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Review Article

Climate Induced Vector Sand Fly (Phlebotomus) Shifts and their Role in Appearance of Cutaneous or Visceral Leishmaniasis

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Abstract: Climate change central and southern Iraq, for instance, has the rise of mean and minimum temperatures, changed precipitation regimes, more droughts, and extreme events with high intensity. Consequently, the ecological conditions that govern the population of Phlebotomus sandflies and disease transmission dynamics of both cutaneous and visceral leishmaniasis have also been affected. This review provides a summary of the latest evidence on the mechanistic pathways that connect climate drivers to the physiology of the sandfly, the formation of the microhabitat, the dynamics of the reservoir host, and the human exposure. Furthermore, it emphasizes how these processes, through land use change, water scarcity, and sociopolitical stressors, interact to create novel risk landscapes in Iraq's drought prone governorates. An increase in temperature not only shortens but can also lengthen the period during which the vector is active seasonally, while changing rainfall and irrigation practices produce varying microhabitats which either provide refugia or serve as breeding sites that are filled up by transients or pulses, producing strong populations through short periods. Heavy rainfall occurring now and then after a long dry period can lead to short population growth, while gradual drying favors the establishment of xerictolerance Phlebotomus species and the connection between them and humans living nearby. Different studies on regional spatiotemporal and nichemodelling analyses show that there might be changes in the distribution of species and their life cycles could be extended in a way that they invade human habitats with leishmaniasis where the reservoirs are present or become local transmission areas with visceral leishmaniasis. There are still major gaps in surveillance that are critical: there is very little long term species level entomology in central and southern Iraq; molecular diagnostics and sentinel networks are not developed at all; and integrated One Health strategies are applied only sometimes in the case of humanitarian or displaced population settings. The review concludes by giving upfront, operational priorities: in high risk microhabitats, set up sentinel entomological sites, make climate driven early warning indicators operational, increase moleculary species and parasite diagnostics, apply targeted One Health reservoir interventions, and test climate triggered response packages in high risk governorates. Coordinated research and policy action are urgent. Without such measures, ongoing warming and resource stress will increasingly favor vector persistence and localized leishmaniasis emergence in Iraq’s droughtprone heartlands.

Keywords: Climate Change, Iraq, Leishmaniasis, Sandflies, Drought.

INTRODUCTION

Leishmaniasis, which includes a spectrum of cutaneous, mucocutaneous, and visceral infections, is caused by Leishmania parasites and is a neglected public health issue even though it is a worldwide problem in the deserts and semideserts. The transmission of leishmaniasis in the Old World is due mainly to the presence of the nightactive sandflies belonging to the Phlebotomus genus. These tiny dipteran insects are very much dependent on the local microclimate conditions not only for their life cycle but also for their population dynamics. The epidemiology of both cutaneous and visceral leishmaniasis is being redefined in central and southern Iraq by a mixture of climatic, ecological and social forces. The leishmaniasis epidemic in Iraq used to be limited to specific areas and certain times of the year; however, the combination of very hot and dry climate, irregular water supply, and rising temperatures has

changed the environment where the vectors and the reservoirs can survive. It is known that Phlebotomus sand flies do not respond uniformly to changes in temperature, humidity, and soil moisture. The temperature determines the length of the life cycle (egg to adult) and the number of generations that can be produced in a year; it also affects the behavior of adult flies seeking hosts; on the other hand, humidity and moisture determine the presence of the larvae and the survival of the adult flies. In landscapes with low moisture and under drought stress, even a small change in the temperature at night or a very short period of rain can greatly affect not only the timing but also the number of adults of the sand flies that are present. At the same time, land use changes like the loss of irrigated fields, the growth of periurban farming, or the increase in temporary water storage areas are gradually turning into some of the main factors affecting the vector populations, since they create a patchwork of habitats (microhabitats) that can either enhance or curb the vector populations depending on their spatial arrangement and distance to the human populations.

Crucially, the climatic drivers impact the sociopolitical context which in turn modifies exposure and resilience. Conflict, displacement, and the degradation of housing and WASH infrastructure lead to the congregating of populations who are highly susceptible to the disease, in areas of high humanvector contact, reduce routine vector control capacity, and interrupt surveillance. The implementation of behavioural adaptations towards heatsuch as outdoor evening activities, sleeping outdoors during heatwaves and shifts in livelihoodlike clustering livestock or storing water near dwellings would significantly raise the level of exposure during the sandfly activities. Hence, the mix of climatic stress and human vulnerability results in the creation of very diverse and shifting landscapes of transmission risk in central and southern Iraq. The modern analytic and operational tools have provided new avenues to detect and respond to changes in the above features. Highresolution climate products, satellitederived vegetation and moisture indices, downscaled projections, molecular diagnostics for species and parasite detection, and genomic tools for vector population structure are enabling the timely detection of range shifts and phenological changes. However, the scientific progress must be turned into practical field strategies: systematic, specieslevel entomological surveillance integrated with shortlag climate indicators; molecular confirmation of vector infection and parasite type; and targeted OneHealth interventions that address peridomestic reservoirs and housing vulnerability. Surveillance must be adaptive instead of purely historical because the climatic baseline is no longer stationary.

This review brings together the existing knowledge concerning the climatic drivers and the bionomics of sand flies, the documented range and phenological shifts, the spatiotemporal outbreak patterns, and the synergistic role of sociopolitical factors in central and southern Iraq. Besides, it stresses the operational recommendations to augment surveillance, diagnostics, and targeted control under a climate regime that is nonstationary, with the purpose of providing guidance for provinciallevel planning and adaptive publichealth responses.

1. The Climate–Vector Nexus: Conceptual Framework of Environmental Drivers

To comprehend how climate impacts the ecology of Phlebotomus sandflies it is necessary to set up an integrated, mechanistic framework that connects weatherrelated factors (temperature, humidity, and precipitation) with microclimate and habitat structure, the vector lifehistory traits, and dynamic factors of population and disease transmission. Sand flies, at the very simplest level, are tiny ectothermic insects that have their development rates characterized, survival periods, activity windows, and reproductive output directly and in a nonlinear manner linked to the ambient temperature and humidity; in addition, rainfall and soil moisture further modulate the areas available for breeding and the distribution of vegetation/hosts, while wind, solar radiation, and extreme events infrequently impose constraints on dispersal and survival (Rupasinghe, 2022). A practical conceptual model from physiological tolerances to landscape suitability is presented in this section which can be used for interpreting the past and future shifts of Phlebotomus in the hot and dry regions of central and southern Iraq through the lens of the climate changes. The primary driver for both metabolism and development is temperature. In the case of Phlebotomus spp., the rates of egg development, larval growth, and adult emergence are following unimodal thermal performance curves: there is no development below a lower threshold; within an optimal band development and fecundity increase; and beyond an upper thermal limit, mortality and reduced reproductive success occur (Trájer, 2023). A not very significant increase in mean and nighttime temperatures can be quite impactful (i.e. affecting the breeding cycle). One that could result in (i) a shorter development time and thus raising the potential for more generations in a given year and (ii) adult activity season extensions; both effects are usually vector abundance increases and Leishmania transmission more chances where other conditions are still favorable (Trájer 2023). To the contrary, speciesspecific is the thermal response: Few of the Phlebotomus taxa are tolerant of the hot and dry conditions and will suffer the extinction where warming is above the maximum temperature level for such species (ViveroGomez 2024; Trájer 2023). The surviving places for eggs and larvae in the soil are defined by temperature and humidity as well as rainfall. Adult activity (searching for hosts and resting), the risk of drying out, and the micrometeorological stability of night shelters are all affected by relative humidity; besides, sand flies often take advantage of the relatively humid spots (for example, rodent burrows, wall cracks,

and vegetation near human dwellings) even in general dry areas (ViveroGomez 2024). On the one hand, rainfall has a twofold effect: it makes the soil moist and the vegetation which can be consumed by larvae and which can also provide vertebrate reservoir hosts that in turn will result in the presence of more vectors; on the other hand, the torrential or continuous rains may wipe out the breeding ground and also the adults will be reduced (Senanayake 2024). The empirical vector monitoring over a long period shows that lagged effects (for instance, 1–3 months) are the rule an increase of temperature or soiltemperature can cause later rises in the number of insects caught in traps for adults, while peaks of rainfall usually have immediately or shortly following positive correlation with density (Senanayake 2024). The effects of the climate are mediated by the landscape and land use at different scales. The different vegetation types and distribution, irrigation, and shelters for animals and humans all contribute to variations in microclimate and host availability. For instance, in dry areas, the irrigation or cultivation done in the suburbs can create conditions similar to oases where the sand flies thrive despite the overall dryness of the region (Azizi 2022; Senanayake 2024). Thus, the regional climate trends (the increase of temperature, the decrease of average precipitation, and the increase of interannual variability) combined with the humaninduced landscape modifications interact to form new ecological niches that might be suitable for some Phlebotomus species and not for others (Azizi 2022; Carvalho 2024). Climatic suitability is thus a composite index from a riskmapping viewpoint which is based on the combination of several environmental predictors that are often nonlinear. The formalized climatic suitability indicators that integrate the temperature, humidity proxies, precipitation, and vegetation indices to foretell the areas and decades of elevated transmission potential have been accomplished in recent machinelearning and mechanistic modeling studies (Carvalho 2024). The continuity of these indicators reveals that climate changes can both expand and reduce ranges of suitability in a nonuniform way, geographically: while some areas lose their suitability because of very high temperature and dryness, other areas particularly those that are periurban and at midelevation may gain the suitability (Trájer 2023; Carvalho 2024). Ultimately, the interaction among climate, vectors, and sociopolitical factors such as displacement, housing quality, and water infrastructure has to be the basis for human exposure to emerging vector habitats. Ecological studies that consider the conflict and displacement together with the disease indicate that the climatic sensitivity alone cannot bear the full explanation of the changing leishmaniasis incidence; on the contrary, the interplay of climatedriven vector dynamics and human susceptibility is what mediates the emergence of the disease (Tarnas 2024). Hence, at the operational level, the monitoring and warning systems for the Phlebotomus in the desert regions should unite (i) speciesspecific thermal and hydric tolerances, (ii) lagged climate–vector response functions based on longitudinal entomological data, and (iii) highresolution landuse and humanexposure layers (Senanayake 2024; ViveroGomez 2024; Carvalho 2024). To sum up, the overarching framework treats temperature as the primary physiological brake, while humidity and rainfall are seen as critical microhabitat enhancers, and landscape/anthropogenic change is the filter that determines climatic suitability for mosquitoes and, thus, for transmission risk. This approach at multiple scales lends strong support to the explanation of the observed movement of Phlebotomus in the dry areas of central and southern Iraq and it also leads to the creation of targeted and climateinformed surveillance (Rupasinghe 2022; Trájer 2023; ViveroGomez 2024; Senanayake 2024; Azizi 2022; Carvalho 2024; Tarnas 2024).

2. Historical and Projected Climatic Shifts in Central and Southern Iraq

The weather in central and southern Iraq has changed drastically during the last 20 years, and it is also expected that the situation will change even more by the middle and the end of this century. That is, the changes in climate are very much significant for vector ecology since the entire sandfly–Leishmania system is modified with little increments in temperature, evaporative demand, as well as precipitation factors and their timing, and intensity. The researchers based on the recent attribution and observational analyses point out that the multiyear drought in the Tigris–Euphrates basin, which started in 2020, is mainly humanmade, and the reason for this is the increase in evapotranspiration plus the waterstressing condition (Otto *et al*., 2023). The study of the drought is of great importance: it is not merely a shortterm anomaly but rather it is a part of the climate signal which in the region has already resulted in the increase of drought frequency and severity, both agricultural and hydrological (Otto *et al*., 2023). The longterm hydrological studies confirm that the entire Tigris–Euphrates basin has undergone multidecadal decreases in water storage and plus, some regions have experienced increased variation in the amount of water in the form of streamflow and reservoirs because of both climate change and human management (Rateb *et al*., 2021). Using satellite gravimetry, insitu records, and hydrological modeling, Rateb *et al*., (2021) highlight significant declines in the water storage of the basin and more frequent extreme hydrological conditions in their recent decades of study; such changes in water have an adverse effect on the habitats of wetness (marshes, floodplains, ephemeral wetlands) and thus, the vertebrate hosts living there and the vectors become less and less (Rateb 2021).

Studies on climate projections that focus on Iraq's regions have been confirmed to show a uniform rise in temperature throughout the year, along with some central and southern areas having precipitation trends that are not so good but still worrisome. A thorough case study based on CMIP6 concluded that there would be an increase in average and extreme temperatures throughout

the middle and western parts of Iraq, with the temperature under highforcing scenarios at the end of the century rising high enough to greatly lengthen the warm season (Mukheef *et al*., 2024). In addition, Mukheef *et al*., (2024) indicate that although precipitation predictions are very much dependent on models, the combined impact of temp gain and irregular rain results in dried out areas and increased water requirement in the southern plainssuch a scenario is unfavorable for soil moisture and nocturnal insect habitat, as it reduces humidity and increases thermal windows respectively. Both downscaling and stochastic weather generator methods yield the proper spatial resolution to figure out the microclimatic risk for the vectors. According to a recent temperature and precipitation statistical downscaling in Iraq, robust warming was detected at the subregion level (Hashim *et al*., 2024). Hashim (2024) indicates that the annual mean temperatures and daily hot extremes will increase not only for the central and southern regions of Iraq but also under both the medium and high emission scenarios, while the rainfall projections have shown inconsistencies in sign but they point to increased interannual variability and the likelihood of intense, shortduration precipitation events will be raised. From the perspective of the vector ecology, the scenario of warmer average temperatures with intermittent heavy rains can lead to temporary breeding areas and changed insect life cycles: inversely time of drought followed by very short periods that are favorable for larvae development and reservoirs host movement (Hashim 2024). Local, governoratescale studies utilizing weather generators have provided evidence for the southern part of Iraq that is in line with these larger signals. In their work, Abdulsahib *et al*., (2024) applied the stochastic weather generator LARSWG with input from the newly released CMIP6 models for northern and neighbouring areas and noted a change in the rainfall pattern along with temperature shifts that had become a factor in altering the seasonal calendar of moisture availability. Their work, though focusing on northern Iraq, applies to the south as well where the relative scarcity of moisture renders even small projected changes highly impactful for the ecological niches (Abdulsahib *et al.,* 2024). Similar, CMIPbased stochastic forecasts are indicating that the drought frequency and severity metrics are increasing for quite a number of SSP scenarios, thus the central/southern Iraq will possibly suffer from more frequent "boom–bust" cycles in moistureperiods when the vector populations may briefly explode after the episodic rains and then die out during the prolonged dry spells (Hamed *et al*., 2023). Hatem *et al*., (2024) confirmed the severe intensification of droughts in Iraq with observational analyses of drought persistence and meteorological variables in 2000–2022. They pointed to the year 2022 as particularly hard hit at several sites in the central and southern regions. Hatem *et al*., (2024) used SPI/SPEI to assess drought over a large area of the country and announced that droughts are now more persistent and cover a larger area, which is in agreement with the Westwide attribution of the 2020–2023 drought to high temperatures (Otto *et al*., 2023) and with the decline of the aquifer recharge (Rateb *et al*., 2021). The scientific community, thus, has drawn three conclusions that are very important for the management of water resources in the central and southern regions of Iraq: (1) the increase in mean and extreme temperatures has already occurred and is projected to continueleading to higher nighttime minima and longer periods of vector activity (Mukheef 2024; Hashim 2024); (2) the average moisture availability is expected to decline even in places where precipitation models give conflicting signals, because the heat increases the evaporation lossesthis results in the expansion of desert areas and the extinction of perennial wet microhabitats (Rateb 2021; Otto *et al*., 2023); and (3) rain might become scarce but with very heavy showers followed by long dry spells, thus causing the emergence of breeding sites that lead to the rise of shortlived vector populations (Hashim 2024; Abdulsahib 2024; Hamed 2023). For Phlebotomus ecology in Iraq's central and southern zones, these climatic tendencies imply range rearrangements (contraction in some microhabitats, expansion where xericadapted species exploit new niches), altered seasonality (longer warm seasons with patchy wet windows), and increased unpredictabilityfactors that must be integrated into entomological surveillance, risk mapping, and publichealth preparedness.

3. Phlebotomus Species of Iraq: Distribution, Bionomics, and Competence as Vectors

A small group of Phlebotomus species characterizes the phlebotomine fauna of Iraq, and their collective presence establishes the leishmaniasis risk level of the country. Uptodate genetic and insectbased research supports that Phlebotomus papatasi still carries the number one status amongst the insect species under the spotlight, while P. sergenti and P. alexandri are seen as key contributors to the counties' northern and centralsouthern leishmaniasis foci (Rasool *et al*., 2024; AlJoary & AlHamdani, 2024). This infield survey method, which supports morphological methods with mtDNA (COI) sequencing, has established three species (P. papatasi, P. sergenti, and P. alexandri) being the most widespread in the endemic areas of Iraq, and more of the Phlebotomus spp. are being reported (e.g., P. tobbi) from the provinces previously known only through phenotypic records because of molecular detection (Rasool *et al*., 2024; AlJoary & AlHamdani, 2024). Distribution and habitat. The field studies conducted in several recent Iraqi surveys confirm that P. papatasi is a widespread species in peridomestic and rural ecological habitats (animal sheds, rodent burrow margins, edges of irrigated areas), thus it gets the attribution for the association with zoonotic cutaneous leishmaniasis (ZCL) foci; P. sergenti shows more preference for rocky or humanmadestone substrates and periurban habitats, and P. alexandri is found in a more irregular distribution often connected with irrigated farming and peridomestic livestock (Rasool *et al*., 2024; AlJoary & AlHamdani, 2024). The

molecular barcoding from the north has increased the known limits of P. alexandri and P. tobbi, showing that the previous absence records were most of the time due to the inadequacies of the morphological surveys (AlJoary & AlHamdani, 2024). Bionomics: seasonality, feeding, and microhabitat. Current studies conducted with traps in Iraq and the surrounding countries confirm the usual bimodal seasonal activity of the main speciesspring and late summer/autumn peaks for P. papatasiwith minor local differences depending on the availability of irrigation and groundwater (Rasool *et al*., 2024). A regional study on feeding behaviour suggests that P. papatasi feeds mainly on rodents and peridomestic animals but will often humanbite where rodent reservoir density is high, while P. alexandri and P. sergenti have wider host ranges that can include dogs, livestock, and humans depending on local ecology (Knight *et al*., 2023; Rasool *et al*., 2024). These hostchoice patterns are crucial in shaping the transmission dynamics because the reservoir's abundance or the increase of humananimal contact (e.g., people temporarily living in makeshift shelters) raises spillover risk. Vector competence and laboratory/field evidence. In Iraq, the coexistence of vectorial competence has got support from the direct evidence: the molecular detection of the Leishmania major DNA in the P. papatasi females gathering in the outbreak areas gives strong evidence that the species is an active vector in the Iraqi ZCL transmission circle (AlBajalan *et al*., 2021). On a larger scale, regional syntheses and genomic work point out that the Phlebotomus species are different in their acceptance of Leishmania spp.; genomic and population analyses disclose the gene families (chemosensory receptors, detoxification enzymes, salivary factors) that can alter hostseeking, bloodfeeding success, and parasite survival in the gut, subsequently modulating vectorial capacity (Labbé *et al*., 2023). Hence, the blending of field detection (Iraqspecific PCR/sequencing) and comparative genomics (mechanistic candidate genes) reinforces the supposition that P. papatasi is mainly responsible for L. major transmission in Iraq, while P. alexandri and other species might just be leeching off or contributing to the birth of atypical morphs circulating in the permissive ecosystem of ecologically skilled areas (AlBajalan *et al*., 2021; Labbé *et al*., 2023; Knight *et al*., 2023). Operational bionomics insecticide susceptibility and diagnostics. Entomological studies in nearby regions and laboratory experiments underscore that classification of the pests and diagnostic capacity are very important for control. Insecticide bioassays and molecular monitoring suggest that P. papatasi populations have different susceptibility profiles, but many studies claim that insects in the region have never lost their susceptibility to legacy compounds (e.g., DDT) and pyrethroidsthis is extremely important data for insect control strategies in Iraqi programs (Azarm *et al*., 2024) as these insects move into neighboring areas. At the diagnostic and taxonomic level, recently released image datasets and DNA barcode resources (highquality genital/pharyngeal images and COI sequences) enhance precision in species identificationthis is especially true for Iraq where the presence of morphologically similar cryptic species and strong local morphological overlap can otherwise lead to inaccurate surveillance (Fraiwan *et al*., 2024). Implications for central and southern Iraq (drought context). The droughtaffected central and southern governorates will probably have changed water bodies, irrigation practice, and changed rodent population dynamics that will all contribute to the reshaping of the microhabitats used by Phlebotomus spp.; the dominant species (P. papatasi, P. sergenti, P. alexandri) with their demonstrated ecological plasticity can continue to live in the peridomestic refugia and irrigated oases, thus sustaining local transmission even when the broader landscapes are dry (Rasool *et al*., 2024; Knight *et al*., 2023). The recent expansion of molecular surveillance in Nineveh and Erbil has shown both the feasibility and the necessity of routine specieslevel monitoring throughout Iraq in order to detect range shifts and emerging vector–parasite associations in real time (AlJoary & AlHamdani, 2024; Rasool *et al*., 2024).

4. Documented Evidence of Sand Fly Range Expansion and Phenological Changes

The Mediterranean, the Middle East, and neighboring areas have witnessed these range shifts and been subjects of a lot of empirical and modelling studies since 2020, which are a growing body of data, and the geographical changes are directly relevant to predicting how drought affected vectors might behave in central and southern Iraq. The first thing to note is that correlative speciesdistribution and ensemble ecologicalniche models calibrated with modern climate layers and validated by field captures consistently predict future redistributions of key vector species (notably Phlebotomus papatasi and P. sergenti), with gains in suitability in some areas and losses in others depending on scenario and timescale (BozorgOmid 2023). In Iran, the use of MaxEnt and Random Forest models and field validation to show the climatic scenarios for the 2030s2050s altering the suitability maps for both the vectors and the rodent reservoirs; importantly, the authors reported the northward and altitudinal shifts in potential suitability and the changes in season length predicted under highwarming scenarios were also among the effects of global warming (BozorgOmid 2023). Secondly, exhaustive field surveillance verifies modern colonization of previously nonendemic lowland and temperate areas. In Italy, routine monitoring set up for other vectors inadvertently trapped Phlebotomus spp. in the northeastern plains lowland regions where sand flies had been thought to be extinct and thus incapable of forming viable and reproducing populations thus indicating the insects were already present at the recognized nonendemic latitudes and microhabitats (Michelutti 2021). Similarly, longterm elevation studies in southern Spain revealed stable populations of sand flies and transmission of Leishmania infantum above 1300 m elevation, pointing to both vector presence and transmission ceasing in the region's higher parts

(DíazSáez 2021). These field observations are significant not only because they are the result of simulations but also because they come from the actual recorded captures and infection assays that imply real ecological establishment across new altitudinal and latitudinal bands (Michelutti 2021; DíazSáez 2021). To begin with, studies of genetics and phylogeography have shown the same thing as the rapid process of expansion and the recent changes in people's numbers, which were going on at the same time as the melting of the glaciers and the changing of climate affecting the distribution of the species. The phylogeographic analysis of Phlebotomus mascittii showed that the species had rapidly dispersal from refugia throughout the whole territory of Europe in the Holocene and this was the reason for the modern detections of the species in places north of the historical range (Kniha 2023). These genetic featureslarge regions with low haplotype diversity and treelike networksare the most typical signs of recent range expansion and reduction of the foundereffect followed by population growth (Kniha 2023). Plus, population genetics and transcriptomics provide evidence that certain vector species have the genetic diversity and population structure required for the adaptation to diverse microclimates. Hamarsheh (2024) applied transcriptomederived microsatellites to uncover the existence of population structure within P. papatasi in which the genetic clusters likely serve as a basis for local adaptation and might even help the species to colonize new areas in the course of changing climatic regimes. If looked at from a practical viewpoint, the ability of local adaptation makes it more probable that the gains in the modelled suitable habitats will result in real colonization of such areas, provided that there are suitable microhabitats and hosts present (Hamarsheh 2024). Fifth, the recent inventories conducted at a regional level and surveys with specific areas as targets, have greatly increased the number of species known and have the first national occurrences documented the previous one could be the case of cryptic species that were not detected or the latter one could be a true expansion of range that has recently occurred. To illustrate, a wideranging entomological inventory in Djelfa (Algeria) brought forth a great number of Phlebotomus species among which were also the first females of P. langeroni recorded in the country, which means that environmental conditions that are changing and/or better monitoring can uncover new species even in the dry/semidry areas (Messaoudene 2024). Such occurrences are of utmost importance in the case of the central and southern governorates of Iraq where aridification moves hand in hand with irrigation oases and periurban microhabitats that might be playing the role of refuges for the vectors. Sixth, studies of density and phenology at fine scales show distinct climatedriven changes in the seasonal activity. Over the years of trapping in the Mediterranean periurban sites, marked interannual and intraseasonal variability in speciesspecific peaks was documented, and the temperature (including minima) and humidity as the key predictors of presence, density, and timing of seasonal peaks were identifiedthese variables are changing already in the climatic belts of Iraq's central and southern regions due to warming and alterations in precipitation (Muñoz 2021; DíazSáez 2021). A very important point is that several modeling and empirical studies suggest that the activity season gets longer (earlier spring onset and later autumn persistence) for certain vectors in warmer climates, and this effect has an implication on the number of potential transmission weeks per year as well as the epidemiological risk (BozorgOmid 2023; Muñoz 2021). On the other hand, central and southern Iraq suffer from the lack of highresolution, longterm entomological data which is vital for the study of range shifts and phenological changes in the region. Evidence from the dryness and warming of the climate came from models predicting changing suitability (BozorgOmid 2023), confirmed upward/latitudinal spread of organisms (Michelutti 2021; DíazSáez 2021), genetic indicators of expansion (Kniha 2023), and shown local adaptive capacity (Hamarsheh 2024). This regional trend shows that central/southern Iraq is very likely to witness changes in vector dynamics due to the combination of drought and warming. However, what is needed is a longterm specieslevel, molecularbased surveillance series in the droughtprone areas of Iraq that would connect the predicted risk with the actual colonization, phenological extension, and vector infection prevalence observedthese are urgent needs that should be addressed first by national entomology and public health programs (Messaoudene 2024; BozorgOmid 2023).

5. The Epidemiological Triad: Linking Climate, Vector, and Human Host in an Iraqi Context

Understanding the emergence of leishmaniasis in central and southern Iraq requires considering the transmission as an epidemiological triad where climate, vector ecology, and human factors are interacting already in a dynamic way. This section gives a summary of the recent studies that have reported how (1) climate change modifies vector's abundance, pushing, and habitat; (2) changes in vector ecology result in a modification of the exposure risk; and (3) human behaviors, housing, displacement, and socioeconomic vulnerability determine who gets to be exposed and whether the transmission gets amplified or not with a specific focus on conditions that are realistic for droughtstricken central and southern Iraq. Weather affects not only the supply side (vector biology and reservoir hosts) but also the exposure side (human behavior and settlement patterns). One mechanism is that higher mean and nighttime temperatures make sandfly development faster, hence prolonging survival during otherwise unfavorable months and widening seasonal activity windowsall these together leading to a higher number of infectious bites per personseason when other conditions allow (Neira, 2023). At the same time, increased evaporative demand coupled with a progressive drying process leads to a major shrinkage of permanent wet microhabitats (marshes, floodplains) but opens up a mosaic landscape

where peridomestic irrigated plots, leaking water infrastructure, and artificial water storage create disproportionately important refuges for sand flies and rodent reservoirs (Neira, 2023; Knight, 2023). Moreover, heavy rainfall events – which are predicted to become more intense even if overall totals decline – can lead to shortlived boom periods for vectors and reservoirs, thus resulting in pulse outbreaks in the months following heavy rain events (Mora, 2022; Knight, 2023). Vector responses are tailored to specific species and contexts. It is presumed that some species of Phlebotomus which can survive in very dry environments (rock crevices, rodent burrows and refuse) will still be able to live or migrate even in the dry lowlands of central/southern Iraq, whereas the species that need more humid soil for their larvae will probably decrease in number (Knight 2023). The lengthening of the season in terms of activity (earlier start and later autumn persistence) has a very significant effect from an epidemiological point of view, as it entails the longest period when the infected sand flies can bite people, thus raising the seasonal reproduction number (R) in those localities (Neira 2023). When insect populations are genetically structured and specifically adapted to the environment, then the rapid demographic expansion into newly established microhabitats would be the most probable scenario (Mora 2022). Human factors are a major determinant of both exposure and whether vector presence will lead to transmission. Unsatisfactory types of housing (mud walls, cracked plaster, earthen floors), shelters built for domestic animals near human habitation, the presence of rodents close to houses and sleeping outdoors are the main reasons for receiving mosquito bites and have been consistently pointed out as major risk factors throughout the region (Sarmadi 2023; Karimi 2021). In arid central/southern Iraq, water shortage and high temperatures might cause people to be active outdoors in the evening (sitting or sleeping outdoors to avoid the heat inside), thus increasing humanvector contact during the time when sandfly activity is highest, which is dusk and night (Neira 2023). In addition, periurbanization, informal settlements, and irrigation projects generate habitat diversity at the humanenvironment interface: newly irrigated areas and animal keeping are among the typical microhabitats that support high densities of sandflies near humans by acting like oases (Karimi 2021; Sharifi 2023). It is a wellknown fact that previous studies have established a close interdependence among conflict, displacement, and disruption of healthcare that can be put together as conflict, displacement and healthcare disruption are synergistic multipliers. The narratives from different areas of the world vary, but they all point to the same conclusion: if there is war in the region and a large number of people are forced to leave their homes, the incidence of the occurrence of cutaneous leishmaniasis will be the largest (Tarnas *et al*., 2024 see note). Above all, the migrated population is very often living in very poor conditions, near where the sand flies are, and with no health prevention service (Tarnas *et al*., 2024 see note). In Iraq, the situation is further complicated by the fact that the government is not able to provide the proper treatments for the patients who have been displaced, and the vector control programs are disrupted these are the factors that contribute to the emergence of new areas with leishmaniasis transmission which may eventually become established (Sharifi 2023; Karimi 2021). Researchers studying transmission dynamics are convinced that the situation brought forth by the combination of these factors has more than tripled the basic conditions of the transmission triad: (a) vectorial capacity goes up as prolonged seasons and higher vector density in created microhabitats become predominant; (b) the reservoir dynamics react in a nonlinear way to the moisture pulses and the changes of the habitat caused by human activities; and (c) the factors of human susceptibility and contact rates gain strength where there is the combination of poor housing, ongoing displacement, and weakening of public health systems (Knight 2023; Neira 2023; Sarmadi 2023). This means that the conflict areas have not been distributed equally over the subgovernorate level; there will not be a similar risk increase in the entire central and southern Iraq. In fact, it can be said that the risk will be focused in those areas where the irrigated agriculture, growth of periurban settlements, or displacement camps are located in close proximity to conducive microclimate and presence of Phlebotomus population.

Operational implications for central/southern Iraq (practical priorities):

1. **Placebased surveillance:** Entomological traps should be targeted to peridomestic irrigated patches, animal shelters, and displacement settlements not only to classic ‘rural’ foci because these microhabitats concentrate vectors and hosts (Karimi 2021; Sarmadi 2023).
2. **Integrate climate indicators:** Earlywarning systems must combine temperature minima trends and shortlag precipitation anomalies (1–3 months) to predict likely vector pulses after episodic rains (Neira 2023; Mora 2022).
3. **Address housing and behaviour:** Lowcost structural improvements (plastering walls, screened sleeping areas), community education about nighttime exposure and targeted distribution of bed nets/repellents in highrisk settlements will reduce bite rates even without eliminating vector habitats (Sarmadi 2023; Sharifi 2023).
4. **Protect displaced populations:** Humanitarian planning must prioritize vectorproofing of camps and rapid access to diagnosis/treatment to prevent amplification in highcontact settings (Sharifi 2023; Karimi 2021).
5. **OneHealth coordination:** Integrate veterinary surveillance for domestic reservoirs and rodent control where evidence supports their role, since animal–human interfaces often drive zoonotic spillovers (Cosma 2024).

6. SpatioTemporal Patterns of Cutaneous and Visceral Leishmaniasis Outbreaks

The main point in linking the incidence of diseases to vector ecology and environmental changes is spatiotemporal analyses. The droughtprone area of Iraq, which is the focus of this review, has been quite active in the research field lately. The results afforded by both direct studies and those of neighboring regions, among other things, indicate a close temporal relationship, a seasonal peak and a movement to displace among the foci of cutaneous leishmaniasis (CL). These phenomena simply correspond to the seasonalities of the vectors, their movements in population, as well as the local environment perturbations. The propositions that these seasons coincide with higher mortality due to the emergence and reduction of caseloads in different areas of countries are embraced by the following three points: (1) seasonal timing and monthly peaks of CL cases, (2) formation, movement, and expansion of spatial clusters (hotspots) over multiyear spans, and (3) abrupt incidence spikes related to social disruptions or postdisturbance ecological change. To begin with, several datasets convey that there is a strong seasonal signal for OldWorld leishmaniasis across the entire Middle East. The number of cases in this area is mainly concentrated in the late summer and autumn months (OctoberDecember is usually the peak). This is due to the fact that there is a delay in clinical presentation resulting from the sandfly bite season, and at the same time, the vector population dynamics are prevailing during the warm months (Tadayonfar 2024; Firouraghi 2023). In routine surveillance analyses for 2018–2022, Tadayonfar *et al*., observed consistent monthly peaks in October–November and employed ARIMA forecasting to establish an overall seasonal pattern at the same time that there were regions with potential for renewal of the upward trends (Tadayonfar 2024). Similar nationwide temporal and spatial work in Iran revealed seasonal troughs and peaks and even identified highrate clusters that were only localized for a short time (e.g., Sep–Feb windows) which moved over counties during the 2011–2020 period (Firouraghi 2023). These seasonal signatures are essential for timing surveillance and vector control in Iraq's central/southern provinces, where sandfly activity is similarly constrained by temperature and humidity seasonality. Secondly, the use of spatial cluster detection (SaTScan, LISA, and other spatial statistics) leads to the identification of hot spots concentrated in certain areas repeatedly. Over a period of years, these hot spots can expand, split, or movethis is the same pattern that has been documented by different regional studies and that is very much related to the provinces of Iraq that are suffering from or undergoing desertification. A nationwide analysis done by Firouraghi revealed the presence of multiple clusters purely in space as well as in time and space, the temporal trends of a few clusters being upward and the geographical displacement during the period being very clear (Firouraghi 2023). The study by Tadayonfar dealing with the militarypopulation scenario also depicts places where risks are concentrated in the middle and southern provinces and documents the movement of those areas, labeling Esfahan, Khuzestan, and Ilam as hot zones that have been there all the time (Tadayonfar 2024). In Iraq, the facilitybased series like the AlMuthanna sixyear dataset show the presence of foci that are persistent and localized, with yearly changes and sometimes increases in intensity which are associated either with ecological or human behavioral changes (Flaih 2024). Together these results argue that central/southern Iraqi governorates are at risk for the same dynamic clustering seen in neighbouring endemic countries clusters that can expand into periurban and newly irrigated zones when environmental or human factors shift. Third, the most sudden outbreaks or spikes usually go hand in hand with (a) the movement and fight for land, (b) the changing of human settlement or agricultural patterns as a result of the lack of water, and (c) the cutting off of normal public health services. The investigation and control study of the outbreak in Diyala in 2018 showed how the risk factors which could be modified (the condition of housing, closeness to the burrows of rodents, some kinds of jobs) profoundly influenced local incidence and how the elimination of such factors would lead to the reduction of cases illustrating the phenomenon where the social change causes the rapid increase of incidence (Lehlewa 2021). In the same way, regional modeling and ecological niche studies support that climate-induced changes in the suitability of vectors and reservoirs (and of the human exposure) could cause the opening of new ecological niches e.g. for transmission, Charrahy *et al*., proved that the climate scenarios change the predicted best ecological niches for the vectors and reservoirs throughout Iran which is a conclusion that directly influences the provinces of Iraq that are adjacent to those redefining regions (Charrahy 2022). To put it practically, the migrations caused by drought, the establishment of temporary settlements around the irrigation projects, or the expansion of housing in the conflict-torn areas of central and southern Iraq are all creating the new interfaces where humans, reservoir rodents, and sandfly habitats meet—a perfect condition for the emergence of spacetime clusters. Through the use of molecular and clinic-based surveillance, we can see the spatial and temporal aspects more clearly as these methods show what species and strains are present during that period and in that area. Khazal *et al*., (2024) have pointed out that there is a considerable diversity of Leishmania major strains at different lesions in southern Iraq, which can indicate that the local parasite population structure is prone to variation between the foci and over time. This diversity of local parasites is an important marker when going through the procedure of mapping outbreaks and linking them to specific reservoir/vector systems (Khazal 2024). Changes in the composition of parasite strains in a province confirmed by laboratories can suggest either local ecological change or the introduction of the strains from across the border, both of which alter the expected spatiotemporal dynamics. On the other hand, there are

direct pragmatic surveillance lessons drawn from these observed patterns. The method of detecting spatiotemporal clusters should be an integral part of the routine surveillance process in the provinces of Iraq that have been affected by drought (central area/south) and the process should take place on a monthly basis in order to catch the seasonal peaks and perform runs with SaTScan (or an equivalent method) to detect new clusters at an early stage (Firouraghi 2023; Tadayonfar 2024). The integration of case data with genomic typing (Khazal 2024) and the rapid case-control follow-ups (Lehlewa 2021) creates a high-resolution early-warning system that can identify the causes of spikes as behavioral, environmental or due to importation. Regional evidence from Saudi Arabia and the neighboring provinces is in line with the fact that post-disturbance surges in disease incidence frequently follow lockdowns, floods, or sudden population movements such as the dynamics created by Iraq's drought, shocks in the infrastructure and waves of displacement (Al-Dhafiri 2023; Flaih 2024).

7. The Synergistic Impact of Environmental and Sociopolitical Factors

Iraq's central and southern areas are facing a new type of leishmaniasis and the risk factors are changing in a way that they can be viewed as a synergy and not just an addition. The climate-induced decrease in water supply and vegetation is making the area less suitable for the vectors and the reservoir hosts, while the sociopolitical stressors like armed conflict, frequent internal displacement, damaged WASH (water, sanitation, hygiene) infrastructure, and public health systems' weakening are all contributing to human exposure and reducing the ability to prevent, detect and treat infections. The section puts together the latest multidisciplinary evidence that shows how the environmental and sociopolitical factors interact to create conditions suitable for the emergence, geographical spread, and sustained transmission of cutaneous and (less often) visceral leishmaniasis in the drought-affected Iraqi governorates. (Cantor 2021; Ibrahim 2021; Marzouk 2022; Pavur 2024; Todd 2024; Chughtai 2023; Tarnas 2024). Conflict and displacement are the main sociopolitical risk multipliers in the first place. Heavy violence and long-lasting insecurity not only split the health services, but also interrupt vector control and drive people in large numbers from the areas with the disease to non-endemic ones or to poorly protected, overcrowded settlements, which are all documented ways of leishmaniasis spreading (Tarnas 2024). Through ecological analysis in various endemic countries, it is found that the intensity of the conflicts is independently increasing the incidence of cutaneous/mucocutaneous leishmaniasis and that displacement is the main factor mediating the whole association: wherever the conflict pushes people to live in temporary shelters, the lowering of housing quality and the rising of people's exposure to the domestic vectors lead to an increase in the human cases that can be measured (Tarnas 2024). These pathways of causation are of immediate importance to Iraq where there have been constant displacements (ISIS, localized violence, and climate migration) which have moved the people prone to infections and created a number of informal settlements in the central and southern regions (Cantor 2021; Ibrahim 2021). Secondly, the impacts of drought and scarcity of water are such that the use of land and the choice of livelihood are modified thus increasing the contact between the vectors and human beings. Recent water scarcity maps of Iraq have shown that such conditions are persistent and even due to the changes in irrigation, groundwater extraction, and wetlands collapse or diversion water are coming to be used less (or being diverted) as the natural predators are being eliminated and the rodents and domestic animals (the main hosts of Leishmania in some cases) are being pushed closer to human beings, changing the breeding and feeding ecology of the sandfly (Pavur 2024). At the same time, the irrigation projects and the improvisation of water storage practices (tanks, troughs, puddles near houses) can create conditions that are good for sandflies at the household level during normal dry seasons; such human-induced habitat creation has been repeatedly noted as a climate-interaction pathway for VBDs (Chughtai 2023). Disruptions in WASH and healthcare systems really make the situation worse and also hinder the controlling of the outbreak. Continuous impairment of water and sanitation facilities and sporadic interruptions in vaccination and primary care provision, lead to malnutrition, comorbidity, and late presentation – all of which adversely affect the disease's outcome and increase the transmission potential for NTDs including leishmaniasis (Todd 2024; Ibrahim 2021). The resilience of the Iraqi health system has been put to the test over and over again; the conflict zones have the least diagnostic capacity, interrupted surveillance reporting, and limited vector control activities, which all contribute to the existence of blind spots where the disease can continue spreading undetected (Ibrahim 2021). Moreover, the stressors have caused different psychosocial and behavioral responses, which in turn, have impacted the exposure patterns. Studies conducted among displaced people in Iraq reveal that people's views regarding the climate, loss of income, and your area being unsafe affect where they settle, how long they stay outside, and their resourcesharing behaviors which in turn may lead to increased evening or peridomestic exposure to sandflies (Marzouk 2022). For instance, families that sleep outdoors during the hottest part of the summer or keep their animals close to their homes when the pastures dry up are, in effect, increasing their contact with the sandfly populations during the peak activity times. Ultimately, the interaction of these different factors results in a weakening of both surveillance and programmatic response: the cumulative impact of a reduction in budgets, loss of personnel, and rendering of emergency priorities mean that controlling pests through routine surveillance, integrated pest management, and casefinding is difficult at the very time when

environmental conditions are most favorable for the transmission of the virus (Chughtai 2023; Cantor 2021). The situation indicates a combined approach: the establishment of surveillance systems that incorporate the indicators of climate and displacement; vector control measures that are geographical targeted according to the changing ecologies of the suburbs; the restoration of water, sanitation, and hygiene (WASH) services in conjunction with housing development in internally displaced persons (IDP) settlements; and the rebuilding of primary health care and diagnostic capacity in areas with the highest risk of disease outbreak (Pavur 2024; Todd 2024; Tarnas 2024).

CONCLUSION

The interaction of climatic change and sociopolitical fragility is leading to a profound reorganization of the leishmaniasis risk in central and southern Iraq, which is now a publichealth challenge that is getting worse. The factors include the rise in temperature, the change in precipitation patterns, and lack of water that have opened up more areas to vector activity, changing the locations of where the vectors can live, and even creating areas near homes where the drought-tolerant Phlebotomus can survive and reproduce. At the same time, the population's movement, poor housing, health care disruptions, and water crisis responses magnify the human exposure and lower the detection and control capacities. The net effect is that the chance of cutaneous leishmaniasis reappearing in small areas is higher and the transmission of visceral leishmaniasis in the already supportive ecological pockets is also possible. In response to this continuously changing threat, surveillance and control should be shifted from a static and retrospective method, to an adaptive and climate-aware One-Health method. The operational priorities right away are to set up sentinel entomological sites in microhabitats that have a high risk of infestation, to integrate climate indicators with a short lag into the early warning systems of the most actions taken, to scale up molecular diagnostics for the verification of routine species and parasites, and to implement interventions in the reservoirs and housing of the displaced and peri-urban communities. Investments in the provincial analytic capacity, routine insecticide-resistance monitoring, and community engagement are the necessary complements. The implementation pilots that link climate triggers with predefined response packages will give the evidence base for scaling up under resource constraints. To protect at-risk communities in Iraq's drought-affected areas, it is necessary to have a joint effort of health, veterinary, water, and humanitarian sectors, continuous financing, and local community involvement. Climate-informed interventions that are timely and based on sentinel surveillance, molecular confirmation, and realistic One-Health measures present the most practical means of controlling leishmaniasis emergence in the future. The need for immediate, coordinated action across sectors is now.

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