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RESEARCH

The potential effects of climate change on the climatic suitability patterns of the Western Asian vectors and parasites of cutaneous leishmaniasis in the mid- and late twenty-first century

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Abstract

Climate change alters the global distribution of leishmaniasis vector sandfly species. However, the possible effect of altering environmental factors on sandfly species varies by species and area. The aim of this study was to project the future potential effect of climate change on the Western Asian occurrence of the sandfly vector species *Phlebotomus papatasi* and *Phlebotomus sergenti* and the parasites *Leishmania major* and *Leishmania tropica* for 2041–2060 and 2081–2100 compared to their modelled climatic suitability patterns in the reference period 1970–2000. The model results suggest that by 2041–2060 and 2081–2100, in the coastal areas of the Levantine countries and the mid-elevation regions of Western Iran and Southeast Turkey, the climatic suitability of all the studied species is predicted to increase. In contrast, the model results suggest the decline of the populations of the studied vectors as well as the disappearance of the parasites in Iraq, North Saudi Arabia, Kuwait, and the inland regions of Western Asian countries. Considering the present-day population density patterns, it can be said that although in large regions of the region, the climatic suitability values are predicted to decrease, the populated Levantine regions seem to be at risk of climate change-facilitated increase in cutaneous leishmaniasis in the second half of the twenty-first century. The model results suggest that climate change will especially increase the climatic suitability of *Leishmania tropica* in the Levantine region in the late twenty-first century.

Keywords Semi-arid regions · Levant · Environmental constraints · Desertification · Parasitic diseases

1 Introduction

Phlebotomine sandflies are vectors of several arboviruses and *Leishmania* parasites, causing significant health outcomes in tropical and subtropical regions (Vivero et al. 2019). About 700 sandfly species have been recorded in the tropics, subtropics, and warmer temperate climate zones of the world (Ali et al. 2016). In West Eurasia and Africa, sandflies, including the members of the *Paraphlebotomus* and *Phlebotomus* subgenera, predominantly occupy the Mediterranean, hot semi-arid tropical, and savanna climatic areas. Over the females of 90 sandfly species can transmit *Leishmania* species, and 20 of them can serve as vectors of *Leishmania* parasites to humans (World Health Organization 2010). Leishmaniasis is considered one of the most important vector-borne parasitic diseases worldwide, in addition to malaria and lymphatic filariasis. About 350 million people are at risk of leishmaniasis infection (Alvar et al. 2012) in about 100 countries around the world (Aronson and Magill 2020). The worldwide prevalence of leishmaniasis is about 12 million (Okwor and Uzonna 2016). Most of the leishmaniasis cases occur in the Eastern Mediterranean and Southeast Asian WHO regions (Pigott et al. 2014). In Afro-Eurasia, *Leishmania* (*Leishmania*) *donovani* (Laveran et Mesnil, 1903) Ross, 1903, which parasite is responsible for visceral leishmaniasis or kala-azar form; *Leishmania* (*Leishmania*) *tropica* Wright, 1903, the cause

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of a generally non-ulcerating cutaneous disease (leishmaniasis recidivans; Gitari et al. 2018); *Leishmania* (*Leishmania*) *major* Yakimoff and Schokhor, 1914, the causative agent of zoonotic cutaneous leishmaniasis; and *Leishmania* (*Leishmania*) *aethiopica* Bray, Ashford and Bray, 1973, which is also associated with cutaneous leishmaniasis, have the greatest human epidemiological importance (World Health Organization 2010).

Climate change has several potential negative health consequences in the Eastern Mediterranean and Middle East that often reinforce each other, including air pollution caused by dust, heatwaves, water shortages, population displacement-caused physical and psychical disorders, and the increasing risk of infectious diseases (Neira et al. 2022). It is very likely that climate change will increase the risk of leishmaniasis in the Eastern Mediterranean Region (Paz et al. 2021; Arikan and Cakir 2023). The possible effect of climate change on leishmaniasis is complex. Climate change alters the annual seasonality of the sandfly vectors (Ready 2008), the availability of suitable habitats (Fischer et al. 2011), and the range of the host animals (Alemayehu and Alemayehu 2017), as well as human behavioral patterns and the probability of human-vector contacts (Salomón et al. 2012). Such sandfly-borne diseases as cutaneous leishmaniasis are typically mentioned as major health problems directly associated with the change (Daoudi et al. 2022). In this sense, the already documented and predicted increase in the annual daily temperature can be beneficial to vectors in many ways (Al- Al-Delaimy 2022). For example, several Eastern Mediterranean sandfly vectors exhibit their metabolic and ontogenetic growth rate peak at high (~28 °C) ambient temperatures (Rawson et al. 2023). It indicates that increased temperatures due to climate change will directly increase the number of annual generations of sandflies and their activity. The future elongation of the activity season of sandfly species is also predicted in the East Mediterranean area (Trájer 2021a, b, c). Furthermore, model simulations predict the future redistribution and the altitudinal upward shift of *L. infantum* and sandfly vector populations (Trájer 2021a, b; Zareichaghabaleki et al. 2019). As an indirect effect, climate change-caused increased aridity facilitates urbanization, migration, and the alteration of agricultural practices, which can also be advantageous for sandfly vectors and increase of the risk of the transmission of *Leishmania* parasites to humans (Knight et al. 2023).

However, future predictions show a heterogenous picture related to the future risk of leishmaniasis in Western Asia. For example, Amro et al. (2022) found that while the incidence of cutaneous leishmaniasis is predicted to increase in the northwestern regions of the West Bank in the Levant, until 2060, in the adjacent regions, the infection risk of this disease is predicted to be diminished. In Iran, predictions show that there will be more overlapping, suitable areas for the co-occurrence of vectors and reservoirs of zoonotic cutaneous leishmaniasis in Iran by 2050, compared to the current situation (Charrahy et al. 2022). It also indicates that the niche and, consequently, the potential ranges of the parasites and their vectors are not completely identical.

However, one of the most important potential impacts of climate change on sandfly-borne diseases is the changes in their worldwide climatic suitability, because this factor directly determines the range of vector-borne diseases (Semenza et al. 2022). The range of abundance of leishmaniasis is in a complex relation to the character of the niche of *Phlebotomus* and *Leishmania* species and the environmental circumstances of an area. For example, in Iraq, most cases occurred in highly populated regions with moderate annual rainfall (Al-Warid et al. 2019). Elevation is another significant explanatory variable in the range of leishmaniasis, which notably influences both climatic factors and human population densities. For example, in Iran, topographical conditions strongly influence the suitability patterns of the leishmaniasis vectors (Trájer 2021a). However, altitude is not an independent explanatory variable since there is a strong correlation between altitude and temperature, as well as precipitation in the lower part of the troposphere (Wang et al. 2011, 2018). In the Eastern Mediterranean WHO region, as the study of Amro et al. (2022) indirectly refers to, the crucial question related to the future range of leishmaniasis is the tolerance of sandfly vectors against the increasing temperatures and increasing drought risk.

An overview of the current distribution of sandflies and their known environmental needs can provide a basis for understanding possible future changes. It is known that several species of sandflies can tolerate the relatively dry and warm climatic conditions of the East Mediterranean region and North Africa. Abundant sandfly populations were found in the Israeli deserts (Wasserberg et al. 2003), on the dry volcanic island of Santorini (Tsirigotakis et al. 2018), as well as in the deserted southwestern part of Tunisia (Jaouadi et al. 2012). The adaptations of certain sandfly subgenera to relatively dry and hot conditions have a deep evolutionary background. Phylogenetic studies revealed that the speciation of the western Eurasian-North African sandfly genera could occur in the Neogene era under relatively dry, semi-arid, and hot summer subtropical climatic conditions (Cruaud et al. 2021). It is also plausible that the speciation of the present-day Mediterranean sandfly taxa happened during the dry and warm Messinian Crisis period, influencing substantially the present-day climatic requirements of the species (Trájer et al. 2021; Kasap et al. 2015). Sandflies also have notable environmental plasticity in the sense that several sandfly species were adapted to humans, mainly to peri-urban environments (Muñoz et al. 2018; Feliciangeli 2004). Sandflies, depending on species, can also be found in shelters in abandoned quarries in or near human settlements

(Chaniotis et al. 1994) and rodent burrows (Müller et al. 2011), as well as in the cracks of buildings (Muñoz et al. 2021). This breeding site plasticity, combined with the predominantly nocturnal-crepuscular activity habit of sandflies (Yared et al. 2015), makes it possible for them to survive both in anthropogenic environments and in hot and dry regions of the world. Because, as we have seen, the role of climatic conditions in the spread of sandflies is emphasized, it is understandable that climate change could significantly change the future occurrence of the leishmaniasis vectors and the diseases in West Asia (Chalghaf et al. 2018). However, the future possible climatic suitability patterns of *Phlebotomus* vectors and *Leishmania* parasites in specific regions require revealing the climatic values that determine the distribution of species on a regional level.

1.1 Aims

Several studies were performed to predict the future American and European climatic suitability patterns and ranges of leishmaniasis and its vectors due to climate change (e.g., Koch et al. 2017), but except for Iran (e.g., Abdolahnejad et al. 2021; Shiravand et al. 2019), relatively little attention has been paid to the countries of Western Asia in terms of predicting the future conditions of leishmaniasis. The aim of the study was to project the potential future climatic suitability patterns of two sandfly and parasite species for the second half of the twenty-first century, in particular in the Mesopotamian and Levantine regions.

2 Material and methods

2.1 The study area, relief, and climatic data

The present study focuses predominantly on the following countries: Israel and the Palestine Territories, Lebanon, Syria, Iraq, and Kuwait but also contains areas from, e.g., North Saudi Arabia, Western Iran, or Southeast Turkey in Western Asia (Fig. 1).

The relief data was based on the ETOPO Global Relief Model (Amante and Eakins 2009). The ETOPO1 Global Relief Model was developed by the National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA) of the United States. ETOPO1 is vertically referenced to sea level and horizontally referenced to the World Geodetic System of 1984 (WGS 84). Cell size for ETOPO1 is 1 arc-min.

Both the reference period and the future climatic data were taken from the WorldClim version 2.1 dataset (Fick and Hijmans 2017). The reference period was 1970–2000. This global climatic model has four spatial resolution resolutions (10, 5, and 2.5 arc-min and 30 s). The spatial resolution used was 2.5 arc-min. The dataset includes 19 "bioclimatic" variables explained in Table 1 in addition to monthly climate data for minimum, mean, and maximum temperatures, precipitation, solar radiation, wind speed, and water vapor pressure.

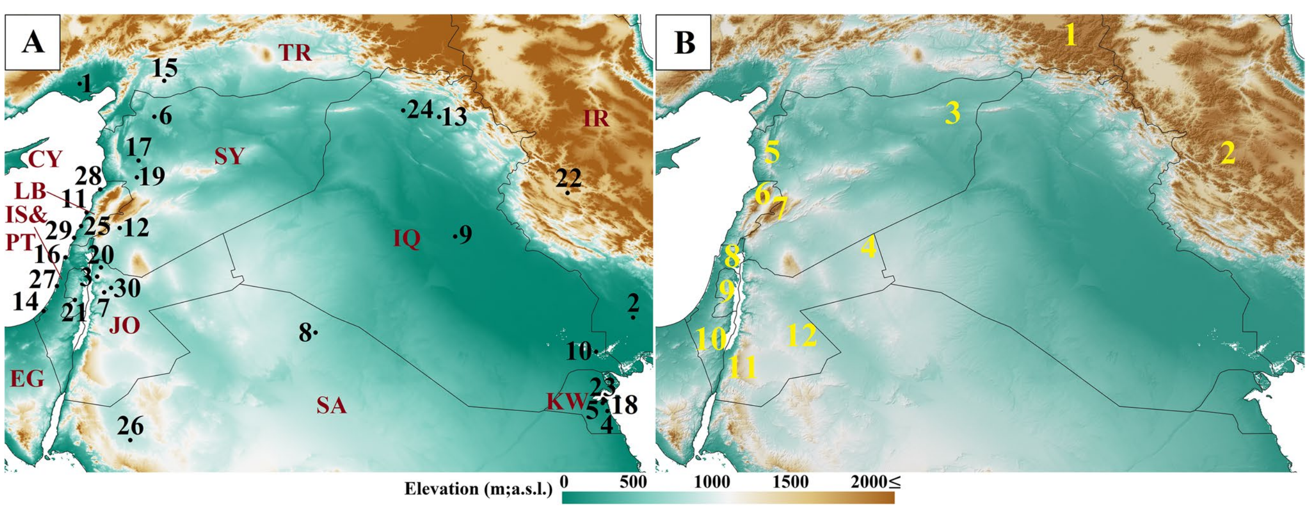

Fig. 1 A: The studied region with the major cities. CY: Cyprus, EG: Egypt, IR: Iran, IS&PT: Israel and the Palestine Territories, IQ: Iraq, JO: Jordan, KW: Kuwait, LB: Lebanon, SA: Saudi Arabia, SY: Syria, TR: Turkey. 1: Aadana, 2: Ahvaz, 3: Ajloun, 4: Al Ahmadi, 5: Al Farwaniyah, 6: Aleppo, 7: Amman, 8: Arar, 9: Baghdad, 10: Basrah, 11: Beirut, 12: Damascus, 13: Erbil, 14: Gaza City, 15: Gaziantep, 16: Haifa, 17: Hama, 18: Havalli, 19: Homs, 20: Irbid, 21: Jerusalem, 22: Kermanshah, 23: kuwait City, 24: Mosul, 25: Sidon, 26: Tabuk, 27: Tel-Aviv, 28: Tripoli, 29: Tyre, 30: Zarqa. B: The main geographical features in the studied region. 1: Taurus Mts., 2: Zagros Mts., 3. Al-Jazira, 4: Syrian Desert, 5: An-Nusayriyah Mts., 6: Mt. Lebanon, 7: Anti-Lebanon Mts., 8: Galil, 9: West Bank, 10: Negev Desert, 11: Jordanian Highlands, 12: Ard As Sawwan Desert, 13: Wadi Rum

Table 1 The selected bioclimatic indices used in modelling

Bioclimatic variable	Explanations	°C/mm
BIO 1	Annual mean temperature	°C
BIO 2	Mean diurnal range (mean monthly (max temperature – min temperature))	°C
BIO 3	Isothermality (BIO2/BIO7) (×100)	°C
BIO 4	Temperature seasonality (standard deviation × 100)	°C
BIO 5	Max temperature of warmest month	°C
BIO 6	Min temperature of coldest month	°C
BIO 7	Temperature annual range (BIO5–BIO6)	°C
BIO 8	Mean temperature of wettest quarter	°C
BIO 9	Mean temperature of driest quarter	°C
BIO 10	Mean temperature of warmest quarter	°C
BIO 11	Mean temperature of coldest quarter	°C
BIO 12	Annual precipitation	mm
BIO 13	Precipitation of wettest month	mm
BIO 14	Precipitation of driest month	mm
BIO 15	Precipitation seasonality (coefficient of variation)	mm
BIO 16	Precipitation of wettest quarter	mm
BIO 17	Precipitation of driest quarter	mm
BIO 18	Precipitation of warmest quarter	mm
BIO 19	Precipitation of coldest quarter	mm

The future potential climatic conditions were based on the downscaled global climate model (GCM) data from CMPI6 (IPCC Sixth Assessment Report; Stockhause et al. 2019). The predictions of the two Shared Socioeconomic Pathways (SSPs) were used in the modelling. The implemented global models were created in the Beijing Climate Center Climate System Model2 (BCC-CSM2-MR) global climate modelling environment. BCC-CSM2-MR is assessed for historical climate simulations from 1950 to 2014 that were carried out using the historical forcing recommended by CMIP6. This climate simulation effectively captures observed global warming patterns of surface air temperature (Wu et al. 2021). It contains the simulated values of the monthly minimum and maximum temperatures and the monthly precipitation values and the values of 19 bioclimatic values for four future periods (2021–2040, 2041–2060, 2061–2080, 2081–2100) and four SSPs (SSP1.26, 2.45, 3.70, 5.85) in four spatial resolutions (10, 5, and 2.5 arc-min and 30 s). For modelling purposes, the 2.5-min resolution versions of the SSP2.45 and SSP5.85 shared socioeconomic pathways-related future climatic models for the periods of 2041–2060 and 2081–2100 were selected and used.

The periods for all model simulations indicate that the results are to be understood as the average value of the given time lags (e.g., the mean simulated value of 2041–2060). The explanation of these bioclimatic values used in modelling can be seen in Table 1.

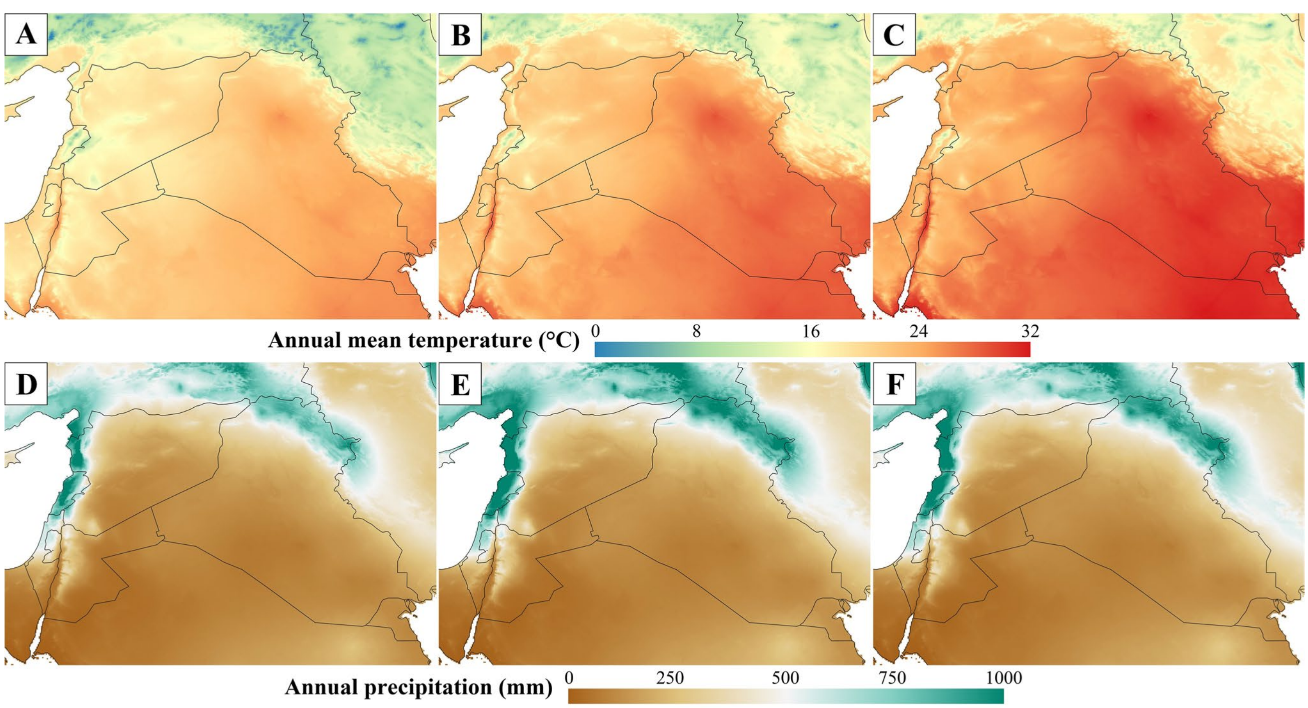

Fig. 2 The annual mean temperature and precipitation sum patterns in the Eastern Mediterranean Region averaged for the period 1970–2000 and the potential future patterns of the same climatic values in 2041–2060 and 2081–2100 based on the SSP5.85 shared socioeconomic pathway

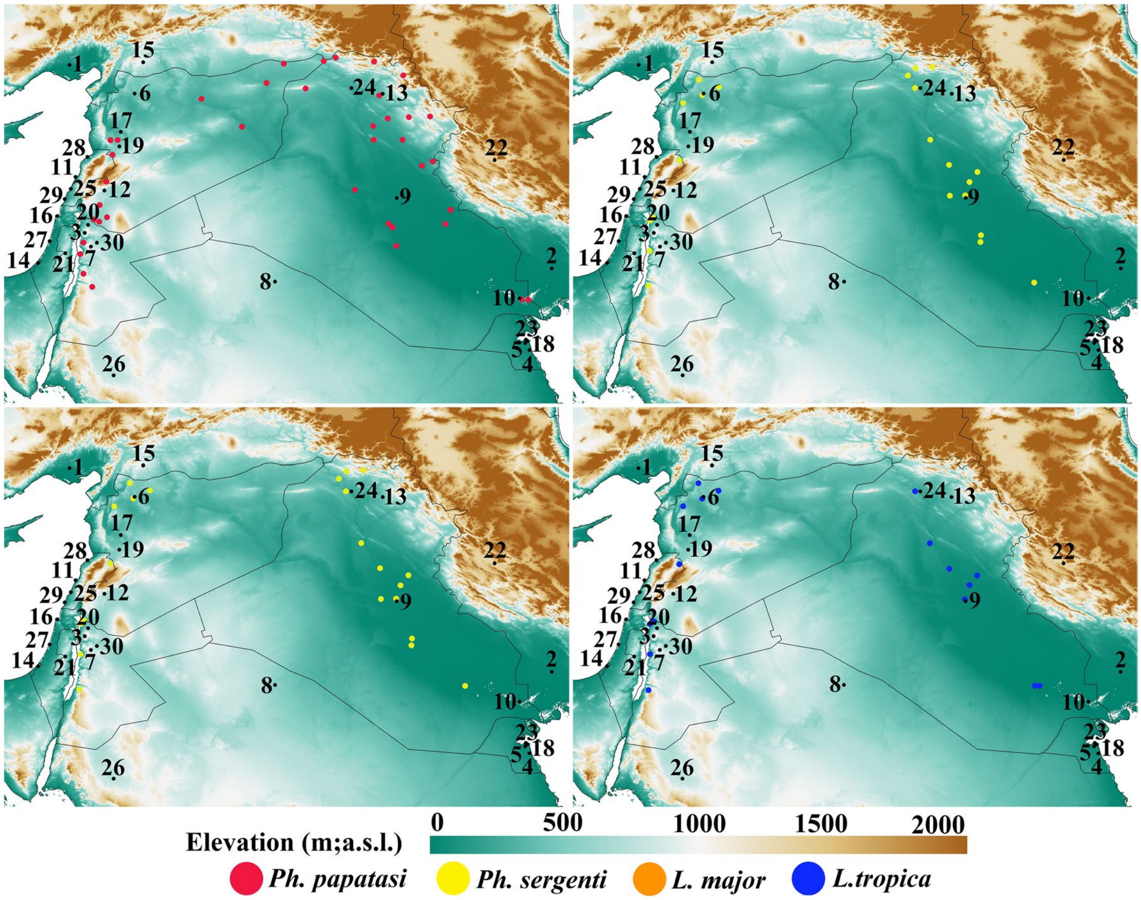

Fig. 3 The occurrence sites of the studied sandfly and parasite species. 1: Aadana, 2: Ahvaz, 3: Ajloun, 4: Al Ahmadi, 5: Al Farwaniyah, 6: Aleppo, 7: Amman, 8: Arar, 9: Baghdad, 10: Basrah, 11: Beirut, 12: Damascus, 13: Erbil, 14: Gaza City, 15: Gaziantep, 16: Haifa, 17: Hama, 18: Havalli, 19: Homs, 20: Irbid, 21: Jerusalem, 22: Kermanshah, 23: kuwait City, 24: Mosul, 25: Sidon, 26: Tabuk, 27: Tel-Aviv, 28: Tripoli, 29: Tyre, 30: Zarqa

The annual mean temperature and precipitation sum patterns in the Eastern Mediterranean Region in 1970–2000, 2041–2060, and 2081–2100 indicate that the annual precipitation sums are somewhat predicted to increase in the second half of the twenty-first century in the mountainous regions. However, this value will plausibly be about the same in the lowland territories. In contrast, the annual mean temperatures will notably increase for the second half of the twenty-first century, especially in the eastern part of the region (Fig. 2).

2.2 The studied species

To fill the existing scientific gap mentioned above, the climatic suitability patterns of the sandfly vectors *Phlebotomus (Phlebotomus) papatasi* (Scopoli, 1786); *Phlebotomus (Paraphlebotomus) sergenti* Parrot, 1917; and the parasite species *L. major* and *L. tropica* were modelled. *Phlebotomus papatasi* is the natural vector of *L. major* (Yaghoobi-Ershadi et al. 2005; Schlein and Jacobson 1999). *Phlebotomus sergenti* is the vector of *L. tropica* (Kamhawi et al. 2000; Svobodová et al. 2003). The occurrence sites of the species were based on the study of Al-Salem et al. (2016). Leishmaniasis occurrences represent the presence of the parasites in 1958–2003 (Pigott et al. 2014). The original dataset obtained by Al-Salem et al. (2016) can be downloaded at Pigott et al. (2015). The range of the vectors was based on the World Health Organization (2015), which represents the recent occurrence of the vectors. The number of occurrence sites was as follows: *Ph. papatasi* ($n=37$ sites), *Ph. sergenti* ($n=21$ sites), *L. major* ($n=19$ sites), and *L. tropica* ($n=17$ sites). The occurrence data were collected in Jordan, Lebanon, Israel, Palestinian territories, and Syria (Fig. 3).

2.3 Modelling of climate suitability patterns

Model results were displayed by Quantum GIS 3.4.4. The Lambert Azimuthal Equal Area (EPSG:3035) was used as a projection system. The steps of the modelling are as follows:

1) The occurrence sites of the two studied sandflies and the two *Leishmania* species were georeferenced based on Al-Salem et al. (2016).

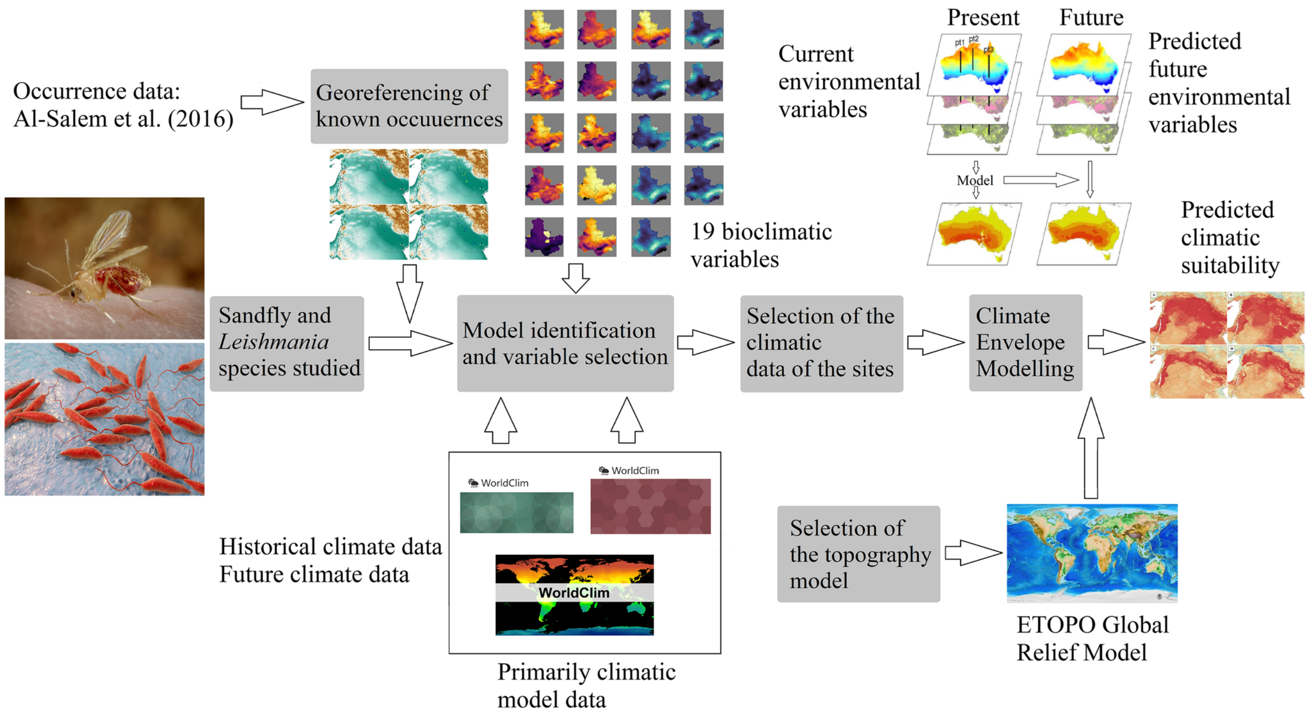

Fig. 4 Illustration of the workflow of climate suitability modelling

2) The 19 bioclimatic layers were sampled by the georeferenced occurrence sites for sandfly and parasite species and climatic ($n = 19$) variables.
3) The minimum and maximum values related to species-bioclimatic variable pairs were determined as the explanation for the climatic extrema of the climatic suitability patterns. This means 38 (2×19) factors in the model in the case of all species.
4) For the modelling of the potential climatic suitability patterns of the studied 2–2 *Phlebotomus* and *Leishmania* species, the above-described extrema of climatic factors were used.
5) In order to show the topographical conditions, the relief representation of the ETOPO global relief model was combined with the model results as an overlay with a visual transparency of 26%.

Figure 4 shows the workflow illustration of modelling.

There is a distribution function within the value range determined by the two distribution-limiting extrema. It shows the distribution maximum for the given climatic factor; however, in the utilized approach, the distribution of the internal is neglected. In other words, the model uses the lower and upper extrema within the range of optimum, but it does not consider the run of the ecological tolerance curve of the species related to a climatic value. Due to this reason, the appearance (presence or absence status) of a species is characterized by true or false (0; 1) values. This approach is equivalent to the logic of Boolean algebra. Boolean algebra is the logical basement of the Multidimensional or Climatic Envelope Modelling Procedure (MDE/CEM) family (Pertierra et al. 2017). This method estimates the climatic suitability values of species regarding their recorded presences (Busby 1991). In this process, a Boolean map of risk zones is created using the climatic hypervolume contained by the minimum and maximum values of climatic variables within the native range of the studied species (Aragon et al. 2010). It should be noted that the studied area of the Middle East makes up only a part of the studied species; the equations can only be displayed for the same region.

Using bioclimatic factors, deterministic unit-step functions can be written in the following general form:

$$1(\mathrm{bio_n}) = \begin{cases} 0 \text{ if } \mathrm{bio_{n\_limit\_min}} > \mathrm{bio_n} \text{ and } \mathrm{bio_n} > \mathrm{bio_{n\_limit\_max}} \\ 1 \text{ if } \mathrm{bio_{n\_limit\_min}} \leq \mathrm{bio_n} \text{ and } \mathrm{bio_n} \leq \mathrm{bio_{n\_limit\_max}} \end{cases}$$

where bio_n represents the n^{th} bioclimatic value, and $bio_{n\_limit.min}$ and $bio_{n\_limit.max}$ are the lower limitation factors (upper and lower extrema) of the given species. As can be seen, the limitation factor values are climate

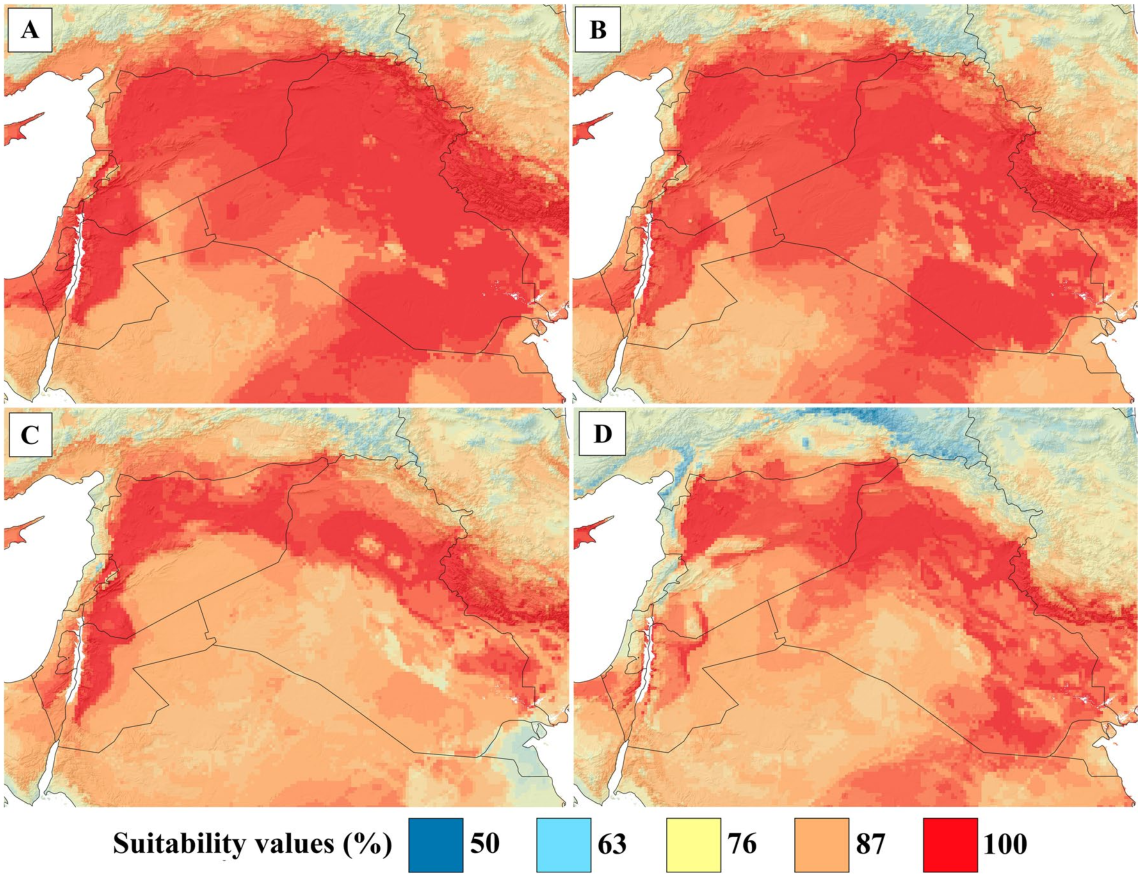

Fig. 5 The potential climatic suitability patterns of *Ph. papatasi* (**A**), *Ph. sergenti* (**B**), *L. major* (**C**), and *L. tropica* (**D**) based on the mean climatic values of 1970–2000

model-independent, and the factors are also independent of each other.

The areas excluded by the minimum and maximum values of the distribution-limiting 19 bioclimatic factors (see Table 1) must be summed by sandfly and *Leishmania* species, and the intersection of the potential area designated by the three factors gives the aggregated distribution area, formally:

$$A\left(bio_{min,max}\right) = bio_{min} - \sum_{i=1}^{19} 0(bio_{min}) \bigcap bio_{max} - \sum_{i=1}^{19} 0\left(bio_{max}\right)$$

where $A(bio_{min,max})$ represents the potential distribution area of the sandfly or *Leishmania* species, which contains the remaining areas after taking into consideration the temperature and precipitation limitations. In the case of each sandfly and *Leishmania* distribution model, the individual presence-absence maps were summarized by adding the 0–1 values of the individual model map results at each point (38 individual maps per model). Due to this, the result values can vary between 0 and 38 at a given site. To enhance clarity, the number of satisfied climatic extremes at a site was converted to percentage values ranging from 0 to 100%. Throughout the remainder of the text, these values will be referred to as climatic suitability values. When presenting the results, the color bar was adjusted to reflect the suitability interval of 50 to 100%, as values below 50% were not observed in the model results.

Supplementary tables 1–4 show the determined and used climatic extrema in modelling.

3 Results

3.1 Modelled values for 1970–2000

The common characteristic of the reference period's models is that the extension of the high-potential climatic suitability value regions of the vectors is notably larger than the similar area of the parasites. While regions with high climatic suitability values (89% <) also cover large regions in Upper Mesopotamia (e.g., in Al-Jazira) and even in the semi-desert regions of Syria, Jordan, Iraq, and Israel in the case of the vectors (Fig. 5A, B), the high climatic suitability

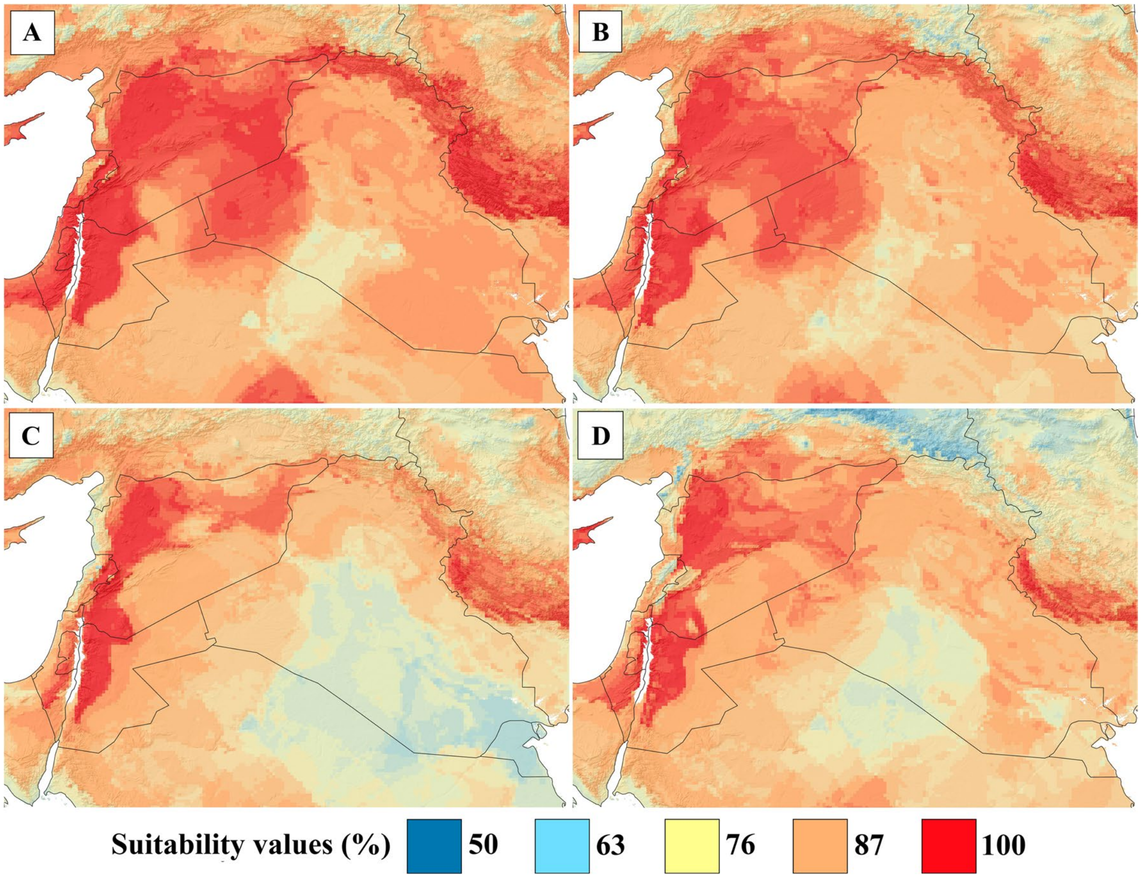

Fig. 6 The potential future climatic suitability patterns of *Ph. papatasi* (**A**), *Ph. sergenti* (**B**), *L. major* (**C**), and *L. tropica* (**D**) for 2041–2060 according to the SSP 245 scenario of the climate models

value regions of the parasites are rather restricted to the line of the fertile crescent (Fig. 5C, D). The models indicate the potential occurrence of the studied species in lowland areas generally and in some mid-elevation regions in western Iran. In general, Northern and Western Syria, Northeast and East Iraq, and Western Jordan seem to be the most seriously affected regions related to *L. major*-caused zoonotic cutaneous leishmaniasis and *L. tropica*-associated non-ulcerating cutaneous leishmaniasis.

The modelled climatic suitability values for West Asian cities can be seen in Supplementary table 5.

3.2 Modelled values for 2041–2060

The SSP 245 and SSP 585 scenario-based models suggest similar future climatic suitability patterns by species. The models predict high (89–100%) future climatic suitability values for *Ph. papatasi* and *Ph. sergenti* in the southern foothills of the Taurus Mts. in Southeast Turkey and in the southwest foothills of the Zagros Mts. in Southwest Iran in 2041–2060 (Figs. 6A, B and 7A, B). Also, high (89–100%) modelled climatic suitability values can be seen in the West and in the case of *Ph. papatasi* in Northeast Syria. In this country, the lowest (68–79%) values can be seen in the driest parts of the Syrian Desert and the high-elevation regions of the An-Nusayriyah Mts. and the Anti-Lebanon Mts. In Lebanon, high (89% ≤) values can only be seen in the coastal regions, while in Mount Lebanon, the modelled suitability values are 68–71%. In Jordan, the predicted suitability values are high (89–100%) in all species for the Jordan Highlands, but relatively low (71–79%) values can be seen in the Syrian Desert part of the country, in the Ard As Sawwan Desert, and in the area of Wadi Rum. In the case of Israel and the Palestine Territories, high (89% ≤) modelled climatic suitability values are predicted for 2041–2060, e.g., in the West Bank and Galil, but lower values in the South Negev (76–79%). In addition, *L. major* exhibits relatively low (76–79%) values along the Mediterranean coasts of the Levant. In Iraq, the highest (89–100%) climatic suitability values can be seen in the western parts of the country. In Kuwait and in Northern Saudi Arabia, the modelled suitability values are lower than 84% in general, and in the case of *L. major* and *L. tropica*, the modelled values can be as low as 53–58%. It can be concluded that similar modelled

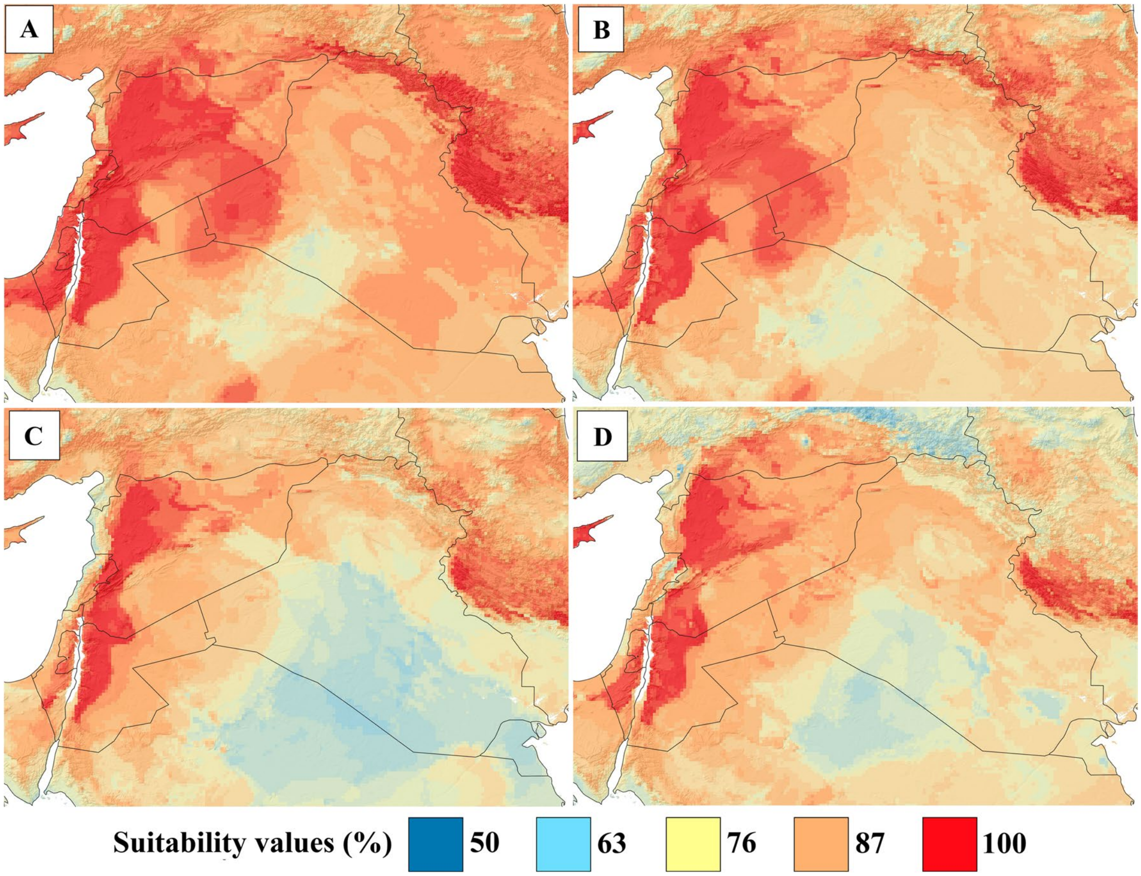

Fig. 7 The potential future climatic suitability patterns of *Ph. papatasi* (**A**), *Ph. sergenti* (**B**), *L. major* (**C**), and *L. tropica* (**D**) for 2041–2060 according to the SSP 585 scenario of the climate models

suitability patterns can be seen in the case of the studied *Phlebotomus* and *Leishmania* parasites, but the potential high suitability pattern area of this *Leishmania* species is narrower in each country, and the southern foothills of the Taurus Mts. and West Iraq do not belong to the potential range of the parasites based on the relatively low (89% >) values (Figs. 6C, D and 7C, D).

Both the SSP 245 and SSP 585 scenario-based distribution models predict a decrease in the climatic suitability values of the studied species in the present-day arid lowland regions of the studied part of Western Asia. The degree of magnitude of the decrease can reach − 15 to − 21%. The models suggest that the sandfly vectors will lose their occurrences in almost the entire area of Iraq and certain regions of Syria (Figs. 8A , B and 9A, B). These negative changes in the climatic habitability of the areas are more marked in the case of the parasites than their vectors, although the geographical trend patterns are very similar. Also, increasing future climatic suitability values can be seen in Northern Saudi Arabia, in Northwest Syria, and in the Mesopotamian parts of Iran, Turkey, and Kuwait. The climatic suitability values do not exhibit notable alterations (range, 2 to − 4%) in all species considering the mid-elevation regions of the Levant, Southeast Turkey, and Western Iran. In contrast, a general increase (11–17%) in the climatic suitability values can be seen in the case of *L. tropica* in the Levant, but it does not seem to be notable in the case of *L. major* (Figs. 8C, D and 9C, D). It should be noted that 18–21% increases in suitability values are predicted in the highest regions of the Levant in the case of all sandfly and parasite species. The modelled climatic suitability values for West Asian cities can be seen in Supplementary table 5.

3.3 Modelled values for 2081–2100

The modelled future climatic suitability values for 2081–2100 show a somewhat more notable contraction of the Western Asian decrease of the studied sandfly species compared to the mid-twenty-first century model results (Figs. 10A, B; 11A, B). For the vectors, the western mountain ranges of the Zagros Mts. and the western, but not the coastal areas of the Levantine countries seem to be suitable in the future, as these ranges exhibit 89–100% values. The modelled climatic suitability values of the parasites indicate

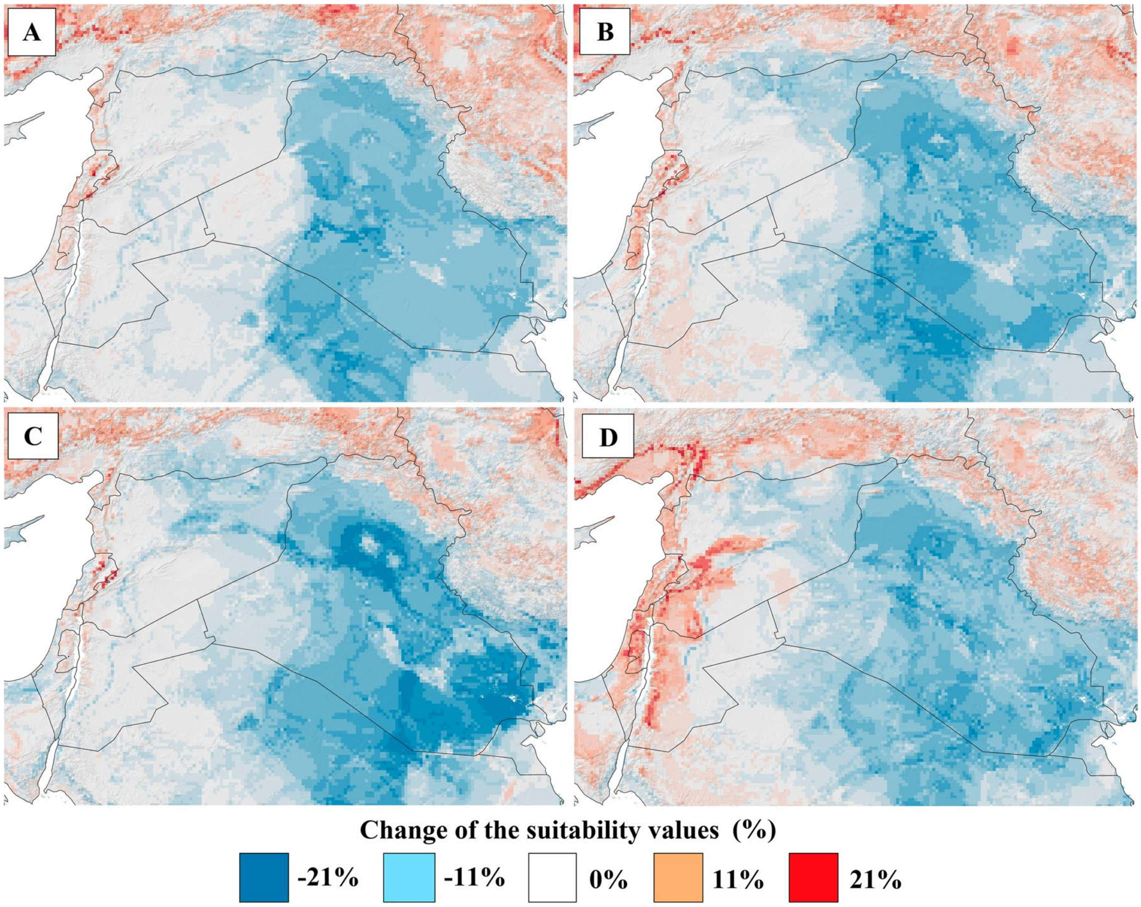

Fig. 8 The changing potential future (2041–2060) climatic suitability values of *Ph. papatasi* (**A**), *Ph. sergenti* (**B**), *L. major* (**C**), and *L. tropica* (**D**) according to the SSP 245 scenario compared to the modelled values for 1970–2000

somewhat narrower potential future ranges on the basis of the relatively small extent of the areas showing high climatic suitability values in Western Iran, where they are restricted to the southwest ranges of the Zagros Mts. (Figs. 10C, D; 11C, D). It is very plausible that cutaneous leishmaniasis will disappear in North Saudi Arabia, Kuwait, and Iraq in 2081–2100.

The level and direction of the modelled climatic suitability values of the two sandfly species suggest that the vectors of cutaneous leishmaniasis will almost totally disappear from Iraq from 2080 to 2100 (Figs. 12A, B and 13A, B). Only the higher-elevation mountainous regions of the Northern Iraqi area and certain Western Iraqi regions around Ar-Rutbah in western Al Anbar province will be suitable for the species. The two studied leishmania parasites are also predicted to totally disappear from Iraq. Similar trends are predicted in North Saudi Arabia, Kuwait, Northeast Syria, and the Mesopotamian areas of Turkey and Iran. In contrast, milder or marked increases (17% ≤) in the climatic suitability values are predicted in the mid- and even in the higher-elevation areas of Southeast Turkey, Western Iran, and the Levant, which show the highest increasing trend (19–21%) in the case of *L. tropica*. Similar change in climatic suitability patterns cannot be seen in the case of *L. major* (Figs. 12C, D and 13C, D). The models predict the isolation of the Levantine and Western Iranian sandfly and parasite populations in the case of all species. The modelled climatic suitability values for West Asian cities can be seen in Supplementary table 5. Figures 10 and 11 show the changing climatic suitability values in 2081–2100 compared to the modelled values of the reference period 1970–2000.

4 Discussion

An interesting outcome of the present study is that climate change may have a heterogeneous effect on sandflies depending on area and species. It is a relatively general observation that the range and the climatically suitable areas of the potential vectors are greater than those of parasites. It can be seen clearly, e.g., in the comparison of the range of the potential vectors of human leishmaniasis and the

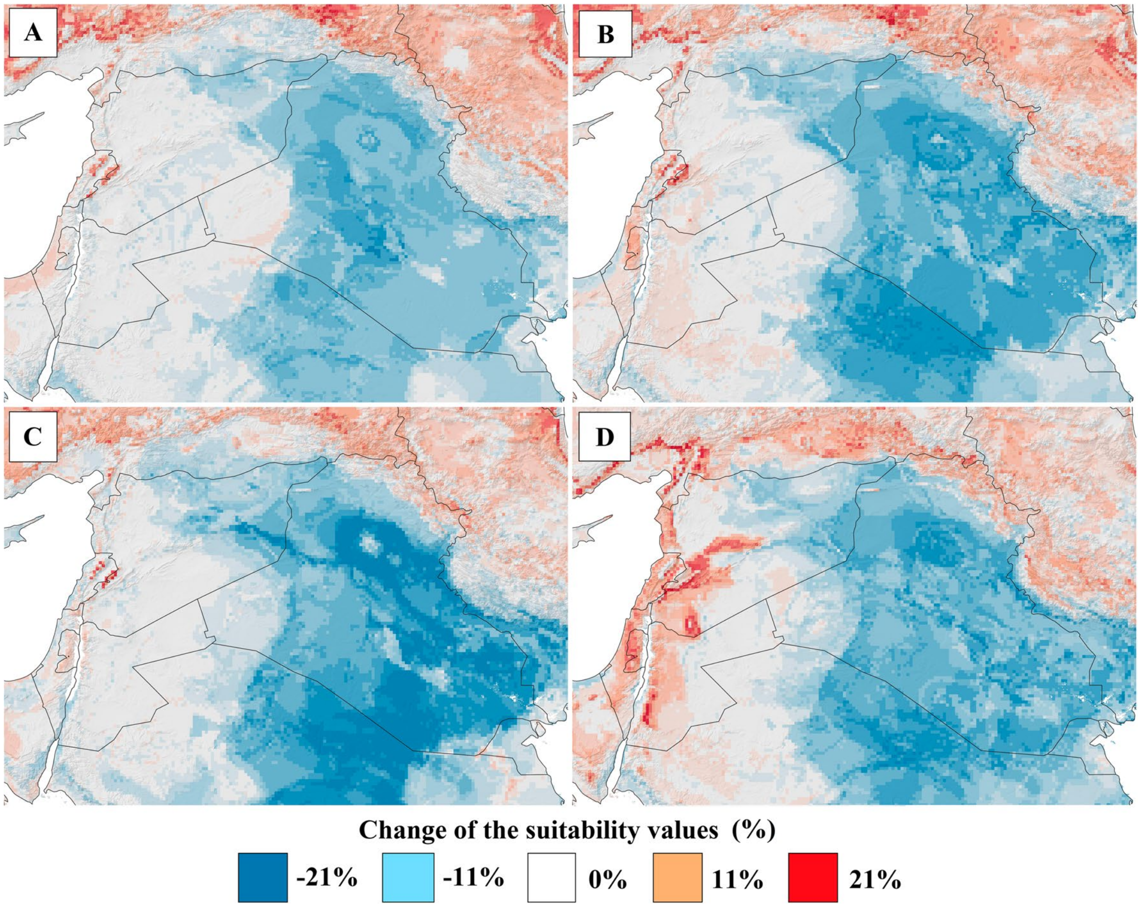

Fig. 9 The changing potential future (2041–2060) climatic suitability values of *Ph. papatasi* (**A**), *Ph. sergenti* (**B**), *L. major* (**C**), and *L. tropica* (**D**) according to the SSP 585 scenario compared to the modelled values for 1970–2000

disease-endemic regions in the Mediterranean (Alkan et al. 2013; Dujardin et al. 2008). The picture emerging from the model hints at the general belief that climate change may generally have a beneficial effect on the occurrence of sandfly species and leishmaniasis. Rather, it can be assumed that the nature of the expected impacts depends on the present-future climatic zone in the area. For example, in the temperate and mild winter climate areas of Europe, the models predict the general spread of the vectors and the parasites (Trájer et al. 2013; Koch et al. 2017). In contrast, at the border of the hot desert climate (Köppen–Geiger *BWh* climate) and hot-summer Mediterranean climate (Köppen–Geiger *Csa* climate) climates, in the hot semi-arid climate climatic zone (Köppen–Geiger *BSh* climate; Kottek et al. 2006), the predictable future climatic alterations can have a negative effect on sandfly distribution. Predictions of the future Köppen–Geiger climatic zones suggest the notable expansion of the hot desert climatic zone in the inland areas of Western Asia (Beck et al. 2018), which can be disadvantageous for both sandflies and the blood host animals.

In this respect, the local tempering effect of larger rivers, including the increased air humidity and soil moisture of the riverbanks, on the occurrence of leishmaniasis forms such as the Tiger and the Euphrates, is questionable. It should be noted, however, that in the desert country of Egypt, even though the Nile crosses the country, there is no positive effect on the spread of, e.g., cutaneous leishmaniasis, which, anyway, occurs in the relatively dry and hot regions of North Libya, Tunisia, North Algeria, and Morocco (Aoun and Bouratbine 2014). In contrast, it is known that the riverbed of the wadies, which contains water only when heavy rain occurs, provides appropriate environments for such sandflies as *Ph. papatasi* and *Ph. similis* in arid environments like the deserted landscape of Southern Sinai (Kassem et al. 2012), the wider region of Aqaba in Jordan (Kamhawi et al. 1995), or the Israeli deserts (Wasserberg et al. 2003). The effect of topographic factors on sandfly occurrence is difficult to estimate and cannot be described simply by altitude as a variable. At the local level, the nature of the relief, the type of bedrock, and shading may play a role in the local occurrence of sandflies (Trájer et al. 2018). However, it should be

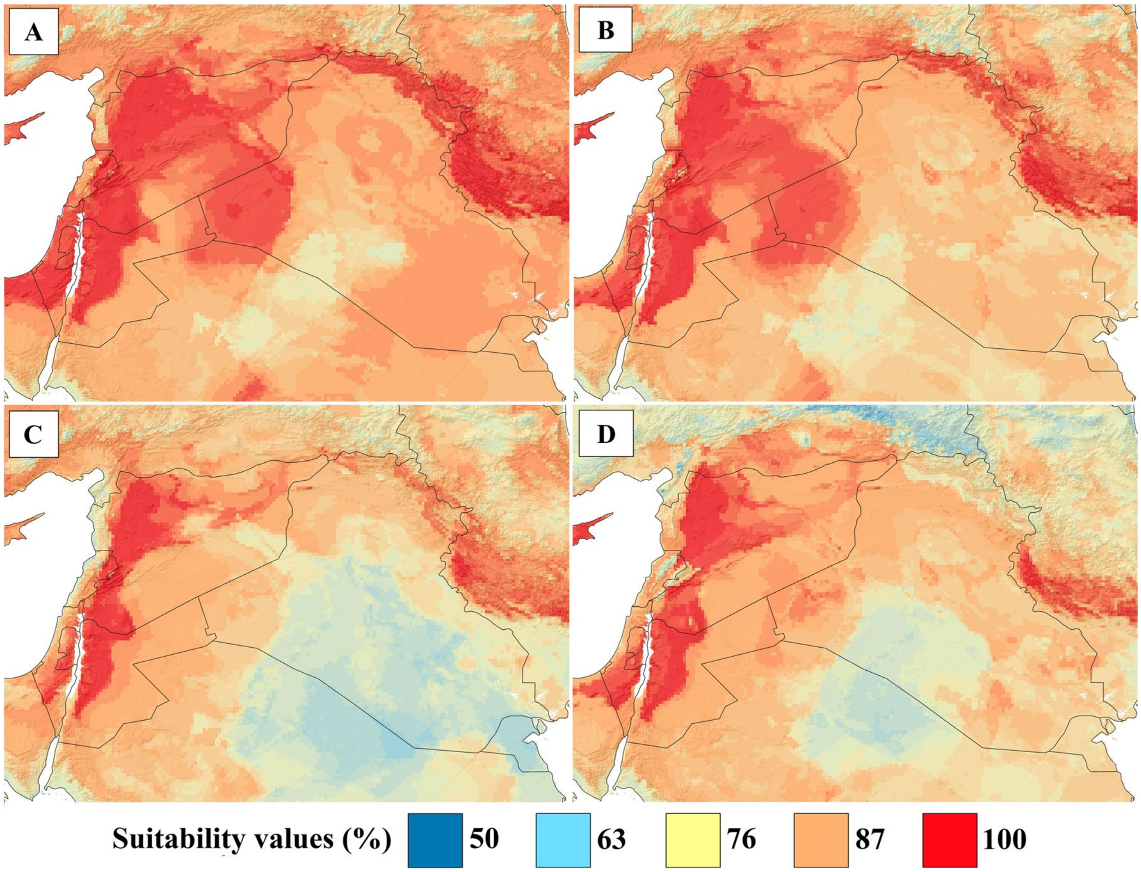

Fig. 10 The potential future climatic suitability patterns of *Ph. papatasi* (**A**), *Ph. sergenti* (**B**), *L. major* (**C**), and *L. tropica* (**D**) for 2081–2100 according to the SSP 245 scenario of the climate models

noted that the impact of these factors on large-scale prevalence may not be significant.

At the end of the twenty-first century, climate projections exhibit a strong warming trend over the whole Western Asian region, especially in the summer season (Bucchignani et al. 2018). Even in the Mediterranean coastline part of the region, in the Levant, the summer mean temperature can increase by 3.5–4.0 °C increase, and in the inner regions, the warming can overwhelm the 5.0–6.0 °C values in this season (Planton et al. 2012). This projected change could cause severe climatic stress for sandfly populations that already live in areas with hot climates, such as the central and southern parts of Mesopotamia, where the average summer temperature reaches 34–39 °C (e.g., in Baghdad and Basra; Trouet and Van Oldenborgh 2013). As was mentioned, sandfly species can tolerate the climate of dry and hot regions. For example, *Ph. sergenti* occurs in the Judean desert (Moncaz et al. 2012), where *L. tropica* co-occurs with their natural vector (Schnur et al. 2004), where the annual temperature is about 100–200 mm and the average high temperature in July reaches or exceeds the 38–39 °C value (Porat et al. 2010; Trouet and Van Oldenborgh 2013). In these kinds of arid and hot environments, *Ph. sergenti* rests and breeds inside caves, in smaller, concealed cracks in the rocky ledges, and sometimes in man-made support walls constructed with large boulders (Moncaz et al. 2012).

It is known that the temperature of the upper layer of the lithosphere heats up and cools relatively slowly relative to the air, and therefore, the daily mean temperature in the more closed caves with neither expressed airflow nor expressed airflow and ventilation differs only slightly from the average annual ambient temperature of the site in general (De Freitas and Littlejohn 1987). For comparison, on the Judean Desert plateau, the annual mean temperature is 21 °C (Porat et al. 2010). The tempered conditions in the caves can provide a mild environment during the hottest parts of the day for sandflies. On the other hand, Mediterranean sandflies are active at relatively high ambient temperatures and low relative humidity values. For example, a Greek study revealed that, e.g., *Ph. papatasi* is active in the thermal and air humidity intervals of 24–29 °C and 40–60%; these values in the case of *Ph. similis* are 24–30 °C and 30–60% (Tsirigotakis et al. 2018). These facts shed light on the fact that by resting the hottest part of the day of the summer months in

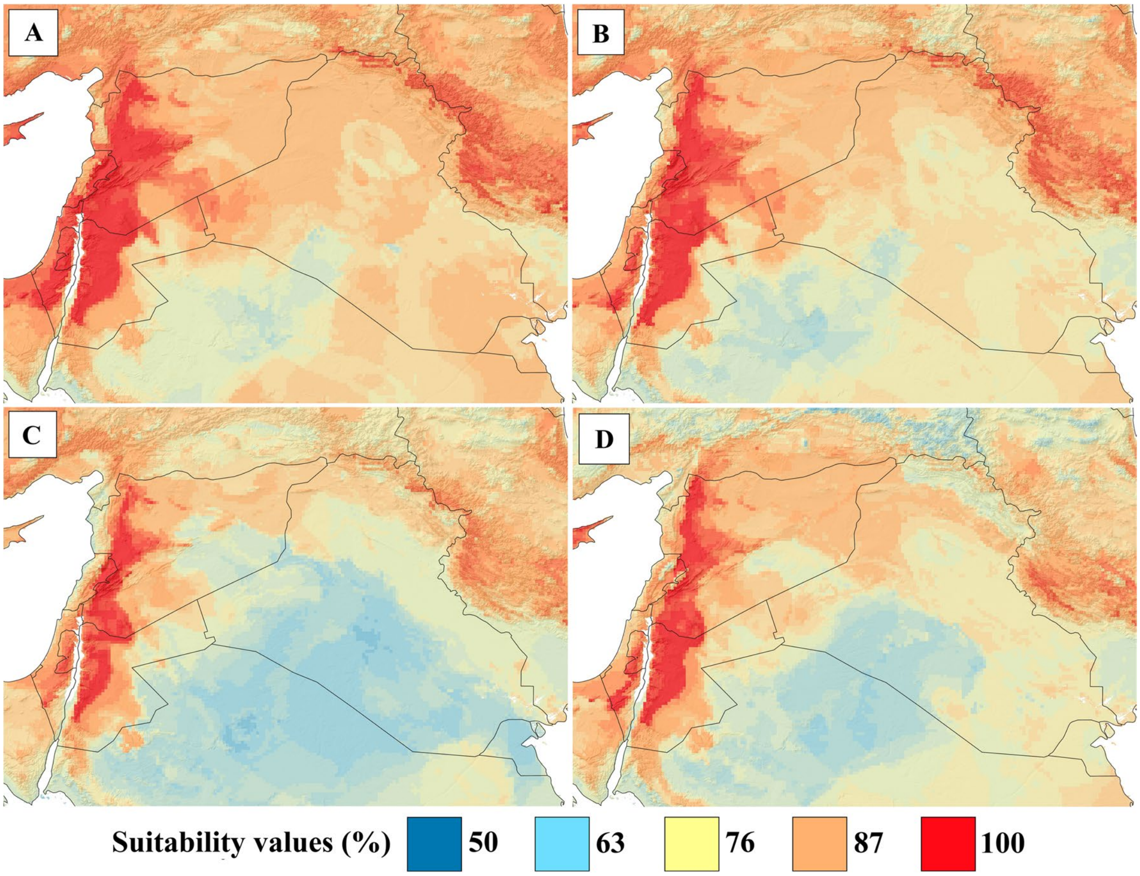

Fig. 11 The potential future climatic suitability patterns of *Ph. papatasi* (**A**), *Ph. sergenti* (**B**), *L. major* (**C**), and *L. tropica* (**D**) for 2081–2100 according to the SSP 585 scenario of the climate models

cool and wet shelter places, sandfly species can colonize both dry and hot areas, but this also has its limits.

Another part of the limitation is associated with the occurrence of potential-blood meal-providing mammals. For example*, Ph. similis* individuals co-occur in their shelters with rock hyraxes in the Judean desert (Svobodová et al. 2006). Rock hyrax (*Procavia capensis* Pallas, 1766) has a wide distribution range that covers large areas of the semi-arid and semi-arid regions of Africa, the Levant, and mainly the western and southern coastal areas of the Arabian Peninsula. The rock hyrax is, of course, just one example of a host animal, but it points out that the ecological needs of these animals in the distribution of vector sandflies should also be examined in future studies. *Phlebotomus papatasi* can also be used as breeding sites for rodent burrows, but domestic bird nests and stables can also serve as shelters (Yaghoobi-Ershadi et al. 2005). In a sandfly collection study that was performed in Algeria, most of the *Ph. sergenti* individuals were caught in the vicinity of Mzab gundi (*Massoutiera mzabi* (Lataste, 1881))'s burrows, showing that both studied sandfly species can take advantage of the microclimatic benefits of rodent burrows in hot arid and semi-arid areas. Although this muddling study does not contain a host element, it can be hypothesized that determined distribution-limiting extrema also include this element of the habitability of an area related to sandfly and parasite species.

Although several studies showed a correlation between altitude and sandfly occurrence (e.g., Ranganathan and Swaminathan 2015; Tsirigotakis et al. 2018), the authors of the present study do not consider this to be a factor to be considered independently under changing climatic conditions. The reason for this decision was that the thermal conditions show a direct correlation with the elevation, which in meteorological and climatological sciences are denoted as the lapse rate. In other words, there is a negative linear correlation between altitude and temperature in the troposphere (Stone and Carlson 1979). However, elevation and annual precipitation also show a characteristic correlation, which in the lower part of the troposphere shows a positive trend along with the increasing elevation (Webb et al. 2003; Suzuki et al. 2011). On the other hand, in the lower part of the troposphere, an increase in altitude will not lead to a significant decrease

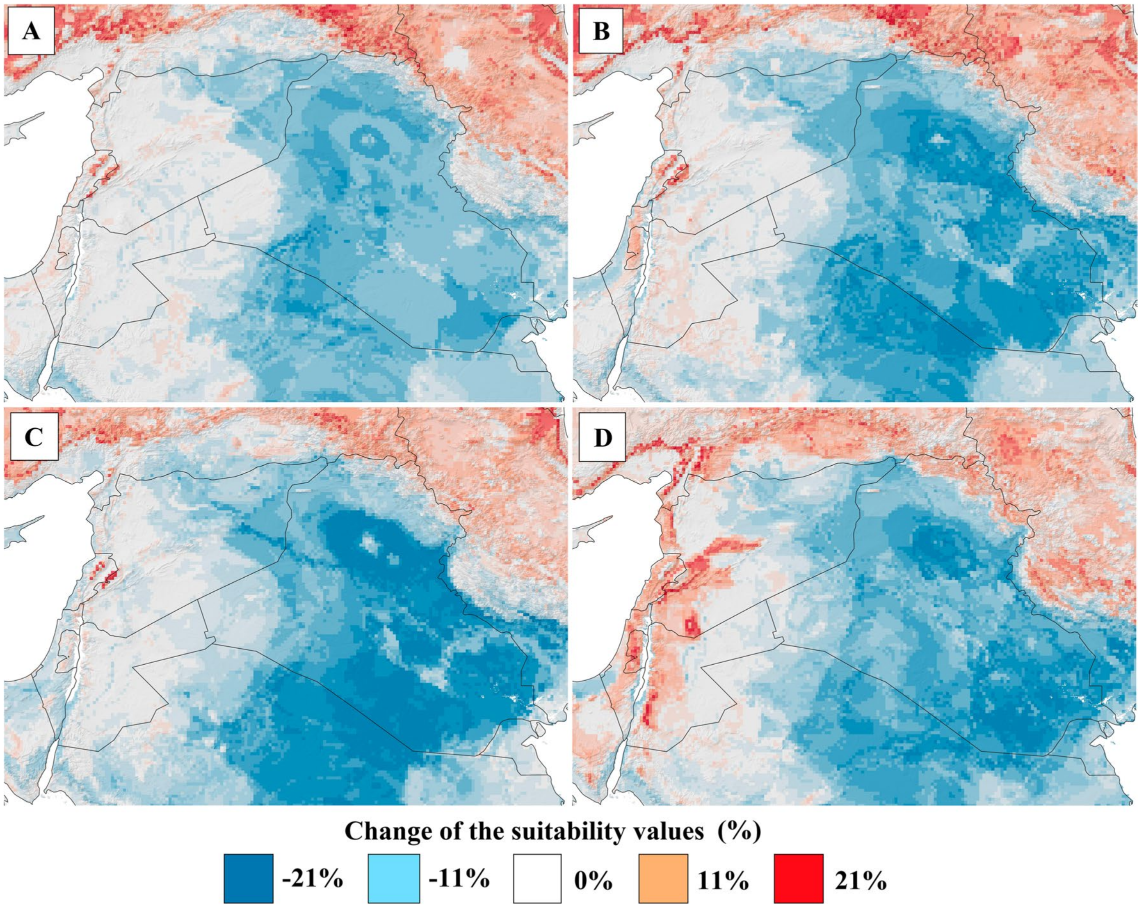

Fig. 12 The changing potential future (2081–2100) climatic suitability values of *Ph. papatasi* (**A**), *Ph. sergenti* (**B**), *L. major* (**C**), and *L. tropica* (**D**) according to the SSP 245 scenario compared to the modelled values for 1970–2000

in air pressure or a significant increase in global radiation. It should also be noted that sandfly populations generally occur in low-altitude areas in the wider Mediterranean area (including North Africa, the Mediterranean coastlines and islands, the Levant, and Mesopotamia), so the effect of the aforementioned factors on Phlebotomine sandfly populations is unknown. For example, all *Ph. papatasi* and *Ph. sergenti* individuals in the Palestinian West Bank were found under 500 m a.s.l. (Sawalha et al. 2003), and in the Aegean Archipelago, no sandflies were captured above 600 m a.s.l. (Tsirigotakis et al. 2018).

Although the role of natural factors in the determination of the distribution area of leishmaniasis is indisputable, human factors can substantially influence the incidence and spread of leishmaniasis. This is also the theoretical limit of the creation of forecasting models, as the human factor is almost unpredictable for the future. Anthroponotic effects influence in several ways the present and the possible future distribution of leishmaniasis. Changing spatial–temporal patterns of leishmaniasis are associated with the occurrence of armored conflicts and the consequent migration pulses, other anthroponotic environmental changes like changes in agricultural practices, urbanization (landcover in general; Colacicco-Mayhugh et al. 2010), and global climatic alterations (Ready 2008). The recent conflicts in West Asia sometimes made hard or impossible the utilization of epidemiological interventions related to leishmaniasis in the last two decades in several regions (Jacobson 2011). It can be stated that the conflicts and the rapid urbanization together, unfortunately, perpetuate poverty, malnutrition, poor housing, and domestic sanitary conditions, which are the major socioeconomic risk factors of leishmaniasis (Nweze et al. 2020). Population movements from the conflict zones could trigger the spread of the disease in the host countries, highlighting the role of a low level of hygiene in the refugee camps in the re-emergence and outbreak of leishmaniasis (Du et al. 2016). For example, the Lebanese outbreak of leishmaniasis could be linked to the migration of Syrian citizens escaping from the war zones (Alawieh et al. 2014). It was not limited to Lebanon, but cutaneous leishmaniasis crises were observed almost in all surrounding countries that are adjacent to Syria (Al-Salem et al. 2016).

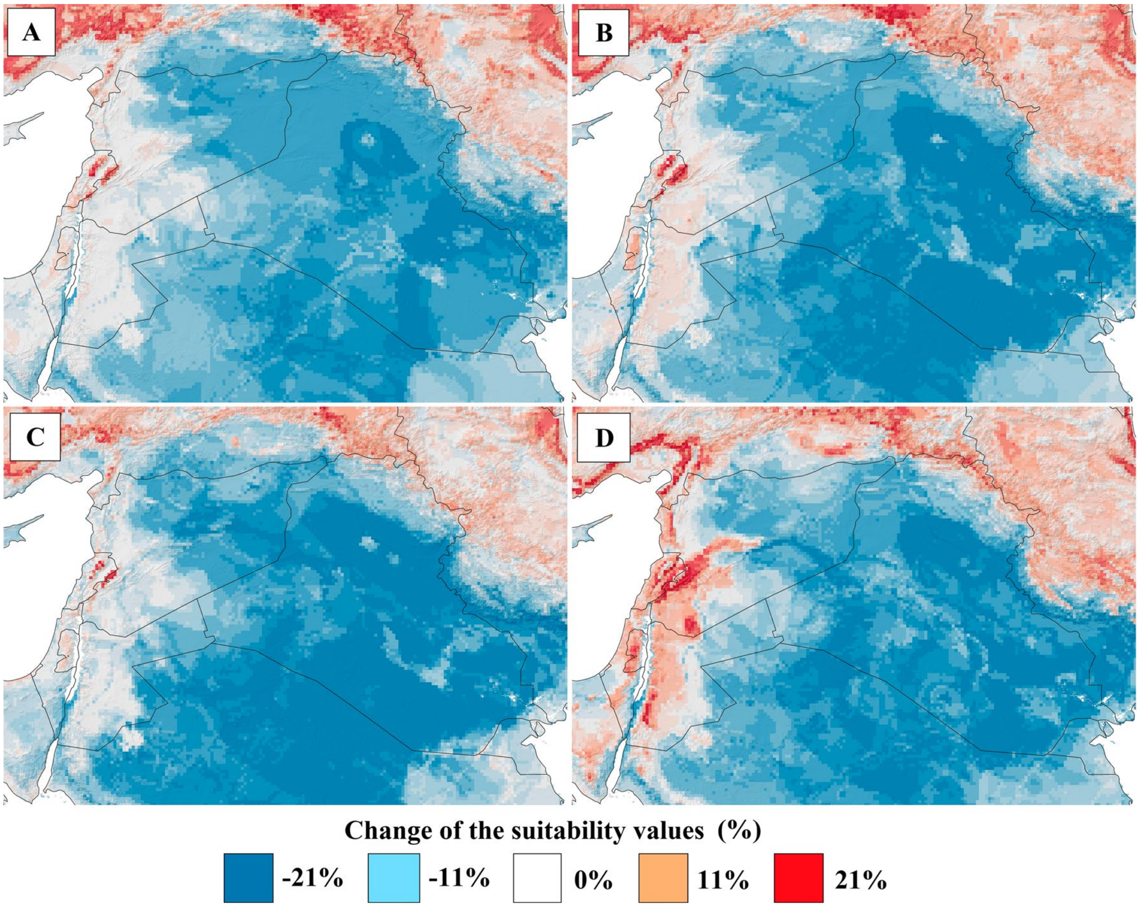

Fig. 13 The changing potential future (2081–2100) climatic suitability values of *Ph. papatasi* (**A**), *Ph. sergenti* (**B**), *L. major* (**C**), and *L. tropica* (**D**) according to the SSP 585 scenario compared to the modelled values for 1970–2000

It also should be mentioned that earthquakes and other difficult to predict in advance natural catastrophes can also increase the risk of leishmaniasis. For example, a new emerging focus of cutaneous leishmaniasis due to *Leishmania tropica* emerged in southeastern Iran, after the earthquake of 2003 (Sharifi et al. 2011). The long-term negative effects of these earthquakes related to the increased risk of leishmaniasis were confirmed by longitudinal studies (e.g., Aflatoonian et al. 2022). Such kind of potential effect can also be assumed after the catastrophic 2023 earthquakes in Southwest Turkey and northern Syria (Ardic and Ardic 2023). Since West Asia is one of the tectonically most active parts of the world (Ambraseys 2001), similar, devastating earthquakes are unfortunately expected to occur in the future in the region. This draws attention to the fact that, in addition to examining the effects of climate change, it is also important to examine natural and social factors in terms of predicting the expected spread of different forms of leishmaniasis.

5 Conclusions

It can be concluded that the future potential range of the climatically suitable areas of cutaneous leishmaniasis exhibits a heterogeneous picture in Western Asia. Although the trends are similar, there are differences both in the case of the vectors and the parasites. In general, the *Ph. sergenti*-transmitted and *L. tropica*-caused leishmaniasis recidivans can increase their climatic suitability in the Levant until the end of the twenty-first century. However, in most cases, it can be concluded that warming will result in the notable retreat of sandfly vector and cutaneous leishmaniasis-causing parasite populations in the mainland areas of Western Asia, which are in the process of strong diversification. In the mid- and some higher-elevation regions of the area, the future establishment of sandfly and parasite populations is projected, mainly in southeast Turkey and western Iran.

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Author contribution Attila J. Trájer conceived of the presented idea, developed the theory, and wrote a major part of the main manuscript text. Ruqayah Ali Grmasha performed the computations, wrote certain parts of the text, and prepared the figures. All authors read and approved the final manuscript.

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Data availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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