Chagas Disease 2

Climate change and *Trypanosoma cruzi* transmission in North and central America

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***Trypanosoma cruzi* is a protozoan parasite that causes Chagas disease in humans. Transmission of *T cruzi* by triatomine vectors is dependent on diverse environmental and socioeconomic factors. Climate change, which is disrupting patterns of human habitation and land use, can affect the epidemiology of Chagas disease by influencing the distribution of vector and host species. We conducted a review using triatomine distribution as a proxy for *T cruzi* transmission in North America (Canada, Mexico, and the USA) and central America (Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama) and investigated the association of *T cruzi* transmission with climate change, identifying 12 relevant studies. Most studies (n=9) modelled the effect of the scenario of climate change on the distribution of relevant vector species and found that global warming could sometimes favour and sometimes hinder triatomine distribution. There is a need for more research in parasite biology and social sciences to further understand how climate change and socioeconomic factors can affect the epidemiology of this neglected tropical disease.**

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Introduction

Chagas disease, caused by the protozoan parasite *Trypanosoma cruzi*, is one of the neglected tropical diseases (NTDs) of greatest public health importance in the Americas. The vast majority of the estimated 6–7 million people living with *T cruzi* worldwide are in the Americas,[1] where Chagas disease disproportionately affects internal and transnational migrants, Indigenous communities, and disadvantaged people in rural areas. An additional 70 million people in the Americas are at risk of transmission. The parasite is primarily transmitted by triatomine insect vectors but can also be transmitted during pregnancy or birth, through the consumption of food contaminated by triatomines, and through transfusion of blood products and organ transplantations. Given the ability of some species of triatomines to colonise dwellings, the threat of Chagas disease is emerging in urban environments in tropical and subtropical cities.[2] The control of Chagas disease and other NTDs is linked with the UN Sustainable Development Goals,[3] and WHO calls for eliminating the disease as a public health challenge by 2030.[4]

Climate change poses several key challenges in the control of Chagas disease and other NTDs.[3,5,6] The potential effect of climate change on parasite biology, distribution of vector and host species, and human migration and interactions with the environment are not well understood,[5,7] and new geographical areas and populations could be placed at risk.[7] Past events such as rising sea levels are thought to have played a role in the diversification of North American triatomine species.[8] Furthermore, as a disease linked with social and environmental factors, Chagas disease has been sensitive to human-induced changes in the environment throughout history. For example, agricultural expansion under the Incas and other precolonial polities, as well as Spanish colonial rule, has been implicated in the domestication and spread of triatomines to new habitats in South and central America.[9] Although vector control initiatives launched in the 1990s have substantially reduced incident infections in the Americas (from approximately 700 000 per year in 1990 to under 30 000 per year by 2015),[1] the emergence of new domiciliary vectors, insecticide resistance, and declining expenditure on vector control programmes, coupled with new socioepidemiological scenarios, such as oral transmission in the Amazon and urban encroachment, pose a threat to the achievements of vector control initiatives within the context of climate change.[3,10] The aim of this review is to explore the effect of climate change on *T cruzi* transmission beyond South America with a focus on North America and central America. This paper is part of a Series on Chagas disease. We have used vector distribution as a proxy for *T cruzi* transmission risk because vector transmission remains the main source of new cases.

Social and environmental factors

Against the backdrop of climate change, *T cruzi* transmission has gained increasing complexity as traditional rural landscapes are affected by deforestation and agricultural expansion and there is rapid and often disorganised urbanisation.[11] Accelerated rural-to-urban migration within endemic countries and transnational migration to non-endemic settings have been partly driven by climate change.[5] Because of the relationship of *T cruzi* transmission with housing materials and socioeconomic conditions, people living with *T cruzi* in rural areas could also be highly vulnerable to the effects of climate change on farming, ranching, and related livelihoods. Studies suggest that transnational migrants are also a high-risk population for *T cruzi*[12] and that non-endemic urban areas are often not well prepared to manage Chagas disease, including the possibility of vertical transmission.

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Moreover, rapid urbanisation and loss of surrounding natural habitats, such as dry tropical forests, could favour the expansion of transmission cycles into urban areas. In fact, triatomines have been reported in several North American cities, including Mérida (Mexico) and Houston (TX, USA).[13,14] Since urbanisation can drive evolutionary changes in triatomines that facilitate their adaptation, the effect of urbanisation on *T cruzi* transmission needs to be further investigated.[15]

Meanwhile, global warming, specifically increasing temperatures, could promote the expansion of the range of some triatomine species from tropical to temperate zones, with the abundance of domestic animals and other host species playing an important role.[16] Local epidemiological dynamics are shaped by sociocultural landscape configurations in which human habitation and land use (for agriculture, grazing, or harvesting of natural products) intersect with domestic and zoonotic transmission cycles.[17,18] For example, the vector species *Rhodnius pallescens* in Panama, which is closely associated with *Attalea butyracea* palms, proved to be more abundant in anthropogenically disturbed areas, although in a worse physical state, than in forested areas. Starved triatomines in habitats shaped by anthropogenic activity are potentially more likely to enter human dwellings in search of a blood meal.[19] How shifting land-use patterns, in response to deepening socioeconomic inequalities and environmental pressures stemming from climate change, affect future scenarios for *T cruzi* transmission remains to be examined. In this sense, there is a need to undertake more integrated multidisciplinary approaches to gain a deeper understanding of the patterns and causes of Chagas disease risk in rural settings, where ecological processes drive transmission and sociocultural processes drive parasite exposure and environmental change.[20]

Chagas disease outside of South America

Much of the current public health literature on Chagas disease has focused on South America, where four of the five countries with the highest burden of disease are located (Argentina, Bolivia, Brazil, and Colombia).[1] Nonetheless, North America, central America, and the Caribbean present a unique epidemiological context, with a mix of both endemic and non-endemic countries, rich diversity of vector species, distinct *T cruzi* genetic profile, and highly dynamic south–north migration process. Central America, which has an estimated 385 000 people living with *T cruzi*,[1] has persistent foci of vector transmission, with some countries facing serious political and economic challenges. Mexico has the third highest estimated burden of the disease (876 000 people living with *T cruzi*),[1] with diverse ecological contexts. Although the majority of the estimated 300 000 people with *T cruzi* in the USA[21,22] are most likely migrants from Mexico, central America, and South America, historical reports in the southern USA suggest that autochthonous transmission is not only possible but also has long been overlooked.[23] The Caribbean is currently not considered an endemic region for Chagas disease,[1] but given the area's close proximity and relationships with endemic Latin American countries and the USA, the risks that socioenvironmental change could pose in the future remain unclear. Migration, which is often driven by the effects of climate change, means that the management of Chagas disease needs to encompass both rural and (increasingly) urban contexts in endemic and non-endemic areas.[16]

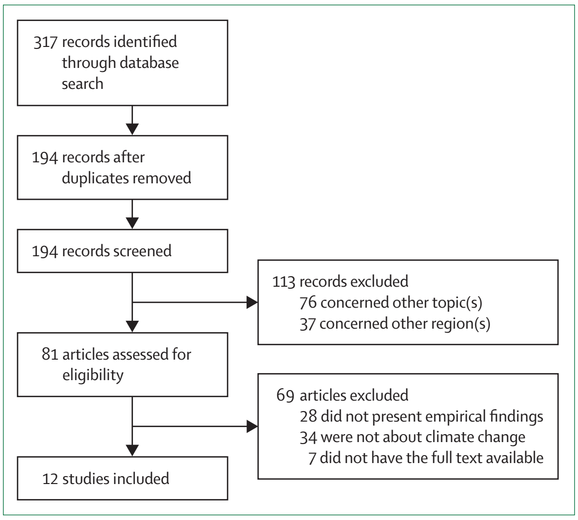

Figure 1: Flowchart of the review process for *Trypanosoma cruzi* transmission.

Selection of studies

After applying our search strategy, 12 studies[16,24–34] met the inclusion criteria (figure 1; table); 11 were originally published in English and one in Spanish.[33] The majority of studies were funded by public or academic institutions, or both in Mexico (n=6)[16,29,30,32–34] or other Latin American countries (n=3),[27,28,31] two were funded by US academic institutions,[24,26] and one by a Canadian public agency.[25] Nine of the 12 included articles modelled the potential distribution of triatomine species under climate change.[16,24,26–29,31,33,34] These modelling studies incorporated bioclimatic data to predict the possible effects of climate change on the geographical range of select triatomine species using different approaches, including ecological niche and species distribution modelling. In seven of nine cases, these studies strictly focused on triatomines and climate, without directly addressing the potential for *T cruzi* transmission to humans, incorporating epidemiological or other analyses. However, Carmona-Castro and colleagues[29] quantified the increased risk of exposure to humans on the basis of the expansion of the triatomine range, and de la Vega and colleagues[27] linked experimental data on triatomine thermotolerance with species distribution modelling. Two studies presented experimental data assessing the effect of rising temperatures on *T cruzi*-infected triatomines.[30,32] Only two studies incorporated methodologies to assess the social, political, or health system

	Caribbean	Central America	North America			Type of study	Main finding
			Mexico	USA	Canada		
Click Lambert et al (2008)[24]	··	··	··	✓	··	Species distribution modelling	Geographical information system and minimum temperature thresholds were delineated for US triatomines and predicted under future climate change scenarios, revealing a northward expansion of the at-risk zone(s); physician surveys in the predicted risk zones showed little awareness of Chagas disease.
Cox et al (2013)[25]	··	··	··	··	✓	Multi-criteria decision analysis	Expert opinions and 40 criteria were analysed to prioritise emerging diseases of most concern in Canada in the context of climate change; Chagas disease was identified as one of the top three.
Garza et al (2014)[26]	··	··	✓	✓	··	Species distribution modelling	Models forecast potential range shift of *Triatoma gerstaeckeri* and *Triatoma sanguisuga* as a result of climate change.
de la Vega et al (2015)[27]	··	✓	··	··	··	Species distribution modelling	Minimum temperature of the coldest month and other physiological factors explain the geographical distribution of *Rhodnius prolixus*.
de la Vega and Schilman (2017)[28]	··	✓	✓	✓	··	Species distribution modelling	Studied species showed high tolerance to desiccation, which could be an important factor in their distribution under climate change scenarios.
Carmona-Castro et al (2018)[29]	··	✓	✓	✓	··	Modelling	Effect of climate change is specific to each species, with those having the greatest current distribution expected to have the largest shifts; increased risk of vector exposure for human populations in North America by 1·48% (urban) and 1·75% (rural).
González-Rete et al (2019)[30]	··	··	✓	··	··	Ecological	Climate change could decrease the survival rates of *T cruzi*-infected *Triatoma pallidipennis*.
Altamiranda-Saavedra et al (2020)[31]	··	✓	··	··	··	Species distribution modelling	Potential distribution of two vector species, *Triatoma maculata* and *Rhodnius pallescens,* in response to different environmental variables.
González-Rete et al (2021)[32]	··	··	✓	··	··	Ecological	Negative effects on the abundance of *T cruzi* in *T pallidipennis* at high temperatures (increased linearly with time at 20°C and, to a lesser extent, at 30°C).
Torres-Delgado et al (2022)[33]	··	✓	✓	··	··	Species distribution modelling	A decrease in the distribution of *Triatoma nitida* was predicted under climate-change modelling, but new areas would become habitats susceptible to vector invasion.
Flores-López et al (2022)[34]	··	··	✓	··	··	Ecological niche modelling	Models predicted a northward shift in the ecological niche of *Dipetalogaster maxima* in Baja California under climate change.
González-Salazar et al (2022)[16]	··	··	✓	··	··	Modelling	Modelling of *T cruzi* transmission under human land use and climate change scenarios predicts that transmission risks would increase under current or worsening environmental scenarios but improve with the implementation of more environmentally sustainable land-use practices.

Table: **Studies on *Trypanosoma cruzi* transmission and climate change included in this review**

Search strategy and selection criteria

To collate current knowledge on the association between climate change and *Trypanosoma cruzi* transmission, we searched for articles published on PubMed and Web of Science between database inception and May 14, 2024, with no restrictions for language. We used the search terms "triatomines", "*Trypanosoma cruzi*", "Chagas disease", "global warming", "climate change", "*cambio climatico*", and "*calentamiento global*", as well as geographical terms for North America—Canada, Mexico, and the USA (excluding Puerto Rico)—and central America—Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama. The Caribbean region—Cuba, Dominican Republic, Haiti, Puerto Rico, and Jamaica—was included in the search strategy; however, no relevant studies were found. We also checked the references of the selected articles for additional records, but no relevant studies were added; therefore, we excluded the Caribbean region from the review. This process led to the identification of 12 studies on *T cruzi* transmission in the context of climate change in North and central America.

dimensions. Cox and colleagues[25] used a multi-criterion decision analysis approach to understand emerging diseases that were of most importance to stakeholders in Canada, and Click Lambert and colleagues[24] incorporated an awareness survey of physicians. We did not find studies that explicitly addressed the effect of climate change on vertical or oral transmission of *T cruzi*. The included studies are described in more detail throughout the review according to geographical regions.

Central America

Central America is one of the global regions that is most affected by and vulnerable to climate change but is less prepared to manage the effects of climate change compared with high-income regions.[35] Drought, rising sea level, coral bleaching, increasing frequency of severe weather events, seasonal irregularity, and variable rainfall are exacerbating the region's many environmental, socio-economic, and political challenges.[35] Climate change is, thus, a profound threat to the region's progress in the control of vector-borne diseases. Chagas disease remains the most important parasitic infection in central America in terms of prevalence and disability-adjusted life-years, predominantly affecting individuals with low income living in rural areas.[10]

Figure 2 shows the current distribution of triatomine species in central America. Among the triatomine species noted in central America, three vector species

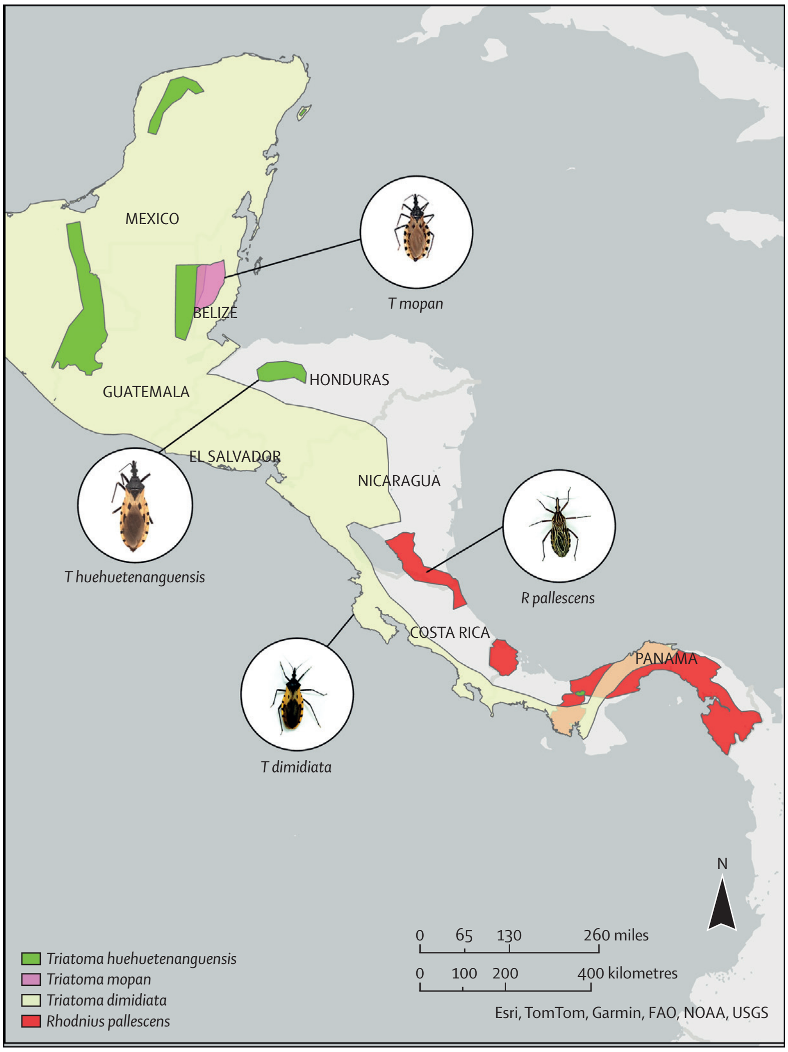

Figure 2: **Principal triatomine species capable of transmitting *Trypanosoma cruzi* in central America**
Current distribution of four important triatomine vectors of *T cruzi* in central America. For more details on methods and sources, see appendix p 2.

See Online for appendix

(*Rhodnius prolixus*, *Triatoma dimidiata*, and *R pallescens*) have historically been responsible for most *T cruzi* infections in the region. A colony collection of *R prolixus*, originating from Venezuela and given to El Salvador in 1912 by a European university, accidently escaped from the laboratory in 1913. *R prolixus* became the most important vector in the region for close to a century in part due to an almost exclusive affinity to domestic and peridomestic habitats.[36] de la Vega and colleagues[27] assessed the relationship of thermotolerance and other physiological factors with the geographical distribution of *R prolixus,* in comparison to that of the South American species *Triatoma infestans*, using species distribution modelling with incorporation of select bioclimatic variables. In addition to geographical modelling, de la Vega and colleagues[27] gathered experimental data incorporating lethal temperature, critical thermal minimum (CT_{min}), and chill-coma recovery time for fifth-instar nymphs of both species. The minimum temperature of the coldest month was identified to be the main factor limiting the distribution of both species, although *R prolixus* showed lower tolerance for cold. de la Vega and colleagues[27] also noted that extending these findings to account for the effects of climate change would require assessing temperature ranges in both domestic and sylvatic microhabitats, including the probabilities of reaching minimum and maximum values of temperature. Furthermore, the lower tolerance of *R prolixus* towards thermal variation (ie, a narrow range for its CT_{min} and critical thermal maximum [CT_{max}]) might have also played a role in the restricted geographical distribution of *R prolixus* to lower latitudes of central America and northern South America in comparison to that of other triatomines such as *T infestans*.[27] These vector characteristics made elimination of *R prolixus* an attainable target. The Initiative of the Central American Countries for Control of Chagas Disease, launched in 1997, was crucial in interrupting transfusion-related transmission and eliminating *R prolixus* by successfully implementing vector control measures based on indoor residual spraying. Central America was certified free of *T cruzi* transmission by *R prolixus* in August, 2011, and the estimated disease incidence decreased from 62 000 new cases per year in the 1990s to 8500 new cases in 2006.[36]

The two remaining important species, *R pallescens* and *T dimidiata*, present a more diverse range of ecosystem preferences. *T dimidiata*, the most important vector in central America, has a wide geographical range, extending from Mexico to Peru, in both domestic and sylvatic habitats.[37] *T dimidiata* is considered a species complex with important differences in morphology,[38] genetics,[39] physiology,[40] and host preferences,[41] which could be associated with the variation in their vectorial capacity.[42] These variations affect the frequency and intensity of the vector-human interface and hence the risk of *T cruzi* transmission.[8] *T dimidiata* is, thus, a versatile vector for which conventional vector control measures such as prevalence estimates by targeted cross-sectional surveys followed by a suitable action or indoor residual spraying are of transient or inadequate effectiveness.[18,43] Furthermore, the vector carries two discrete typing units in the region—TcI and TcIV. TcI shows marked diversity supporting the detection of high vectorial mobility and an absence of association among host, vector, and ecotopes in the central American isthmus.[44] However, *T dimidiata* presented a lower tolerance for arid conditions than *T infestans* and other South American species.[28]

R pallescens is the most important vector species in Panama. The ecological niche of *R pallescens* is closely related to palm trees (*A butyracea*) that proliferate in previously forested ecosystems modified for cropland and livestock production.[45] Increasing anthropogenic activities in the region could, therefore, shift the vector's ecology to a synanthropic behaviour, expanding the distributional latitudes of the vector.[3,31] Furthermore, modelling suggested

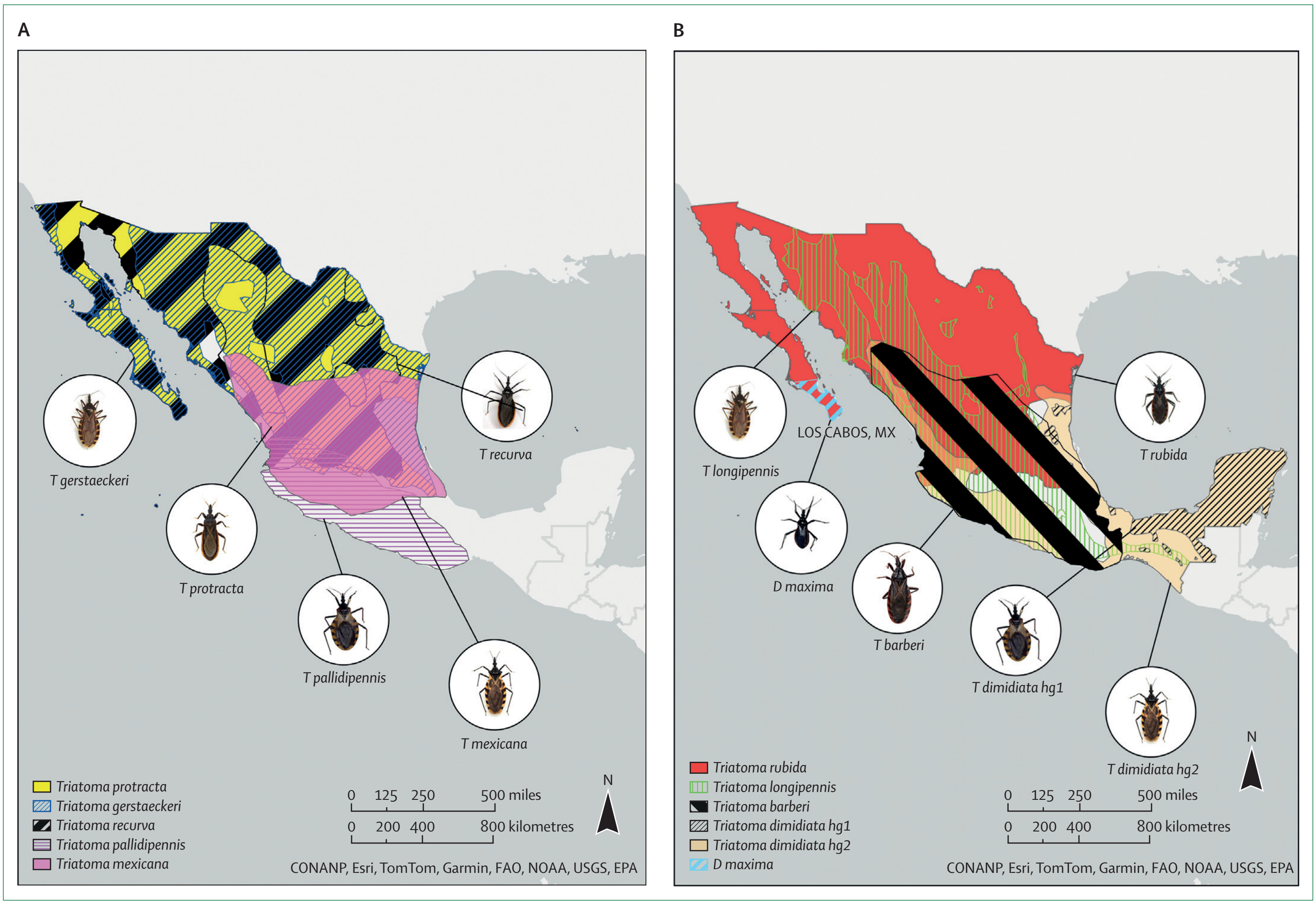

Figure 3: **Principal triatomine species capable of transmitting *Trypanosoma cruzi* in Mexico**
Current distribution of major triatomine vectors of *T cruzi* in Mexico (A and B). For more details on methods and sources, see appendix p 2.

environmental suitability for extension of the species to parts of Costa Rica, Nicaragua, Belize, and Yucatán.[31]

Torres-Delgado and colleagues[33] modelled the effects of climate change on the distribution of *Triatoma nitida* using the Beijing Climate Center Climate System Model. Although not currently a main vector in the region, *T nitida* is a highly adaptable sylvatic species that has previously been reported to invade homes in Guatemala.[46] Torres-Delgado and colleagues found a trend towards decreasing distribution and also noted that new areas could become susceptible to habitation by *T nitida*. The effect of present-day demographic changes in central America, including unplanned urbanisation, population growth, land-use change, and biodiversity loss, in tandem with socioeconomic factors such as improved housing conditions, forced migration, and animal and plant trade, on the dynamics of Chagas disease needs to be better understood.[3]

North America

Mexico

The study of the effect of climate change on the risk of Chagas disease in Mexico has primarily focused on vector–parasite interactions or the geographical responses of vectors. Important vector species of Mexico are shown in figure 3. Vector–parasite interactions have been investigated by experimental studies and the geographical responses of vectors by correlational ecological niche modelling.

Two studies with experimental approaches have been conducted on the Mexican *Triatoma pallidipennis* species to investigate the effect of increasing temperatures on both the immune function of *T pallidipennis* against *T cruzi*[30] and the abundance of *T cruzi* parasites during infection in the vector.[32] In both studies, as temperatures increased, vectors showed a decrease in their immune system capacity against *T cruzi* infection and therefore had reduced survival. Furthermore, the number of parasites in the midgut of insects increased at intermediate temperatures (30°C) but decreased at 34°C, which was the limit of the temperature range tested. Therefore, based on the experimental results, there is an anticipated reduction in vector capacity due to climate change.[30] On the other hand, we identified two studies that used correlational approaches to infer how the geographical distribution of Mexican triatomines would be affected in different climate change scenarios[29,34] and one study that additionally included an analysis of the compound effect of human-modified landscapes.[16]

Carmona-Castro and colleagues[29] analysed the influence of climate change, represented by different Representative Concentration Pathways 4·5 and 8·5, on the potential distribution of 20 vector species and the *T cruzi*-vector relationship for 2050 and 2070. Two different ecological niche modelling algorithms were used to mitigate software bias, which concluded that climate change will have idiosyncratic effects on species, with *Triatoma recurva* and *Triatoma sanguisuga* showing higher increments in habitat suitability area, representative of Nearctic species with currently larger geographical ranges. Although *Triatoma protracta* has one of the largest territorial distributions, the potential geographical range and mean elevation are expected to slightly decrease. *T sanguisuga*'s potential distribution could extend northward or southward.[26] In contrast, neotropical species with smaller ranges will experience reductions or no substantial changes between current and future potential distributions. *Triatoma barberi*, *Triatoma longipennis*, and *Triatoma mexicana* are expected to have high reductions in their habitat suitable area. Carmona-Castro and colleagues[29] also analysed human exposure to vectors under climate change scenarios and concluded that the highest increment in human exposure to any vector in Mexico will be for *T recurva* and *T protracta*.

Using the same approach, Flores-López and colleagues[34] investigated how *Dipetalogaster maxima*, the largest triatomine of the Americas with one of the smallest ranges—located at the tip of the south Baja California peninsula in La Paz, Mexico—will respond to climate change. Flores-López and colleagues[34] assessed whether vector and *T cruzi* niches will be coupled under these scenarios and concluded that both the vector and parasite will have overlapping suitable areas when they are moving northwards. Flores-López and colleagues,[34] who also assessed human exposure to distributional shifts, suggested that the popular tourist destination of Los Cabos, Mexico is potentially in a high-risk zone for the circulation of *T cruzi*.

Using a correlative ecological niche modelling approach that employs a Bayesian data mining framework, González-Salazar and colleagues[16] predicted *T cruzi* transmission cycles under future land-use and land-cover change (LUCC) in climate change scenarios for 2050 and 2070 in Mexico.[16] In addition to modelling 21 vector species, the study included mammals hosting the parasite as part of the vector niches (biotic factors). By correlating *T cruzi* transmission cycle presence (ie, vector or host presence, or both) with LUCC, González-Salazar and colleagues[16] characterised environmental conditions (ie, eco-epidemiological landscapes) that might favour pathogen transmission, and among their main results, they anticipated a growing pattern of domiciliation processes in *T cruzi* transmission, mainly governed by LUCC towards urbanisation and forest degradation (ie, human-modified landscapes). Accordingly, Chagas disease could become an emerging health problem in urban areas.

USA

In the USA, triatomines are endemic and have existed for thousands of years,[47] with the currently recognised distribution including the 28 southernmost states (figure 4). Furthermore, human transmission of *T cruzi* has a long history in the southern USA, with the parasite DNA detected in a 1150-year-old mummy in south Texas,[48] and *T cruzi* is detected in wildlife reservoirs and domestic dogs in most regions where triatomines are found. Despite the wide spread presence of vectors and the parasite in the environment, autochthonous human infections in the southern USA are rare, with only 76 cases reported between 2000 and 2018.[49] Although these case reports reflect only a subset of true local infections, which could affect up to 10 000 people,[21] aspects of vector biology (including potentially prolonged post-feeding defecation intervals and socioeconomic conditions) appear to keep triatomines predominantly in outdoor or sylvatic habitats where humans are at less risk of infection (but where dogs and wildlife could readily be infected).[50] For example, a large triatomine community science programme across the southern USA revealed that only 607 (26%) of 2334 triatomines encountered by humans and submitted to the programme from 18 states were found indoors.[51] However, domestic infestations by triatomines have long occurred in the southern USA, with increasing awareness of transmission risk and the problem of human bites by the vector leading to anaphylaxis.[52]

Despite the history of triatomines and *T cruzi* in southern USA, new reports of triatomine encounters or cases of human or animal Chagas disease are often casually linked to climate change or even human migration. For example, a compilation of triatomine reports from the mid-country states of Illinois and Missouri[53]—both of which are states where triatomines are a part of the natural environment—led to news coverage with titles such as "Problematic bug makes its way to Springfield [Illinois]; Global warming leads kissing bug to migrate from Latin America".[54] In terms of bringing attention to neglected vectors or diseases, such news attention is welcome, but the links to climate change reported therein might be inaccurate or premature. To understand whether with climate change, expanded vector distributions or increased human or animal burden of the associated Chagas disease will be observed now or in the future, there is a need for historic and current baseline data based on which change can be measured; however, such data are lacking. The need for such data is especially true along what is currently recognised as the northern distributional limits of triatomines, where population densities are low and there is inadequate awareness (eg, Wyoming and Delaware),[55,56] and thus, vector encounters might be interpreted as resulting from a newly arrived vector.

There are 11 species of triatomines known to occur in the USA (locally known as kissing bugs), with a subset of species regularly encountered by humans, which are implicated in human bites or the transmission of *T cruzi* to humans or animals. These key species in southern USA include

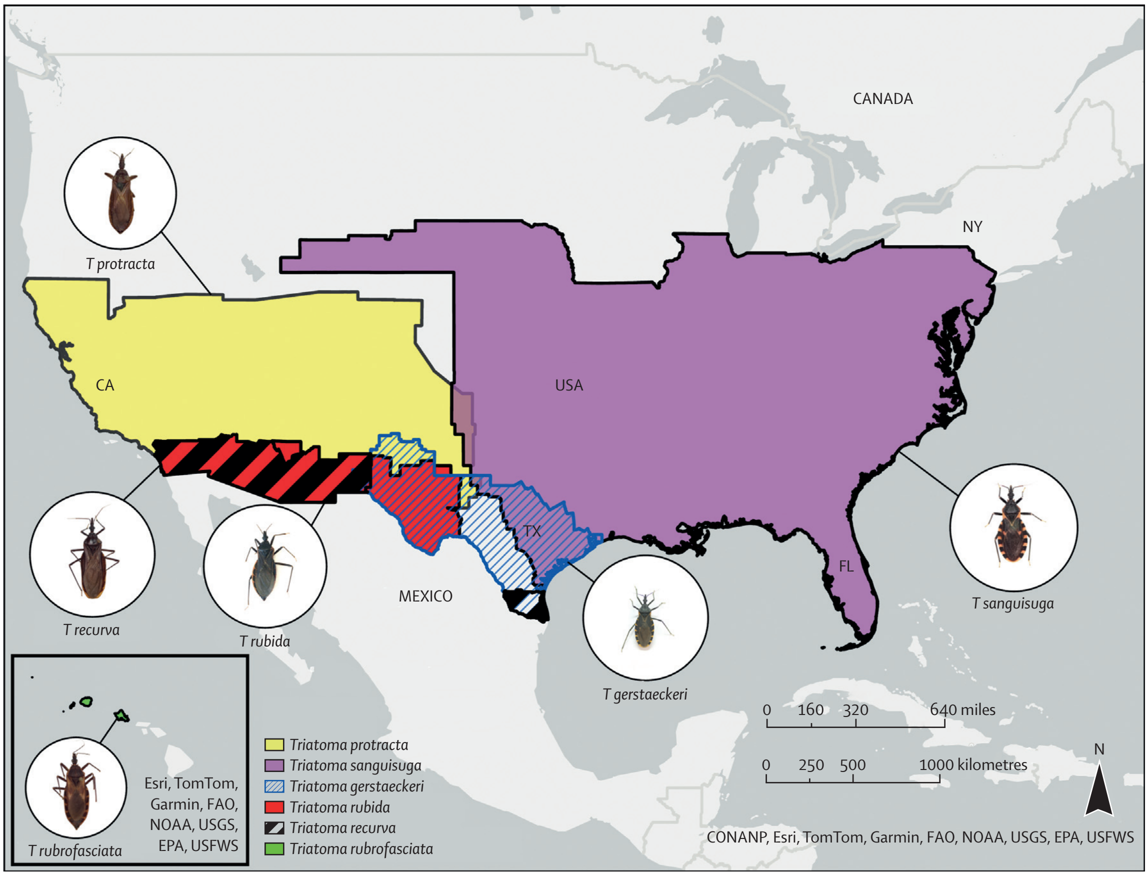

Figure 4: **Principal triatomine species capable of transmitting *Trypanosoma cruzi* in the USA**
Current distribution of major triatomine vectors of *T cruzi* in the USA. For more details on methods and sources, see appendix p 2.

Triatoma gerstaeckeri, *T sanguisuga*, *Triatoma rubida*, *Triatoma indictiva*, *Triatoma lecticularia*, and *T protracta*; quantitatively, these six species are the most encountered by humans, as indexed by a community science programme (figure 2).[51] Infection prevalence varies by species, with one multispecies study of adult triatomines showing 61·6% infection by *T gerstaeckeri,* 21·7% by *T sanguisuga*, and less than 10% by all other tested species.[57]

Results from our literature search revealed a paucity of research on climate change, triatomines, and Chagas disease from the USA, with only four articles meeting the search inclusion criteria. Click Lambert and colleagues[24] used a geographical information system and minimum temperature thresholds to delineate occurrence zones for three species known to transmit *T cruzi* and showed a predicted northward expansion of the at-risk zone under future climate change scenarios. Furthermore, Click Lambert and colleagues[24] used physician surveys in the predicted risk zones to conclude that there is little awareness of Chagas disease. Finally, Garza and colleagues[26] used maximum entropy models to predict a northern shift of *T gerstaeckeri* and southern shift of *T sanguisuga* from their current ranges due to climate change.

Canada

Our search strategy only yielded one study related to Chagas disease in Canada. Cox and colleagues[25] solicited expert opinions and analysed 40 criteria to prioritise emerging infectious diseases of most concern in Canada in the context of climate change and identified Chagas disease as one of the top three diseases. To date, there have been no reported cases of autochthonous Chagas disease in Canada, which is well north of the range of vector species. Garza and colleagues[26] modelled scenarios where *T sanguisuga*, which has already been found as far north as Illinois and Wyoming, could move northwards, although Garza and colleagues do not explicitly mention Canada.

Discussion

Despite the relevance of climate change and the need to control NTDs to achieve the UN Sustainable Development Goals,[3] research examining the effect of climate change on *T cruzi* transmission beyond South America is only beginning to emerge. We identified 12 studies that explicitly focused on the effect of climate change on *T cruzi* transmission; most of the studies modelled future trends in the distribution of vector species. Although climate change could enable expansion of some vector species northward, few studies focused on the USA and Canada and only slightly more on Mexico and central America. The current literature suggests that the relationship between climate change and *T cruzi* transmission is not straightforward. Triatomine populations might decline in some scenarios but might expand into new areas in other cases. Anthropogenic effects, such as deforestation, not only contribute to climate change but also affect habitats available to triatomine populations. Key questions remain about how triatomines will adapt to such changes.

Nine of the 12 studies included in this current review modelled the potential effects of climate change on select triatomine species, most using species distribution modelling with the incorporation of key bioclimatic variables. One major challenge for these types of studies is being able to account for the diversity of factors that affect both triatomine distribution and any implications for epidemiological scenarios of *T cruzi* transmission risk. Although most models account for trends in temperature and precipitation, there are inherent uncertainties, and other factors such as shifts in populations of reservoir species, changing patterns of human migration or land use, and changes in the health system (such as improved prevention or treatment of *T cruzi* infection) are often not incorporated in the modelling exercises.[26] Even with these limitations, these studies suggest heterogeneous effects of climate change, with some species occupying new niches or expanding range and others declining.

Only one of the modelling studies also attempted to quantify the increased risk of human exposure by considering both rural and urban populations.[29] Alternatively, de la Vega and colleagues[27] combined geospatial modelling with experimental data on thermotolerance, urging future researchers to expand on the approach by incorporating estimates of the force of transmission. Another crucial approach for future research would be to triangulate or corroborate predictions from geospatial models with longitudinal data from field observations, particularly in areas considered at high risk for increased triatomine presence under climate change. Citizen science approaches could be incorporated into the effort.[58] Additionally, social science research and qualitative methods could provide key insights on how climate change, anthropogenic activities, and the risk of *T cruzi* transmission interrelate with each other. Epidemiological analyses can also incorporate a climate-relevant perspective, for example, by investigating the association between predicted changes in vector habitat and incidence of transmission over time.

Extended periods of higher temperatures can contribute to an elevated risk of exposure to triatomines. Furthermore, extended warm seasons can create an opportunity for sylvatic species of triatomines to transition into more domestic settings. As the climate becomes more favourable for the vectors, there is concern that the vectors could adapt and thrive in areas that had previously been less conducive to their survival.[59] This shift could bring triatomines closer to human habitation, including urban areas, thereby increasing the risk of Chagas disease transmission. Most physiological traits in ectothermic arthropods respond to temperature non-linearly, from zero at a CT_{min} increasing exponentially to a thermal optimum before returning to zero at a CT_{max}. The effect of climate change on the thermotolerance range of vector-borne diseases is, therefore, non-linear.[60] Thus, temperature affects not only the geographical range of arthropods but also many transmission-related cycle traits such as oviposition and developmental rate, adult life span, population density, biting rate, and the pathogen's development in the vector (ie, extrinsic incubation period).[60]

Temperature is, however, just one of the many interrelated environmental factors that influence the complex transmission cycles of vector-borne infections in nature. Within this ecological niche, humidity, precipitation, and host aspects such as reservoir availability and susceptibility, population numbers, and movement play a less understood role. Furthermore, additional research is needed to understand how the effects of climate change-linked events, such as severe storms or droughts, affect *T cruzi* transmission dynamics outside of South America. For example, one study recorded a marked increase in *T dimidiata* abundance in Yucatán (Mexico) in the wake of Hurricane Isidore in 2002.[61]

The government and public health response to climate change and vector-borne diseases, particularly Chagas disease, involves a multifaceted approach that should be aimed at addressing the complex interplay among environmental shifts, disease transmission, and human behaviour. As climate change influences the geographical distribution and exposure risks of triatomines, governments will need to implement adaptive strategies such as increasing surveillance systems to monitor vector populations and subsequent disease prevalence in changing environments. Predictive modelling has shown that Chagas disease is one of the top three diseases of concern in Canada because of increased temperatures and precipitation from climate change.[25] Public health campaigns should emphasise community education and empowerment on vector control measures, focusing on at-risk regions but also including intersectoral cooperation and integrated pesticide management as part of the sustainability plan.[62] As research initiatives explore the ecological effect of climate change on vector habitats, this information will need to be shared with public health policy makers and professionals, aiding in the development of targeted interventions, including monitoring vector distribution patterns, implementing preventive measures, and raising awareness among communities at risk. In Mexico and the USA, there is inadequate awareness of this emerging disease, requiring changes in health systems to respond effectively to the disease.[63] Priorities to manage this public health challenge include control programmes to prevent new cases through vertical transmission, blood transfusion, or organ transplant and health system interventions to increase clinician awareness of Chagas disease.

The efficacy and long-term viability of vector control measures are intricately tied to the acceptance and adaptation of the community members in the face of the effects of climate change. Active participation of communities in the planning phase, involving collaborative decision making on logistics and coordination, is pivotal for the development of vector control programmes that are not only responsive to community needs but also resilient to climate-related challenges.[64,65] Reduction in exposures and risks could be improved by fostering a more sustainable and community-driven approach to mitigate the effects of Chagas disease. This approach might involve educating communities with less knowledge or awareness of triatomines and using a more participatory action research methodology to increase engagement in the implementation and evaluation of a control strategy. Citizen science approaches to understanding vector transmission in different contexts provide a promising path forward.[57,58] An ecohealth model to reduce exposure risks considers the social and cultural aspects of the affected communities, recognising that local practices, housing structures, and socioeconomic factors affect vulnerability to Chagas disease.[9] This model will require involving local stakeholders in the planning and implementation of effective interventions.

Triatomine-integrated vector management programmes focus heavily on reducing the vector burden within communities and follow a structured approach relying on five key concepts: (1) advocacy, legislation, and social mobilisation; (2) collaborative efforts between health sectors and other stakeholders; (3) an integrated approach such as multifaceted pest management programmes; (4) evidence-based decisions on policies within the programme; and (5) capacity-building mechanisms designed in the structure of the programme.[62,66] Policy making environments for triatomine-integrated vector management programmes should involve local and national governments; health, agricultural, and environmental sectors; and international bodies such as those found within the Pan American Health Organization and WHO. Ecohealth initiatives for the triatomine vector *T dimidiata* have been implemented successfully.[67] Another ecohealth approach implemented in two rural villages in Yucatán, Mexico led to a calculated reduction in the incidence of Chagas disease by 32%.[68] Within the USA, an integrated pest management approach to tackle triatomine invasion into homes has been developed in Florida, but further studies are under way to evaluate these strategies.[66,69] Overall, with anthropogenic and climatic changes being observed in North America, local and vector-specific integrated vector management programmes will need to be developed. Triatomine control methods that already exist or are under development include biological control mechanisms, environmental insecticide, genetic control via engineered symbionts that are delivered to triatomines to make them resistant to *T cruzi* infection, deployment of mass trapping devices, xenointoxication from host-targeted interventions, and environmental modifications and ecohealth-driven management strategies.[70]

Climate change is a complex occurrence with profound implications for a disease that is intimately linked with human socioeconomic conditions and interactions with the environment.[9] Anthropogenic factors such as land-use change, housing conditions, vector control measures, and migration can affect the geographical range and magnitude of vector-borne diseases such as Chagas disease. More research is needed to better understand how climate change will shape the epidemiology of Chagas disease in North America's diverse ecological and socioeconomic contexts. Future studies should examine the effect of a warming planet on the parasite's dual host cycling adaptation, population density, and diversity, as well as parasite prevalence and virulence,[71] phenotypic traits, microbiome, gene expression, immunity, and vector competence.[72] Moreover, social science research can strengthen the understanding of how phenomena such as migration and agroindustrial expansion, as well as changing human relationships with the environment, will affect future domestic and zoonotic transmission cycles.

Although we did not identify studies that explicitly focus on vertical or food-borne transmission of *T cruzi*, the implications of climate change on these routes certainly deserve further attention. Food-borne transmission of *T cruzi*, better known as oral Chagas disease, carries profound implications for human health and potential manifestations of climate change. Little is known about the direct route of oral ingestion, but several mechanisms exist, including ingestion of contaminated foods or beverages with the parasite, consumption of undercooked infected wildlife, and even possible transmission from an infected opossum through anal gland secretions. More research is needed to address concerns for oral transmission in North America and recognition of this route of transmission with migration and climatic changes.

This study had limitations. We searched only two databases, and although we strived to be as exhaustive as possible, some studies could have been missed, especially from the grey literature. We did not include studies from South America, yet reviewing the South American literature could have important relevance for North America as both *T cruzi* strains and triatomine species (eg, *T dimidiata*) often extend to both the continents. de Souza and colleagues[3] provided an expert review on the effects of climate change on Chagas disease, covering literature published in South and central America. We also did not review studies that examined the effects of climate change on important animal host species, which would have been difficult to implement given the wide host range of reservoir species and independence of most of these studies to Chagas disease.[41,73] Moreover, many studies that do not specifically consider climate change could, nevertheless, provide important baseline data that facilitate the measurement of future shifts in disease epidemiology and the distribution of host and vector species.

In conclusion, the effects of climate change will create new challenges for the communities affected by NTDs and thus should be understood within the complex socioeconomic and environmental factors that shape the epidemiology of diseases such as Chagas disease. In North America, rapid urbanisation, deforestation, and migration (often fuelled by the effects of climate change) are crucial factors that need to be considered when planning a public health response. Collaboration among North and South American countries and the involvement of the affected communities in developing solutions will help to ensure the sustainability of programmes to contain the burden of one of the continent's most neglected diseases.

Contributors

CF conceptualised and designed the research. CF and AV-T were in charge of the literature search and methodology. AV-T, NIA-H, CNI-C, CF, SAH, GLH, PS-G, and NB performed the formal analysis. CF, NIA-H, SAH, AV-T, PS-G, and MV wrote the original draft. CF, AV-T, NIA-H, CNI-C, SAH, GLH, PS-G, NB, and MV conducted critical review and editing of the manuscript.

Declaration of interests

We declare no competing interests.

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