitability will be concentrated on the northern coasts and southwest of the country, although areas in the northwest and west will provide good ecological niches for this species. It should be noted that in the northwest of the country, areas prone to the presence of this mosquito species will increase significantly. Comparing the current climate

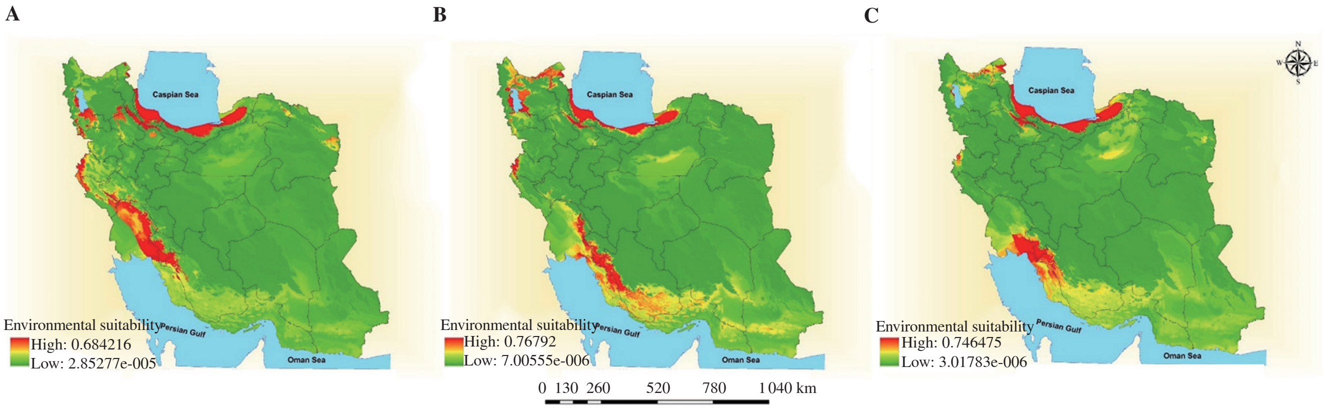

Figure 7. Environmental suitability for *Aedes albopictus* in Iran in 2070s under different climate change scenarios (A: RCP2.6, B: RCP4.5, C: RCP8.5).

conditions (Figure 1B) with RCP4.5, habitat suitability will decrease from a maximum of 78% in the current situation to 77% in RCP4.5 (Figure 5B). The environmental variable with the greatest impact on the model was the average annual temperature (Bio1). Given that the AUC is 0.925, the model provides a very good prediction.

In RCP8.5, hot spots in terms of habitat suitability will be significantly reduced compared to the current situation (Figure 1B) and will be concentrated on the northern coast of the country, northwestern regions, and parts of the southwestern region of the country. Also, habitat suitability will decrease from a maximum of 78% in the current situation to 75% in RCP8.5 (Figure 5C). The environmental variable with the greatest impact on the model was the average annual temperature (Bio1). Given that the AUC is 0.925, the model provides a very good prediction.

3.4. Modelling the main vectors of dengue fever and chikungunya in the 2070s

3.4.1. Habitat suitability for Aedes aegypti

Figure 6 shows the habitat suitability for *Ae. aegypti* in the 2070s concerning three climate change scenarios. In RCP2.6, compared to the current climatic conditions (Figure 1A), the hot spots will decrease significantly in terms of habitat suitability and will be concentrated on the northern and southern coasts of the country. Also, habitat suitability will decrease from a maximum of 48% in the current situation to 45% in RCP2.6 (Figure 6A). The environmental variable with the greatest impact on the model was the temperature of the wettest month of the year (Bio8). Given that the AUC is 0.9, the model provides a very good prediction.

In RCP4.5, compared to the current climatic conditions, hot spots will be significantly reduced in terms of habitat suitability and will be concentrated on the northern and southern coasts of the country (Figure 6B). These areas will cover almost all coastal areas of the three southern provinces of the Caspian Sea. Comparing the current climate conditions (Figure 1A), habitat suitability will decrease from a maximum of 48% in the current situation to 41% in RCP4.5. The environmental variable with the greatest impact on the model was the temperature of the wettest month of the year (Bio8). Given that the AUC is 0.902, the model provides a very good prediction.

Compared to the current climatic conditions, hot spots in the south of Fars Province, north of Hormozgan, south of Kohgiluyeh and Boyer-Ahmad, and south of Kerman in terms of habitat suitability will decrease significantly under RCP8.5 and will increase in the northern and southern coasts of the country (Figure 6C). These areas will cover almost all coastal areas of the three southern provinces of the Caspian Sea, and the probability of the presence of this mosquito in the Gilan and Golestan provinces will be much higher than in the current situation. Compared to the current climate conditions (Figure 1A), the maximum habitat suitability in the current situation is equal to 48% and in the RCP8.5 will be reduced to 45%. The environmental variable with the greatest impact on the model was the average annual temperature (Bio1). Given that the AUC is 0.902, the model provides a very good forecast.

3.4.2. Habitat suitability for Aedes albopictus

Figure 7 shows the habitat suitability for *Ae. albopictus* in the 2070s according to three different climate change scenarios. In RCP2.6, compared to the current climatic conditions, the areas prone to the presence and establishment of this species will be concentrated mainly in the north and west of the country. On the other hand, the areas that were suitable for this species in the south and southeast of the country will not have the necessary conditions for its establishment in the 2070s under the RCP2.6 scenario (Figure 7A). Comparing the current climate conditions (Figure 1B), the maximum habitat suitability in the current situation is equal to 78% and in RCP2.6 will decrease to 68%. The environmental variable with the greatest impact on the model was the average annual temperature (Bio1). Given that the AUC is 0.924, the model provides a very good prediction.

In the RCP4.5, compared to the current climatic conditions, the areas prone to the presence and establishment of this species will decrease mainly in the south and southeast of the country, and in contrast, in the north and northwest of the country will increase significantly (Figure 7B). Compared to the current climate conditions (Figure 1B), the maximum habitat suitability in the current situation is equal to 78% and will decrease to 76% in RCP4.5. The environmental variable with the greatest impact on the model was the average annual temperature (Bio1). Given that the AUC is 0.925, the model provides a very good prediction.

In the RCP 8.5 scenario, areas prone to the presence and establishment of this species will be mainly concentrated in the north, southwest, and parts of the northwest of the country and the extent of areas prone to the presence of this species in the south of the country will be reduced (Figure 7C). The maximum habitat suitability in the current situation is equal to 78% and will decrease to 74% in the RCP8.5. The environmental variable with the greatest impact on the model was the average annual temperature (Bio1). Given that the AUC is 0.927, the model provides a very good prediction.

4. Discussion

Except for two studies conducted in southeastern Iran[9,25], there was no information to predict the suitable habitats for *Ae. aegypti* and *Ae. albopictus* in the country. We comprehensively predicted the possible distribution ranges of two important species as the main vectors of dengue fever and chikungunya by 2070 in Iran. To evaluate the performance of the MaxEnt model, the area under the curve was examined. The values were higher than 0.9 for both species in different scenarios which indicated high accuracy prediction for areas prone to the presence of these vectors.

According to studies in this field, it can be said that any long-term temperature change will increase or decrease the suitable habitats for vectors[26]. Temperature affects the gonotrophic cycle of both species[27]. For example, a change in the average annual temperature has increased the duration of vector activity by several months and led them to higher latitudes[28]. Generally, in our study, only the northern strip and the steppe habitats of the southern strip are desirable for the presence of these species. It seems that areas from the tropical part of the country from Sistan and Baluchestan to the eastern parts of Kermanshah provinces as well as the northern strip of the country have higher habitat suitability for both species. However, with global warming and rising temperatures, we have seen that in different scenarios, the southern regions of the country have less capacity for these important vectors, and conversely, the areas prone to their presence in the north, northwest, and west of the country will increase. The result of this part of our study is in agreement with modeling the present and future distribution of *Ae. aegypti* and *Ae. albopictus* under climate change scenarios in Mainland China[22]. On the other hand, unlike *Ae. aegypti*, under the current climate the best ecological niches for *Ae. albopictus* includes the northwestern regions of the country and compared to *Ae. aegypti*, it can grow at lower temperatures. Similar to the results of our study, in Canada and the United States, suitable habitats for *Ae. albopictus* and *Ae. aegypti* is projected to expand northward by 2100, while the expansion of *Ae. albopictus* is predicted to be faster and further north than *Ae. aegypti*[18]. It seems that *Ae. albopictus* may be more affected by climate change and spread to other regions. A study on the global distribution of *Ae. aegypti* and *Ae. albopictus* yielded *Ae. aegypti* has affected more parts of South Africa, South America, and Australia, while *Ae. albopictus* affects the northernmost parts of the world[29]. Another study predicted that higher latitude would become more suitable for the survival of *Ae. albopictus*[22]. Agree with our findings, all these studies show that the *Ae. albopictus* moves to higher latitudes.

According to the output of all climate change scenarios in this study, the northern and southern regions of Iran are likely to be more at risk. Indeed, two studies conducted in Iran showed the presence of *Ae. albopictus* is more in the southern regions of Sistan and Baluchestan Province[9,25]. It is noteworthy that there are very important ports in these areas and trade exchanges are established with different countries of the world, some of which are native areas of the presence of *Ae. aegypti* and *Ae. albopictus*. Therefore, it is necessary to design and implement very accurate and regular entomological monitoring activities at these entry points. Otherwise, due to the susceptibility of these areas to the establishment and development of the two important vectors of dengue fever and chikungunya, there is a risk of their establishment and localization in the country. Transportation lines have been considered one of the most important infrastructures for the expansion and transfer of the mentioned species in most studies[30,31] which need to be considered to control these vectors and prevent their transfer and spread in the country.

As it is predicted that the climatic conditions in the world will change[32], so appropriate habitat of vectors will also be affected. According to forecasts, the temperature will increase and the extent of the presence of vectors of these diseases will change in response to climate change[11,33]. Considering the increasing trend of temperature in the north and northwestern region of Iran[34], widespread droughts in the country and water cuts also lead to the storage of water in containers in homes. This will increase the capacity for oviposition of *Ae. aegypti* and *Ae. albopictus*, especially in areas that have suitable environmental conditions for the growth and development of these species[35]. Therefore, it is necessary to do entomological monitoring programs in these areas to find the important vectors. Accurate studies to catch the larvae of these mosquitoes in water containers should be done.

At present, Iran is in contact with very strong distribution zones for these vectors, including India and Pakistan from the east and Oman from the southeast[6]. Due to the high spread of these two species, it is necessary to think of appropriate strategies to control their populations inside and outside the country. For example, controlling ships entering from the Indian Ocean and the Sea of Oman in the south of the country can be considered an external strategy, and raising awareness of inland road routes is an internal strategy.

According to our models, the Jackknife test showed that the temperature of the wettest season of the year (Bio8) and average annual temperature (Bio1) were the most effective factors in predicting the model for *Ae. aegypti* and *Ae. albopictus*, respectively. *Aedes albopictus* shows greater adaptability to annual temperature differences. In a previous study, *Ae. albopictus* was shown to be more adaptable to wider temperature ranges than *Ae. aegypti*[27]. This explains why *Ae. albopictus* can grow in a wider geographical area in the north of Iran where the temperature is very different.

The small number of points from which *Ae. aegypti* and *Ae. albopictus* were caught in Iran was one of the limitations of our work for modelling. Our model can only roughly reflect the adaptability of *Ae. aegypti* and *Ae. albopictus* to environmental variables. To understand the specific impact of the environment on mosquito survival and reproduction in Iran, further research on the ecology of these two mosquito species is required.

Although there is still hope that *Ae. aegypti* and *Ae. albopictus* have not been established in Iran, the country is exposed to the attack of these two dangerous vectors. Predictive models give us good insight into the right places for the establishment of vectors of diseases. According to the model outputs obtained in this study, the relevant authorities should focus entomological monitoring on border cities, ports, and cities with international airport terminals in areas with high potential for the establishment of these two vectors. In case of the entry of these dangerous insects, necessary measures should be taken to eradicate them and prevent their establishment or transfer to other parts of the country. Due to the suitable climatic conditions of the southern, northern, and northwestern regions of Iran for the establishment of both vectors, the need for capacity building for the surveillance and control of vectors has a high priority.

Conflict of interest statement

The authors declare that there is no conflict of interest.

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Authors' contributions

MMS advised on the accuracy of the data on which the modelling is based, FBO and SH collected the data, MK advised the analysis method, AAHB conceptualized and designed the study, analysed the data, and drafted the manuscript. All authors discussed the results and implications and commented on the manuscript at all stages.

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