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Climate Change Will Increase the Vector Capacity of the Aedes aegypti in South America: A Systematic Map

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1. Introduction

The mosquito *Aedes aegypti* (Diptera: Culicidae) is the vector of several arboviruses that significantly impact the global burden of disease, including dengue (DENV), chikungunya (CHIKV), and Zika (ZIKV). The diseases brought on by these arboviruses have garnered considerable attention in the last few decades. The incidence of the geographical spread of human disease caused by these viruses has increased dramatically within their range, in addition to occurring in new geographical locations (Kraemer et al., 2015). Notable outbreaks include the major ZIKV outbreak in the Americas in 2014 (Chang et al., 2016), the CHIKV outbreak on Réunion Island in 2005 (Borgherini et al., 2007), and a severe DENV outbreak in Rio de Janeiro in 2002 (Nogueira et al., 2005). A troubling concern is the vector's ability to adapt effectively to varying environmental conditions (Mohammed & Chadee, 2011.) Indeed, the mosquito has evolved remarkably quickly into a competent vector. It is thought to have evolved from a zoophilic treehole ancestral mosquito named *Aedes aegypti formosus* in Sub-Saharan Africa (Powell & Tabachnick, 2013; Brown et al., 2014), and was introduced into the New World with the slave trade, from which it immediately spread globally (Brown et al., 2014). As the vector is poikilothermic, it was able to respond rapidly to the changes in the environment and eventually settled into empty natural niches (Mohammed & Chadee, 2011; Powell & Tabachnick, 2013). In time, the *Ae. aegypti's* peridomestic habits and endophagic disposition established it as an opportune vector for emerging tropical diseases (Moncayo et al., 2004).

Currently affecting millions of people globally, these tropical infectious diseases are among the most critical global health concerns. Present efforts to reduce the incidence of these infectious diseases center around vector control, including larvicide application, indoor residual spraying (IRS), and mosquito surveillance (Lippi et al., 2019). Except for yellow fever (YFV), presently, there is no vaccine for the arboviruses that the *Ae. aegypti* mosquito transmits (Kantor, 2018), which impairs efforts to decrease the significant disease burden it imposes. As such, monitoring the current range and predicting changes in the distribution of the vector is a crucial strategy for effective disease control planning (Messina et al., 2015). While a considerable level of interest has been invested in this emerging field of research, it was not clear from an exploratory literature search whether South America is represented at the same levels as the African and Southeast Asian regions. DENV, CHIKV, and lymphatic filariasis, all transmitted by the *Ae. aegypti* mosquito, are classified by the World Health Organization (WHO) as neglected tropical diseases (NTD) (World Health Organization, n.d.). Although the UN did not include NTDs in the Millennium Development Goals (MDGs), they were subsequently included in the Sustainable Development Goals (SDGs) as measurable targets, with the purpose of ending epidemics (Vanderslott, 2019). In South America, the burden of disease from these arboviruses has significantly impeded economic development and represents significant opportunity costs. Therefore, it is imperative that this region not be overlooked (Franco-Paredes et al., 2007).

1.1. Vectorial Capacity

A limiting factor in the *Ae. aegypti's* geographic distribution has been its inability to tolerate temperatures below 15°C (Brady et al., 2013); therefore, it has predominantly settled in tropical and subtropical regions (Weaver, 2014). Recent reports predict that global temperatures will increase between 1.4-5.8°C, and in Latin America between 1.0-4.0°C by 2050 (Intergovernmental Panel on Climate Change, 2007). Consequently, a growing concern is how it will impact the vectorial capacity of the mosquito. In addition to range, temperature plays a pivotal role in a variety of characteristics of the *Ae. aegypti*: frequency of blood meals (Scott et al., 2000); sex ratio in larvae (Mohammed & Chadee, 2011); development duration (Farjana et al., 2011); population density (El Moustaid & Johnson, 2019); pathogen transmission (Reinhold et al., 2018); and adult survival rate (Culbert et al., 2019). Thus, it is crucial to examine how increasing temperatures may potentially affect *Ae. aegypti*'s competence as a vector.

The *Ae. aegypti* mosquito transmits arboviruses, or "arthropod-borne viruses," which are predominantly RNA genomes that have a high rate of mutation and thus evolve rapidly. Temperature can impact the rate at which viruses replicate in the mosquito's midgut, shortening the extrinsic incubation period (EIP) and reaching the salivary glands at an accelerated rate (Winokur et al., 2020). Additionally, *Ae. aegypti* mosquitoes can transmit DENV, ZIKV, and CHIKV vertically; that is, infected female mosquitoes can pass the viruses on to their progeny (Alonso-Palomares et al., 2019). This ability has contributed to the maintenance of viruses during inter-epidemic periods (Lequime & Lambrechts, 2014).

1.2. Blood Feeding

Given that the mode of disease transmission in the *Ae. aegypti* mosquito is through blood-feeding, it is essential to understand what factors affect the frequency of blood meals. The *Ae. aegypti* mosquito is highly anthropophilic; therefore, it feeds predominantly on humans (Liebman et al., 2014) and seldom supplements blood meals with plant sugar (Scott et al., 2000). Attempts to understand which members of the population are more likely to be bitten by the mosquito have remained inconclusive. However, factors that appear to increase the likelihood of bites include larger body size, due to increased heat signature and CO2 production, as well as decreased human movement (Liebman et al., 2014).

Compared to other mosquito species that typically ingest one blood meal per ovarian cycle, the female *Ae. aegypti* mosquito is unique in that it will ingest multiple blood meals throughout a gonotrophic cycle (Scott et al., 2000). This behavior is known as multiple feeding, and as the number of blood meals increases, the rate of transmission for vector-borne pathogens can potentially exponentially increase as well (Scott & Takken, 2012). There is a negative relationship between body size and multiple feedings; that is, smaller females will require more blood meals to improve their fecundity, thereby increasing their contact with hosts (Farjana & Tuno, 2013). Previous studies have established a negative relationship between temperature and body size due to shortened development time (Mohammed & Chadee, 2011; Tun-lin et al., 2000), suggesting that an increase in temperature would eventually lead to an increase in the frequency of blood meals. Female *Ae. aegypti* mosquitoes were found to partake in higher instances of blood-feeding between 26°C and 35°C (Reinhold et al., 2018). This is especially disconcerting when considering that as temperatures pass 25°C, the sex ratio in *Ae. aegypti* larvae show significantly more females emerging (Mohammed & Chadee, 2011). An increase in the number of smaller females requiring a higher frequency of blood meals would ostensibly lead to heightened contact with hosts, consequently increasing the likelihood of pathogen transmission. Indeed, increased contact between humans and *Ae. aegypti* populations have been associated with the dramatic rise in the incidence rate of DENV and YFV in recent decades (Monath, 1994).

1.3. Development

Aside from the previously established negative relationship with body mass, increasing temperatures have further effects on the development of the *Ae. aegypti* mosquito. The eggs of the *Ae. aegypti* have a unique property in that they hatch simultaneously when exposed to water, as opposed to irregularly, as is the case in other species of mosquitoes. This property lends itself well to rapid population growth and will likely aid the *Ae. aegypti* in establishing colonies in new niches. Indeed, data suggests it may be able to find success in areas where the temperature is in the range of 25-35°C (Farjana et al., 2011). The rate at which females lay eggs increases as temperatures rise, leading to a more substantial amount of eggs being laid more frequently (Yang et al., 2009).

The adult mortality rate begins to increase exponentially at 35°C, suggesting that it may be the upper limit for the vector. Similarly, at 25°C, larvae begin to experience higher mortality rates. The probability of surviving from egg to adulthood diminishes past 25°C and vanishes completely upon nearing 40°C (Moustaid & Johnson, 2019).

Mosquitoes use a variety of methods to locate a host, such as thermal and chemical detection, and as such, flight activity is intrinsically linked to their success in blood-feeding. Data suggests that the temperature range in which the female *Ae. aegypti* can fly sustainably is 15-35°C, with the optimal temperature appearing to be around 21°C (Reinhold et al., 2018). Humidity has been shown to have little to no effect on flight performance (Rowley & Graham, 1968). This illustrates a broad spectrum of temperatures in which the female *Ae. aegypti* can fly reliably in pursuit of blood meals. Female *Ae. aegypti* mosquitoes use a specific frequency of wing-beats to attract a mate, and this frequency has likewise been shown to vary with ambient temperature. Notably, there is a linear relationship, with frequency increasing between 8-13Hz for every degree °C and male *Ae. aegypti* were shown to react more favorably to higher frequencies (Villarreal et al., 2017). This implies adaptability to improve the chances of mating during times of abiotic stress in order to increase fitness.

1.4. Spatial Distribution

The natural niche of the *Aedes aegypti* mosquito has primarily been dictated by its inability to survive below 10°C and above 40°C (Reinhold et al., 2018). This has historically afforded regions outside of that range inherent protection; however, reports suggest that temperate zones formerly outside the endemic range are among the most at risk of being negatively impacted by climate change (Rohr et al., 2011). In the past century, a 30% increase in CO_2 production raised global surface temperatures by 0.5°C (Wigley et al., 1992). Minimum temperatures are increasing disproportionately, and current climate change predictions expect this trend to continue. Such scenarios could increase the epidemic potential in regions previously unburdened by disease (Patz et al., 1998). The *Ae. aegypti* mosquito primarily resides within latitudes 32° N to 32° S, and projection models estimate that that will soon expand to 35° N to 35° S (Alaniz et al., 2018). Current statistical models predict the *Ae. aegypti* mosquito will be able to establish itself in at least three new countries by 2080, bringing its spatial distribution to 159 countries total (Kraemer et al., 2019). This would potentially put 49% of the global population at risk of arboviral transmission (Kraemer et al., 2019). Given the mosquito's peridomestic preferences and ability to lay eggs in small amounts of water, it will not be much affected by changing precipitation levels or decreased vegetation (Kraemer et al., 2015). Previous studies have established that domestic water storage practices are more significant predictors of mosquito reproduction than rainfall (Southwood et al., 1972).

Presently, an estimated 100 million people are infected annually by the *Ae. aegypti* mosquito (Messina et al., 2019), and this number is predicted to increase to close to a billion by the end of the century (Ryan et al., 2019). The population at risk may be significantly lowered if climate policy, such as the Paris Agreement (UNFCCC), is enforced to limit global warming to below 2°C (Liu-Helmersson et al., 2019). Reducing the emission of greenhouse gases will limit the increase of the *Ae. aegypti's* expansion, and in turn, limit the burden of disease in the areas it inhabits (Kraemer et al., 2019).

2. Methods

2.1. Search Criteria

We conducted a systematic search in the PubMed database for articles that assessed the relationship between temperature and the vectorial capacity of the *Aedes aegypti* mosquito. Search parameters specified English or Spanish languages and publication dates between January 1, 1988, and March 30, 2020. We developed the search strategy using the synonymous search terms provided in Appendix 1. Studies that did not include climate change as an element of analysis were excluded. Studies before 1988 were excluded to restrict the results to the current era of climate change, which is defined as the year the Intergovernmental Panel on Climate Change (IPCC) first convened (Huq & Toulmin, 2006). Studies without full-text availability were not excluded. We used Zotero to manage studies and data.

2.2. Study Design

For this study, we utilized a systematic map approach to assess the current state of research on this topic and followed the recommendations made by the Social Care Institute for Excellence (Bates et al., 2007) as well as the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Moher et al., 2009). The search strategy was not limited by article study design. Studies were only eligible for inclusion if they met the following criteria: the study population was the *Aedes aegypti* mosquito; the effect of climate change on the *Aedes aegypti* was examined; and the outcome was an influence on the mosquito's vectorial capacity.

2.3. Data Extraction

One reviewer (LM) screened titles and abstracts using DistillerSR, then screened the included full-text articles. One reviewer (LM) subsequently extracted the geographical region and country the study was based in, the study characteristics, then evaluated the quality of the study and recorded the data in a standard form. Only studies that evaluated climate change's potential effect on the *Ae. aegypti* population were used in the analysis, while studies that only focused on temperature outside of the context of climate change were excluded. All articles were grouped according to the region in which the study occurred.

3. Results

Our initial search in PubMed yielded 1058 articles after the removal of duplicates, and 503 remained after the full-text screening (Figure 1). Only 83 articles met the inclusion criteria and were subsequently included in the analysis (Table 1). [Appendix].

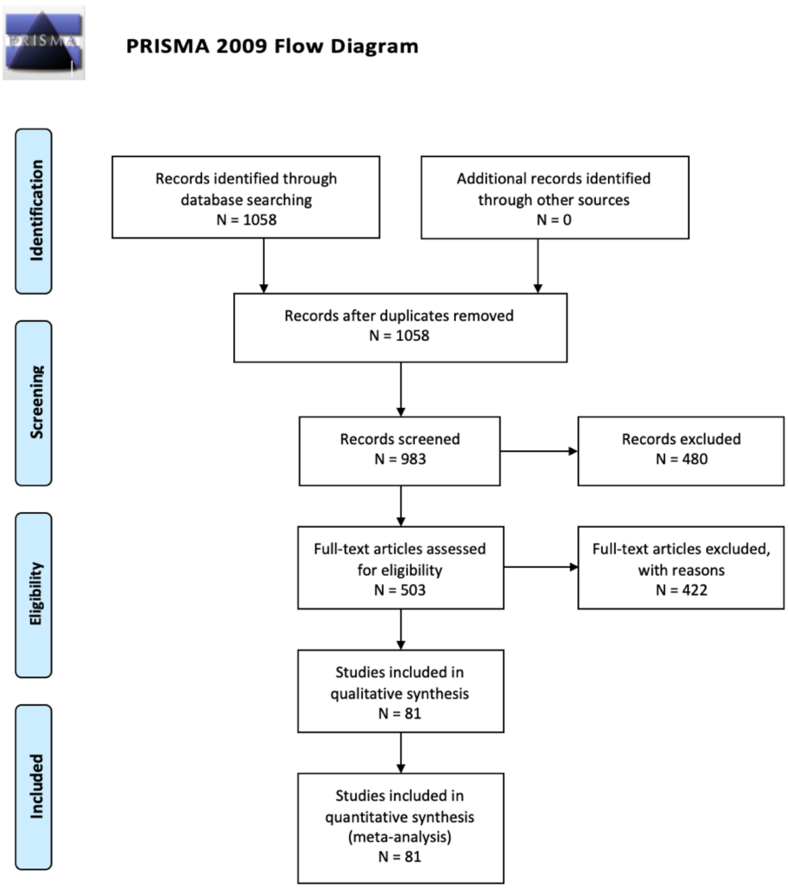

Figure 1: PRISMA flowchart of studies included in analysis

Although our inclusion criteria set the publication date to be from 1988 to 2020, most of the included studies were published in late 2000 and on. Fig. 2 illustrates the quantity of included studies per publication year. There was a significant increase in the number of studies published on this topic in 2019.

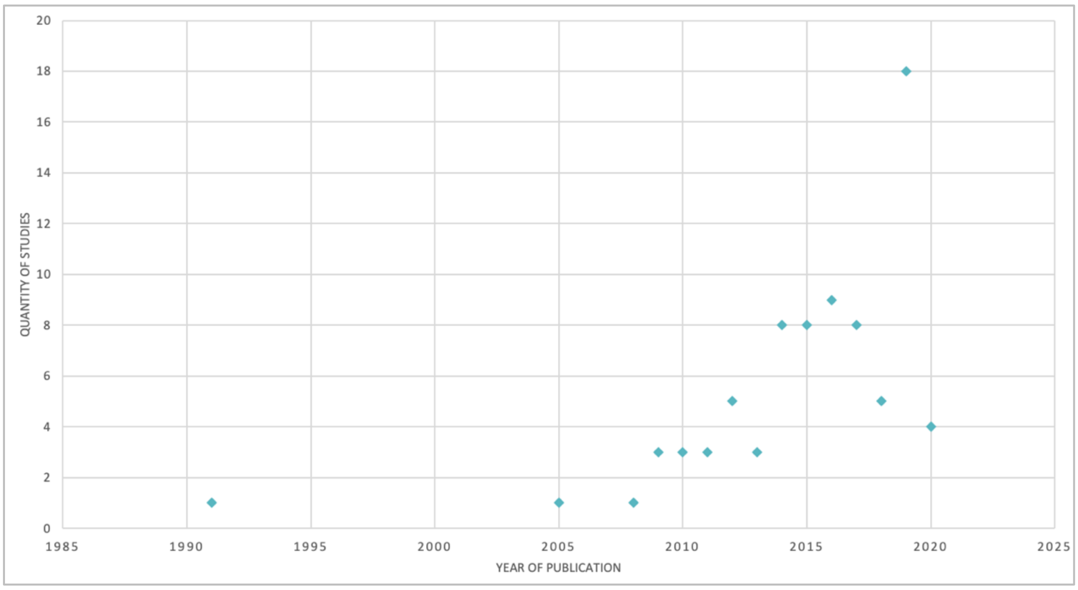

Figure 2: Publication dates and quantity of studies included in analysis

Asia and North America were the regions with the highest number of published articles (n= 23, 28%; n= 15, 18%), followed by Europe (n= 14; 17%). [Figure 3]. In South America, most of the studies were on Brazil or Argentina (n= 2; 20%), but overall only five of thirteen countries in South America were represented in the literature [Figure. 4]. The *Ae. aegypti* mosquito is endemic in thirteen South American countries (Leta et al., 2018), yet no literature was included in the analysis that focused on eight of those countries. This leaves 62% of South America unrepresented. The areas in South America most heavily impacted by the *Ae. aegypti* are Brazil, Colombia, and Venezuela (Torres & Castro, 2006), yet Colombia and Venezuela were not well represented in the literature.

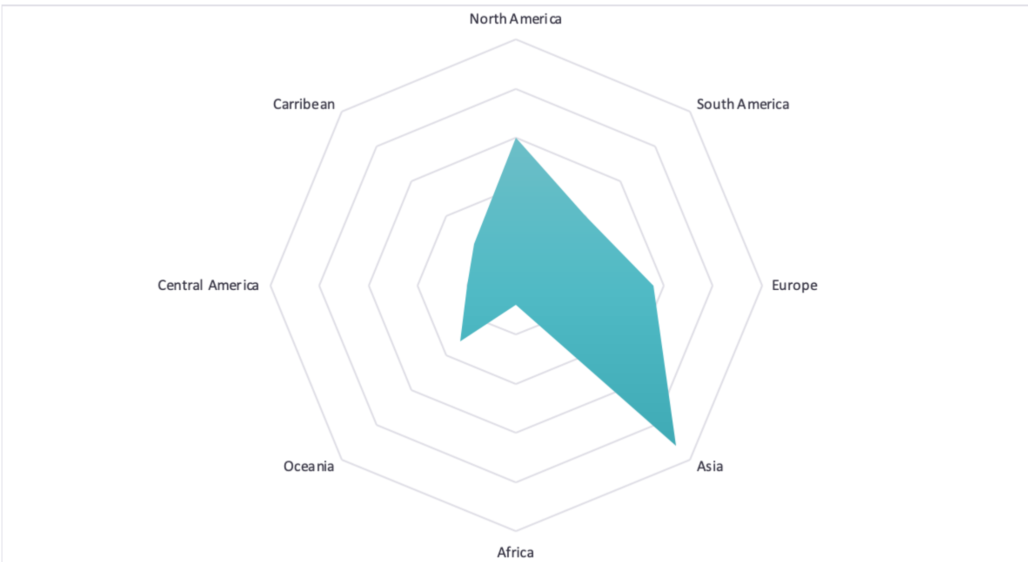

Figure 3: Spider map of geographical regions represented in included studies

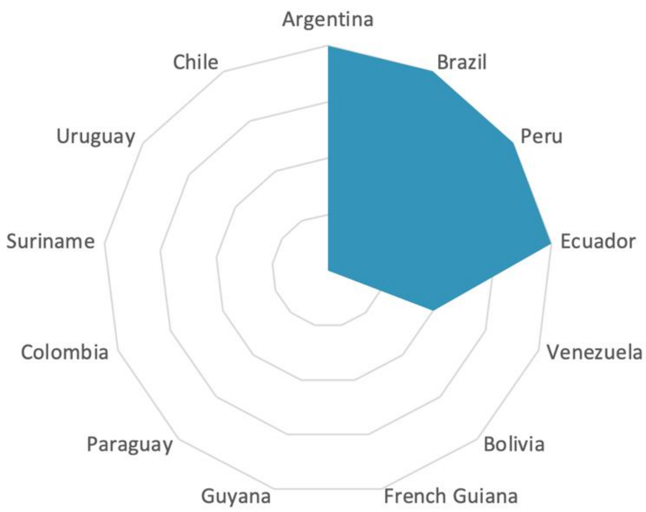

Figure 4: Spider map of South American countries represented in included studies

4. Discussion

The use of spider maps is an effective tool for summarizing the relative proportions of a measure across multiple dimensions. The spider maps included here illustrate, clearly, that the intellectual production on this important issue is limited. The results of a systematic review of the literature are quickly illuminated through these illustrative methods. As represented in Fig. 3, the literature is produced in only some regions of the world. This is important because climate change is predicted to disproportionately impact developing countries, and thus it is critical to understand how these areas will be affected by this topic (United Nations, 2019). In Fig. 4 we see that though South America suffers a significant burden of disease from this vector, the scientific work on the topic is limited. The spider map can quickly convey the gaps in knowledge and unmet need that faces South America.

With 70% of the global dengue burden affecting Asia, it was not surprising that the area would be well represented in the literature (Bhatt et al., 2013). Conversely, despite *Aedes*-borne arboviruses ravaging many areas of Africa, they were poorly represented in the literature (Weetman et al., 2018). This may be due to several factors, including the misclassification of many fevers as malaria in regions where the public health infrastructure lacks resources (Stoler et al., 2013). North America and Europe both had strong representation in the current literature, despite not being under significant threat from the *Aedes aegypti* mosquito yet, compared to the other regions (CDC, 2020). South America was not far ahead of neighboring regions Central America and the Caribbean, which had similar numbers of literature captured, although it should be noted that South America is the sub-region most impacted by the *Ae. aegypti* in Latin America and the Caribbean (LAC) (Torres & Castro, 2006).

While under-represented in the literature, it is worthwhile to establish estimates of the impact of these infectious diseases. It is difficult to find statistics on South America alone, as the continent is generally grouped together with the other components of LAC when publishing reports. In 2016, the Americas reported 2.38 million cases of dengue, of which

1.5 million were reported in Brazil alone (WHO, 2020). The economic cost this burden of disease presents on the health care systems in this region is significant. In 2010, the total cost induced by dengue fever alone in South America was approximately USD 1.4 billion (Shepard et al., 2011). The 2009 epidemic in Argentina cost approximately USD 10.7 million (Cafferata et al., 2013). The public healthcare systems in LAC are overburdened and overstressed, in addition to being largely underfunded. With these systems already overwhelmed by ongoing health emergencies due to tuberculosis (TB), DENV, and YFV, an increase in the burden of disease will strain the capabilities of LAC healthcare (Litewka & Heltman, 2020).

Several of the diseases the Aedes aegypti transmits have been classified as NTDs due to their strong correlation with poverty (WHO, 2010); therefore, it is essential to note that poverty is high in LAC, with approximately 30.8% of the population living below the poverty line, and 11.5% living in extreme poverty (ECLAC, 2019). Furthermore, 76.8% of the population falls into low-income to lower-middle-income brackets (ECLAC, 2019). These numbers are comparable in South America, with 23.3% and 6.4% of its population living in poverty and extreme poverty, respectively (CEPAL, 2019). That translates to around 184 million people living in poverty in that region (ECLAC, 2019). While regions such as Africa or Asia also have high instances of poverty, LAC is unique in that it has the highest income inequality in the world (Belizán et al., 2007). The impact of the COVID-19 pandemic on the region is expected to result in the worst recession in a century, leading to further inequality (United Nations, 2020).

The burden of disease in South America is confounded with high poverty rates and the inequality affecting vulnerable populations. In particular, indigenous populations tend to be disproportionately affected by vector-borne infectious diseases that arise during conflict (Hotez et al., 2008). The healthcare systems in LAC are segmented and fractured, which poses a major obstacle in increasing access to healthcare, particularly for those from lower socioeconomic status (Frenk & Gómez-Dantés, 2018). In many LAC countries, healthcare for those living in poverty is provided by a Ministry of Public Health, which is often poorly financed and historically has provided lower quality of care compared to the services provided by the private sector (Cotlear et al., 2014). With the COVID-19 pandemic expected to impact the most disadvantaged populations disproportionately, reform will be necessary to prepare for future crises (Busso & Messina, 2020).

5. Limitations

This study was limited by restricting the search to a single database and would benefit from an expanded search into multiple databases. In particular, a cursory search into Spanish language databases during the literature review found several studies that were not captured in PubMed. In addition, much of the data was constricted by the grouping of South America into LAC, and searches in Spanish had to be made in order to find the necessary conclusions.

6. Conclusion

By the end of the century, if nothing is done to limit climate change, it is predicted that close to a billion people annually are at risk of being infected by the *Aedes aegypti* mosquito (Ryan et al., 2019). Much of this will occur in developing countries, impacting agriculture, water availability, increasing the incidence of vector-borne diseases, and damage the GDP (Ravindranath & Sathaye, 2002). With its high rate of poverty and inequality, South America will be especially vulnerable to the expanded range and improved vector capacity of the *Aedes aegypti* mosquito. Compared to regions such as Asia or North America, South America does not appear to be as well represented in the current literature on this topic. It is clear from our results that more research is needed to be conducted on South America in order to fully understand how this region, in particular, will be affected in the coming century.

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Supplementary appendix

Supplement to: Climate Change Will Increase the Vector Capacity of the Aedes Aegypti in South America

Supplementary panel 1: Search strategy in PubMed

Climate Change

1. climate change (MeSh term (Medical Subject Headings)) AND aedes aegypti (key word)
2. climate change (MeSH term) AND dengue (MeSH term)
3. climate change (MeSH term) AND zika virus (MeSH term)
4. climate change (MeSH term) AND chikungunya fever (MeSH term)
5. climate change (MeSH term) AND chikungunya virus (MeSH term)
6. climate change (MeSH term) AND yellow fever (MeSH term)
7. climate change (MeSH term) AND yellow fever virus (MeSH term)

Aedes Aegypti

1. aedes aegypti (key word) AND temperature (key word)
2. aedes aegypti (key word) AND vector capacity (key word)
3. aedes aegypti (key word) AND vector competence (key word) AND temperature (key word)
4. aedes aegypti (key word) AND vector competence (key word)
5. aedes aegypti (key word) AND spatial distribution (key word)

Supplementary panel 2: Details of 81 publications included in systematic map and analysis

Title	Publication Year	First Author	Region	Country	Topic
Global climate change and infectious disease	1991	Shope	North America	USA	The effects of climate change on infectious diseases
Seasonal fluctuation of Aedes aegypti in Chaco Province, Argentina	2005	Stein	South America	Argentina	The seasonal fluctuation of Ae. aegypti with change in climate conditions
Dengue virus-mosquito interactions	2008	Halstead	North America	USA	Mosquito-dengue infection dynamics and the role of temperature
Assessing the effects of temperature on the population of Aedes aegypti	2009	Yang	South America	Brazil	How temperature affects the population of Ae. aegypti
Dengue and climate change in Australia: predictions for the future should incorporate knowledge from the past	2009	Russell	Oceania	Australia	Modeling future activity of dengue with climate change using historical data of distribution of vector
Australia's dengue risk driven by human adaptation to climate change	2009	Beebe	Oceania	Australia	Future increased risk of Ae. aegypti range expansion in Australia is due to installation to domestic water storing containers
Present and future arboviral threats	2009	Weaver	North America	USA	Potential future of arboviruses in new geographical regions
Climate variability and increase in intensity and magnitude of dengue incidence in Singapore	2009	Ling Hii	Asia	Singapore	How weather influences the increase of dengue incidence
Potential influence of climate variability on dengue incidence registered in a western	2010	Herrera-Martinez	South America	Venezuela	The effect of climate variability on dengue incidence

pediatric Hospital of Venezuela					
Dengue transmission in the Asia-Pacific region: impact of climate change and socio-environmental factors	2011	Banu	Asia	Multiple	Impact of climate change on dengue transmission
Effects of different temperature regimens on the development of Aedes aegypti mosquitos	2011	Mohammed	Caribbean	Trinidad & Tobago	The effects of increased water temperatures on the development of Ae. aegypti mosquitos
The role of climate variability and change in the transmission dynamics and geographic distribution of dengue	2011	Thai	Asia	Vietnam	The effect of global climate on the transmission of infectious diseases
Effects of temperature and diet on development and interspecies competition in Aedes aegypti and Aedes albopictus	2012	Farjana	Asia	Japan	How temperature and diet affect development in tow aedine species
Climate-based models for understanding and forecasting dengue epidemics	2012	Descloux	Europe	France	Analyze and model the relationship between climatic factors and dengue outbreaks
Global climate change and its potential impact on disease transmission by salinity-tolerant mosquito vectors in coastal zones	2012	Ramasamy	Asia	Brunei	The impact of rising sea levels on mosquito vectors
The dengue virus mosquito vector Aedes aegypti at high elevation in Mexico	2012	Lozano-Fuentes	Central America	Mexico	Climate warming could lead to Ae. aegypti proliferating in high-elevation communities
Climate change, population immunity, and hyperendemicity in the transmission threshold of dengue	2012	Oki	Asia	Singapore	The effects of temperature change, population immunity, and

					hyperendemicity on mosquito density
Cooler temperatures destabilize RNA interference and increase susceptibility of disease vector mosquitoes to viral infection	2013	Adelman	North America	USA	Climate variables may influence mosquito-borne viral diseases by way of affecting the antiviral immunity of vectors
Climate and dengue transmission: evidence and implications	2013	Morin	North America	USA	Climate change affects dengue transmission in complex ways
The effects of weather and climate change on dengue	2013	Colón-González	Central America	Mexico	The influence weather has on dengue incidence
Vectorial capacity of Aedes aegypti: effects of temperature and implications for global dengue epidemic potential	2014	Liu-Helmersson	Europe	Sweden	The role diurnal temperature range (DTR) plays in dengue epidemics
Macroclimate determines the global range limit of Aedes aegypti	2014	Capinha	Europe	Portugal	The distribution of the Ae. aegypti may increase in the future if new domestic environments become available
Climate change and dengue: a critical and systematic review of quantitative modelling approaches	2014	Naish	Oceania	Australia	The risk of dengue associated with climate change
Climate change and the potential global distribution of Aedes aegypti: spatial modelling using GIS and CLIMEX	2014	Khormi	Asia	Saudi Arabia	The risk of climate change on the spatial distribution of Ae. aegypti
Spatio-temporal distribution of dengue and lymphatic filariasis vectors along an altitudinal transect in Central Nepal	2014	Dhimal	Asia	Nepal	Increasing temperatures have resulted in expansion of spatial

					distribution of Ae. aegypti
Climate change and the emergence of vector-borne diseases in Europe: case study of dengue fever	2014	Bouzid	Europe	Multiple	Estimating dengue risk in Europe under various climate change scenarios
Assessing climate variability effects on dengue incidence in San Juan, Puerto Rico	2014	Méndez-Lázaro	Caribbean	Puerto Rico	Evaluating the possible impact of climate change on dengue transmission
Bionomic response of Aedes aegypti to two future climate change scenarios in far north Queensland, Australia: implications for dengue outbreaks	2014	Williams	Oceania	Australia	Investigating impacts of future climate change on dengue virus transmission
Dengue: recent past and future threats	2015	Rogers	Europe	Multiple	Discussion on statistical dengue models
Climate change influences on global distributions of dengue and chikungunya virus vectors	2015	Campbell	North America	USA	Global potential distributions of virus vectors in relation to climatic variation
Risk factors for the presence of chikungunya and dengue vectors, their altitudinal distribution and climatic determinants of their abundance in central Nepal	2015	Dhimal	Asia	Nepal	Climatic variables as predictors of virus vectors abundance
Clustering, climate and dengue transmission	2015	Junxiong	Asia	Singapore	Climatic and non-climatic risk factors of dengue transmission
Spatial models for prediction and early warning of Aedes aegypti proliferation from data on climate change and variability in Cuba	2015	Ortiz	Caribbean	Cuba	Models for predicting spatial distribution patterns of Ae. aegypti based on climate variability

Climate change and spatiotemporal distributions of vector-borne diseases in Nepal	2015	Dhimal	Asia	Nepal	A systematic review on the effect of climate change on the spatial and temporal distribution of disease vectors
Increasing dengue incidence in Singapore over the past 40 years: population growth, climate and mobility	2015	Rocklöv	Asia	Singapore	Evaluating the main drivers for the increase in dengue incidence
Socio-economic and climate factors associated with dengue fever spatial heterogeneity: a worked example in New Caledonia	2015	Teurlai	Europe	France	The factors affecting the spatial and temporal distribution of dengue
The interrelationship between dengue incidence and diurnal ranges of temperature and humidity in a Sri Lankan city and its potential applications	2015	Ehelepola	Asia	Sri Lanka	Determining the correlation between diurnal temperature fluctuation and dengue incidence
Aedes aegypti in Latin American and Caribbean region: with growing evidence for vector adaptation to climate change?	2016	Chadee	Caribbean	Multiple	The impact of climate change on ecology of Ae. aegypti
Urban climate versus global climate change – what makes the difference for dengue?	2016	Misslin	Europe	France	Urban DTR as a predictor for dengue incidence
Climate change and Aedes vectors: 21st century projections for dengue transmission in Europe	2016	Liu-Helmersson	Europe	Multiple	How increasing temperatures may increase the spread of vector-borne disease
Projections of increased and decreased dengue incidence under climate change	2016	Williams	Oceania	Australia	Predicting changes in dengue transmission due to climate change

Dengue in a changing climate	2016	Ebi	North America	USA	Evaluating potential changes to dengue transmission due to climate change
Climate change and the arboviruses: lessons from the evolution of the dengue and yellow fever viruses	2016	Tabachnick	North America	USA	Evaluating the potential impact of climate change on arboviruses
The correlation between dengue incidence and diurnal ranges of temperature of Colombo district, Sri Lanka	2016	Ehelepola	Asia	Sri Lanka	Determining the correlation between DTR and dengue incidence
Climate change influences potential distribution of infected Aedes aegypti co-occurrence with dengue epidemics risk areas in Tanzania	2016	Mweya	Africa	Tanzania	Estimating potential distribution of dengue epidemic risk areas
An analysis of the potential impact of climate change on dengue transmission in the southeastern United States	2016	Butterworth	North America	USA	Projected shifts in dengue transmission risk driven by climate change
Declining prevalence of disease vectors under climate change	2016	Escobar	South America	Ecuador	Climate change may be threating certain vector species with extinction
Global risk model for vector borne transmission of zika virus reveals the role of El Niño 2015	2016	Caminade	Europe	United Kingdom	Development of a R_0 mathematical model for transmission risk of ZIKV driven by climate
Joint efforts of climate variability and socioecological factors on dengue transmission: epidemiological evidence	2017	Akter	Oceania	Australia	Assessing the epidemiological evidence on how both climate variability and socioecological factors affect

					dengue transmission
Modelling the effects of global climate change on chikungunya transmission in the 21st century	2017	Tjaden	Europe	Germany	Modelling projections of how climate change will impact chikungunya transmission in new areas
Dengue burden in India: recent trends and importance of climatic parameters	2017	Mutheneni	Asia	India	Evaluating the various interactions influenced by climate change that drive dengue transmission
Outbreaks caused by Aedes aegyptis due to El Niño in a coastal area of Peru	2018	Ruiz	South America	Peru	Analyzing the impact El Niño had in the incidence of dengue
Climate change and dengue fever transmission in China: evidence and challenges	2017	Li	Asia	China	Summarizing empirical evidence on dengue impacted by climate change
Present and future of dengue fever in Nepal: mapping climatic suitability by ecological niche model	2018	Acharya	Asia	Nepal	Understanding potential range shift of dengue risk areas due to climate change
Environmental factors can influence dengue reported cases	2017	Carneiro	South America	Brazil	Global climate change contributes to increases in arbovirus transmission
The potential impacts of 21st century climatic and population changes on human exposure to the virus vector mosquito Aedes aegypti	2018	Monaghan	North America	USA	How choosing alternative socioeconomic pathways will influence Ae. aegypti exposure in the future
Limiting global-mean temperature increase to 1.5-2 °C could reduce	2018	Colón-González	Latin America	Multiple	Model for predicting the

the incidence and spatial spread of dengue fever in Latin America					impact of climate change on dengue
Effects of the environmental temperature on Aedes aegypti and Aedes albopictus mosquitos: a review	2018	Reinhold	North America	USA	A review on the effect of temperature on two mosquito vectors
Past, present and future of Aedes aegypti in its South American southern distribution fringe: what do temperature and population tell us?	2019	Carbajo	South America	Argentina	How human population and air temperature correlated with spatial distribution of Ae. aegypti
Mapping the global potential distributions of two arboviral vectors Aedes aegypti and Ae. albopictus under changing climate	2018	Kamal	Africa	Egypt	Assessing the influence climate change will have on spatial distribution of two mosquito vectors
Modeling the present and future distribution of arbovirus vectors Aedes aegypti and Aedes albopictus under climate change	2019	Liu	Asia	China	Modeling predictions of the impact climate change will have on the distribution of mosquitoes
Dengue fever in Punjab, Pakistan: knowledge, perception, and adaption among urban adults	2018	Bakhsh	Asia	Pakistan	Determine the knowledge, perception, and adaption regarding dengue fever in survey responders
Urban and semi-urban mosquitoes of Mexico City: a risk for endemic mosquito-borne disease transmission	2019	Dávalos-Becerril	Central America	Mexico	Vector surveillance from Mexico City over five years
Climate change may enable Aedes aegypti infestation in major European cities by 2100	2019	Liu-Helmersson	Europe	Multiple	Analyzing how climate change will affect the spread of Ae.

					aegypti into new areas
Modelling the potential distribution of arbovirus vector Aedes aegypti under current and future climate scenarios in Taiwan, China	2019	Liu	Asia	Taiwan	Modelling potential future changes to the habitat of Ae. aegypti in Taiwan
Global expansion and redistribution of Aedes-borne virus transmission risk with climate change	2019	Ryan	North America	USA	Modeling the global transmission risk by two mosquito vectors in current climates and comparing to climate change projections
Geographic shifts in Aedes aegypti habitat suitability in Ecuador using larval surveillance data and ecological niche modeling implications of climate change for public health vector control	2019	Lippi	South America	Ecuador	Modelling the current spatial distribution of Ae. aegypti and projecting future scenarios with climate change
Temperature impacts on dengue emergence in the United States: investigating the role of seasonality and climate change	2019	Robert	North America	USA	Modelling how DTR fluctuations could affect potential dengue suitability
The current and future global distribution and population at risk of dengue	2019	Messina	Europe	United Kingdom	Projecting how climate change may change global environments to be more suitable for dengue
The effect of global change on mosquito-borne disease	2019	Franklinos	Europe	United Kingdom	A review on whether climate change will impact mosquito-borne diseases
Estimating past, present, and future trends in the global	2019	Liu-Helmersson	Europe	Sweden	Modelling estimated change in Ae. aegypti

distribution and abundance of the arbovirus vector Aedes aegypti under climate change scenarios					population and distribution due to climate change
Thermal biology of mosquito-borne disease	2019	Mordecai	North America	USA	Reviewing how temperature dependence of vector transmission can be predicted using trait-based approaches
Climatic conditions: conventional and nanotechnology-based methods for the control of mosquito vectors causing human health issues	2019	Ahmed	Asia	Pakistan	Reviewing the impact of nanotechnology-based and conventional approaches on malaria and dengue fever control
Environmental suitability for Aedes aegypti and Aedes albopictus and the spatial distribution of major arboviral infections in Mexico	2019	Lubinda	Central America	Mexico	Modelling of environmental suitability for two mosquito vectors
Co-developing climate services for public health: stakeholder needs and perceptions for the prevention and control of Aedes-transmitted diseases in the Caribbean	2019	Stewart-Ibarra	Caribbean	Multiple	Identify climatic and health perceptions and needs in regards to arboviruses
Dengue incidence and sociodemographic conditions in Pucallpa, Peruvian Amazon: what role for modification of the dengue-temperature relationship?	2020	Charette	South America	Peru	Assessing the sociodemographic effect of the dengue-temperature relationship to identify potential heightened risk due to climate change

The dengue epidemic and climate change in Nepal	2020	Pandey	Asia	Nepal	How climate change is affecting dengue infection spread by two mosquito vectors
Climate change, health and mosquito-borne diseases: trends and implications to the pacific region	2020	Filho	Oceania	Fiji	How climate change will affect human health
Projecting the future of dengue under climate change scenarios: progress, uncertainties and research needs	2020	Xu	Oceania	Australia	Review what information is available on how climate change will affect dengue transmission
Current and projected distributions of Aedes aegypti and Ae. albopictus in Canada and the US	2020	Khan	North America	USA/Canada	Modelling ecological niches for two mosquito vectors
A spatial-temporal study for the spread of dengue depending on climate factors in Pakistan (2006-2017)	2020	Shabbir	Asia	Pakistan	Used geographical information system maps over several years to identify the intensity of the spread of dengue

Supplementary panel 3: List of publications included in systematic map and analysis

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