Neglected Tropical Diseases in the Context of Climate Change in East Africa: A Systematic Scoping Review

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Abstract. East Africa is highly affected by neglected tropical diseases (NTDs), which are projected to be exacerbated by climate change. Consequently, understanding what research has been conducted and what knowledge gaps remain regarding NTDs and climate change is crucial to informing public health interventions and climate change adaptation. We conducted a systematic scoping review to describe the extent, range, and nature of publications examining relationships between NTDs and climatic factors in East Africa. We collated all relevant English and French publications indexed in PubMed®, Web of Science™ Core Collection, and CAB Direct® databases published prior to 2019. Ninety-six publications were included for review. Kenya, Tanzania, and Ethiopia had high rates of publication, whereas countries in the Western Indian Ocean region were underrepresented. Most publications focused on schistosomiasis ($n = 28$, 29.2%), soil-transmitted helminthiasis ($n = 16$, 16.7%), or human African trypanosomiasis ($n = 14$, 14.6%). Precipitation ($n = 91$, 94.8%) and temperature ($n = 54$, 56.3%) were frequently investigated climatic factors, whereas consideration of droughts ($n = 10$, 10.4%) and floods ($n = 4$, 4.2%) was not prominent. Publications reporting on associations between NTDs and changing climate were increasing over time. There was a decrease in the reporting of Indigenous identity and age factors over time. Overall, there were substantial knowledge gaps for several countries and for many NTDs. To better understand NTDs in the context of a changing climate, it would be helpful to increase research on underrepresented diseases and regions, consider demographic and social factors in research, and characterize how these factors modify the effects of climatic variables on NTDs in East Africa.

INTRODUCTION

Climate change has been labeled as one of the biggest health challenges of the 21st century,^{1–4} and it is likely to worsen the global burden of neglected tropical diseases (NTDs).^{5,6} Neglected tropical diseases are a collection of largely preventable and/or treatable diseases described by the WHO as diverse yet grouped because “all are strongly associated with poverty, all flourish in impoverished environments, and all thrive best in tropical areas, where they tend to coexist”⁷ (p. iii). These diseases are largely neglected in research, partly because NTDs are typically a threat in low-resource settings and have low visibility elsewhere in the world.⁷ The global burden of NTDs is substantial; in 2015 alone, 991 million people were treated for at least one NTD, and climate change is expected to increase the spread and burden of disease.^{5,8} For instance, eight of nineteen WHO-identified NTDs are vector-borne (Chagas disease, chikungunya, dengue, dracunculiasis, human African trypanosomiasis, leishmaniasis, lymphatic filariasis, and onchocerciasis) and, therefore, highly sensitive to climate change.⁹

The impacts of climate change are likely to be greatest on populations in low-resource settings,^{1–4} and the associated impacts can amplify the burden of NTDs, which already disproportionately affect these groups.^{7,10,11} Low-income countries often lack the resources and infrastructure that will be necessary for adapting to regionalized climate change, resulting

in challenges addressing public health issues such as the burden of NTDs.³ For example, the East African region of sub-Saharan Africa is an area particularly sensitive to negative health outcomes associated with climate change due to lack of financial security, heavy reliance on climate-sensitive subsistence agriculture, limited health infrastructure, and political instability and conflict.¹² East Africa also already has a high burden of NTDs. For example, the East African region known as the Horn of Africa (Djibouti, Eritrea, Ethiopia, and Somalia) has historically accounted for the second largest number of annual visceral leishmaniasis cases globally.¹³ In Tanzania, Ethiopia, and Kenya alone, an estimated 90 million people are at risk of lymphatic filariasis.¹⁴ Dracunculiasis remains endemic in only four countries globally, two of which are in East Africa (Ethiopia and South Sudan).¹⁵ The existing high burden of NTDs in East Africa combined with barriers to climate change adaptation could pose a significant threat to public health.

A number of reviews have been published to synthesize research about NTDs, with focuses on the burden of disease, control efforts, and socioeconomic inequities associated with NTDs on regional and global scales.^{16–23} There are also reviews investigating associations between climate and individual NTDs.^{24–31} However, to our knowledge, there are no reviews that synthesize the literature on all NTDs in the context of climate and none focusing on East Africa as a region. Scoping reviews are particularly useful systematic approaches to explore broad research areas, which have not been reviewed in the past,³² such as the associations between NTDs and climate in East Africa. Unlike for traditional systematic reviews (e.g., Cochrane-style reviews), the scoping review methodology does not require a narrow review question, which may be difficult to frame in areas where the current state of knowledge is not well understood.³² Furthermore, climate–health research is complex and involves

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many different study methodologies; scoping review methodologies provide a systematic, rigorous, replicable, and transparent mapping of the research topic, while not being restricted to the inclusion of only certain types of studies, as is often the case for traditional systematic reviews and meta-analyses.³² The depth at which scoping reviews describe the literature varies. A scoping review, which broadly describes the characteristics of the current body of literature, can be “a useful way of mapping fields of study where it is difficult to visualize the range of materials that might be available”³² (p. 21). There is considerable heterogeneity in NTDs, the climatic conditions which affect them, and the geographical characteristics of East African countries; this variability makes it difficult to anticipate what has been studied on climate–NTD associations in East Africa, yet an overview of the available literature is important to begin to synthesize the current state of knowledge and identify areas for further investigation. Thus, the goal of this review was to examine the extent, range, and nature of publications examining relationships between NTDs and climatic factors in East Africa. Specific objectives were to 1) describe the characteristics of the current body of the literature on NTD–climate associations, and 2) identify research gaps in the existing literature. Changes in climate can have a profound impact on the future distribution, frequency, determinants, and severity of NTDs—all factors that are important in determining the success of public health interventions and goals such as those outlined in Supplemental Material S1. Thus, understanding the state of knowledge about the relationships between climate and NTDs is essential to informing effective control of global disease burdens in a changing climate for which limited synthesis of key insights is currently available.

METHODS

We conducted a systematic scoping review of available peer-reviewed research, governmental and non-governmental reports, and post-secondary institutional theses relating climatic factors and NTDs in East Africa. We followed systematic scoping methods that were developed by Arksey and O'Malley³² and advanced by Levac et al.³³ and Pham et al.³⁴ A published review protocol does not exist for this study. The review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines; the PRISMA checklist is available in Supplemental Material S2.

Search strategy. To generate search strings, the PubMed[®] Medical Subject Headings database was consulted to identify relevant indexing terms for “climate change,” “global warming,” “season,” “meteorology,” “weather,”³⁵ and each WHO-identified NTD (Buruli ulcer, Chagas disease, chikungunya, dengue, dracunculiasis, echinococcosis, food-borne trematodiasis, human African trypanosomiasis, leishmaniasis, leprosy, lymphatic filariasis, mycetoma, onchocerciasis, rabies, schistosomiasis, soil-transmitted helminthiasis, taeniasis/cysticercosis, trachoma, and yaws).³⁶ Similarly, the CAB Direct[®] Thesaurus was consulted to identify subject terms compatible with the database's unique indexing and controlled vocabulary to include in the adapted search string. Because Web of Science[™] does not use controlled vocabulary, generation of new indexing search terms was not necessary for the use of the search string within this database. In consultation with an academic librarian, an inclusive search string consisting of disease outcomes, regions, and

climate variables was created for use in the PubMed and Web of Science Core Collection databases and adapted for compatibility with the CAB Direct database (Table 1). Because of the hierarchical nature of the controlled vocabulary in CAB Direct, some population, exposure, and outcome terms from the original search string were covered within a broader term (e.g., “helminthoses” captured both schistosomiasis and soil-transmitted helminthiasis). Date and language restrictions were not imposed on the search, although all search terms were in English. The search was conducted on July 13, 2016 in all three databases. Update searches were conducted in June 2017 and September 2019 to include all articles published through the end of 2018. In addition, a manual search of all *PLOS Neglected Tropical Diseases* issues published since the journal's inception through 2018 (October 2007–December 2018, $n = 134$ issues) was conducted by a single reviewer to identify any relevant articles not captured in the database searches.

Study selection. All original citations returned from the three databases were uploaded into DistillerSR[®] software and automatically de-duplicated. Screening forms were created based on the predetermined inclusion and exclusion criteria (Table 2, Supplemental Material S3). Published studies and correspondence were eligible, as well as governmental and nongovernmental reports and graduate or undergraduate theses or dissertations.³⁵ All publications had to exceed 500 words in length to be eligible for review. All NTDs recognized by the WHO as of July 13, 2016³⁶ were included for review. Chikungunya is not always identified as an NTD by the WHO, but it was listed on the original WHO web source³⁶ and thus included. The East African region was defined as per the United Nations Statistics Division's geographical region groupings at the time of the original database search, which included 18 countries (Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, Seychelles, Somalia, South Sudan, Uganda, Tanzania, Zambia, and Zimbabwe), two territories (British Indian Ocean Territory and French Southern and Antarctic Territories), and two French regions (Mayotte and Réunion).³⁷ The two territories were not included in this review, as they have no permanent residents.³⁸ Historical country names were identified using the Central Intelligence Agency World Factbook³⁸ to determine the modern territorial equivalent for screening and data extraction purposes, where appropriate. Although South Sudan is recognized as a country within East Africa, the country Sudan is not and, thus, was excluded from the search string. Climate and meteorological variables (see exposure search terms, Table 1) were defined as per a published protocol for a systematic review involving climate and health outcomes.³⁵

A two-stage screening approach was conducted. Level 1 screening involved two independent reviewers screening the titles and abstracts of all citations for the relevant inclusion/exclusion criteria. Citations that included a human population of interest and reported on any of the WHO-identified NTDs in East Africa in the title or abstract were promoted to Level 2 screening. If the population, disease, or location was unclear, the citation was also promoted to Level 2 screening. Level 2 screening involved a review of the article's full text. Publications without full text available in English or French were excluded. Articles that described an impact of climate, seasonality, or meteorological variables on a human disease metric for any of the WHO-identified NTDs in East Africa were included in the review. Conflicts during the Level 1 and 2 screening were

TABLE 1

Search strings prepared for PubMed and Web of Science Core Collection databases, as well as CAB Direct database to identify articles relating climatic factors and NTDs in East Africa

Search string for PubMed and Web of Science Core Collection		
Population search terms	(East* AND Africa*) OR Burundi* OR Comoros OR Comoran* OR Djibouti* OR Eritrea* OR Ethiopia* OR Kenya* OR Madagascar OR Malagasy OR Malawi* OR Mauriti* OR Mayotte OR Mahoran OR Mozambi* OR Réunion* OR Rwanda* OR Seychell* OR Somali* OR “South Sudan” OR “South Sudanese” OR Uganda* OR Tanzania* OR Zambia* OR Zimbabwe*	
Exposure search terms	(climat* AND change*) OR “greenhouse effect” OR “atmospheric pressure” OR barometric OR cloud* OR cold OR cool OR “dew point” OR drought OR flood OR heat* OR hot OR humid* OR meteorolog* OR precipit* OR rain* OR season* OR storm* OR sunshine OR temperature* OR “UV” OR “ultraviolet radiation” OR vapor OR vapor OR warm OR warming OR weather OR wind OR windy OR winds	
Outcome search terms	“neglected tropical diseases” OR “NTDs” OR “neglected diseases” OR “buruli ulcer” OR “mycobacterium ulcerans” OR “Chagas disease” OR “Chagas’ disease” OR “trypanosoma cruzi” OR dengue OR “break-bone fever” OR “breakbone fever” OR chikungunya OR dracunculiasis OR dracunculosis OR “guinea worm disease” OR “guinea worm infection” OR echinococcosis OR “hydatid cyst” OR hydatidosis OR “echinococcus granulosus” OR “echinococcus multilocularis” OR treponematos* OR yaws OR frambesia OR “treponema pertenue” OR trematodiasis OR “foodborne trematode infection” OR fascioliasis OR “fasciola hepatica” OR “fasciola gigantica” OR clonorchiasis OR “Chinese liver fluke disease” OR “clonorchis sinensis” OR opisthorchiasis OR “cat liver fluke disease” OR “opisthorchis viverrini” OR “opisthorchis felineus” OR paragonimiasis OR “lung fluke disease” OR paragonimus OR trypanosomiasis OR “sleeping sickness” OR “trypanosoma brucei” OR rhodesiense OR gambiense OR leishmaniasis OR kala-azar OR leishmania OR leprosy OR “Hansen disease” OR “Hansen’s disease” OR “mycobacterium leprae” OR filariasis OR elephantiasis OR “wuchereria bancrofti” OR “brugia malayi” OR “brugia timori” OR mycetoma OR actinomycetoma OR eumycetoma OR “Madura foot” OR maduromycosis OR Onchocerciasis OR “river blindness” OR “onchocerca volvulus” OR Rabies OR hydrophobia OR lyssa OR schistosom* OR bilharziasis OR bilharzia OR “katayama fever” OR (soil-transmitted AND helminth*) OR hookworm OR “necator americanus” OR “ancylostoma duodenale” OR whipworm OR “trichuris trichiura” OR roundworm OR “ascaris lumbricoides” OR “nematomorphia infection” OR taeniasis OR “taenia infection” OR “taenia solium” OR “taenia saginata” OR “taenia asiatica” OR cysticercosis OR neurocysticercosis OR trachoma OR “chlamydia trachomatis” OR “Egyptian ophthalmia”	
Search string for Cab Direct database†		
Population search terms	Geographic location‡ search field	“East Africa” OR Burundi OR Comoros OR Djibouti OR Eritrea OR Ethiopia OR Kenya OR Madagascar OR Malawi OR Mauritius OR Mayotte OR Mozambique OR Réunion OR Rwanda OR Seychelles OR Somalia OR “South Sudan” OR Uganda OR Tanzania OR Zambia OR Zimbabwe
	Abstract search field	(East* AND Africa*) OR Burundi* OR Comoros OR Comoran* OR Djibouti* OR Eritrea* OR Ethiopia* OR Kenya* OR Madagascar OR Malagasy OR Malawi* OR Mauriti* OR Mayotte OR Mahoran OR Mozambi* OR Réunion* OR Rwanda* OR Seychell* OR Somali* OR “South Sudan” OR “South Sudanese” OR Uganda* OR Tanzania* OR Zambia* OR Zimbabwe*
Exposure search terms	Subject term‡, Abstract, Title search fields	climate OR “climate change” OR “global warming” OR meteorology OR seasonality OR weather
Outcome search terms‡	Subject term‡, Abstract, Title search fields	“Buruli ulcer” OR dengue OR “chikungunya virus” OR dracunculiasis OR echinococcosis OR treponematos* OR “trematode infections” OR trypanosomiasis OR leishmaniasis OR leprosy OR “lymphatic filariasis” OR mycetoma OR onchocerciasis OR rabies OR helminthoses OR taeniasis OR cysticercosis OR trachoma

NTDs = neglected tropical diseases.

† Search field exclusively uses terms from the CAB Direct Thesaurus.

‡ The original search string was too extensive for the CAB Direct database to process, and therefore, it was reduced to include only terms from the database's controlled language. All populations, exposures, and outcomes were captured in the reduced search string.

recorded and discussed until consensus was reached. During the manual search of *PLOS Neglected Tropical Diseases*, the titles of all documents were reviewed by one reviewer, followed by the full text of any article deemed potentially relevant as per the inclusion/exclusion criteria. A second reviewer confirmed whether the included full texts met the eligibility criteria.

Data extraction. A data extraction form (Supplemental Material S4) was developed and imported into DistillerSR, and data extraction was completed by a single reviewer according to the predetermined criteria (Supplemental Material S5). Extracted data included publication identifiers, the region/country of interest, the type of settlement, NTDs of interest, climate variables of interest, and demographic and social factors considered in the publication. Inclusion of Indigenous peoples was determined based on identification of participants as Indigenous by the authors of the publication. When unclear in the publication, Indigenous

identity was defined according to the 2013 United Nations Declaration on the Rights of Indigenous Peoples guidelines, which include a group's self-identification as Indigenous, a special attachment to traditional land for physical and spiritual sustenance, and experiences of social exclusion or discrimination due to their distinct culture.³⁹ There is distinction between the effects of sex (i.e., biological) and gender (i.e., socially constructed) on health, yet these distinctions are often not addressed in health research.⁴⁰ For the purposes of this review, sex was defined as any reference to differences in NTD outcomes for males and females, whereas gender was defined as any reference to differences in NTD outcomes in the context of social or cultural differences between males and females.

Data analysis. Cohen's kappa statistics for inter-rater agreement were calculated in DistillerSR for each screening level (Supplemental Material S6). Risk of bias analyses are not conducted in scoping reviews.^{32–34} Frequency counts

TABLE 2
Inclusion and exclusion criteria for selection of articles relating climatic factors and NTDs in East Africa

Included	Excluded
<ul style="list-style-type: none"> • All publication dates • Full text published in English or French • Published study, published correspondence, governmental report, nongovernmental report, or postsecondary institutional thesis (exceeding 500 words in length) • Region of interest is East Africa (regional, national, or subnational level) • Outcomes of interest reported in relation to humans • Explicit reference to an impact of climate change and/or global warming and/or seasonality (relative to climate) and/or meteorological conditions on an NTD in a human population for at least one paragraph at the full-text level 	<ul style="list-style-type: none"> • None by publication date • No English or French full text publication • Newspaper/magazine articles, meetings, conference proceedings, books, or publications less than 500 words in length • Region of interest outside East Africa • Outcomes of interest described solely in relation to disease vectors or reservoirs, or in an animal population • Lacking, non-explicit, or passing reference (defined as fewer than one paragraph at the full text level) to an impact of climate change and/or global warming and/or seasonality (relative to climate) and/or meteorological conditions on an NTD in a human population

NTDs = neglected tropical diseases.

were tabulated for article characteristics, regional characteristics, NTDs, climate variables, and demographic and social indicators. A series of logistic regressions were used to investigate the unconditional effect of the publication date on the odds of the publications reporting on each East African country, each NTD, climatic variables, and demographic and social indicators. All statistical analyses were performed in Stata[®] IC version 14 for Windows. ArcMap[™] version 10.6 was used to map publication frequency data.

To examine trends in the amount of publications on NTDs in the context of climate change over time, temporal cluster detection scans were conducted in SaTScan[™] version 9.6 to identify any high- or low-count clusters of publications from 1950 to 2016. A purely temporal (i.e., nonspatial) retrospective scan test was applied with a Poisson distribution and 999 Monte Carlo permutations. Data were analyzed at yearly aggregation, with a maximum scanning window of 50% of the total time available in the dataset. All scans were conducted using a standard alpha value ($\alpha < 0.05$). A spatial cluster detection scan was also conducted (Supplemental Material S7).

RESULTS

The database search returned 3,031 publications from the three databases (Figure 1). De-duplication resulted in 2,166 original publications included for screening. The hand search identified two relevant articles included for the review that were not returned by the database search. A total of 96 publications (83 original research articles, 11 reviews, one published letter/correspondence, and one postsecondary institutional thesis) met all inclusion criteria for review (Figure 1, Supplemental Material S8). The reviewers agreed on the inclusion status of 93.7% (2,030/2,166, kappa = 0.67) and 91.6% (503/548, kappa = 0.74) of citations at the Level 1 and Level 2 stages of screening, respectively. Consensus was reached between the two reviewers for all publications without requiring an arbitrator. Four full texts (publication dates: 1914, 1958, 1971, and 1992) could not be located for screening after extensive searching by authors and a university interlibrary loan service, resulting in their exclusion from the review. Individual study characteristics for all extracted data are available in Supplemental Material S9.

Publication counts have increased over time. The date of publication ranged from 1956 to 2018. Most included publications were published in the 2010s ($n = 42$, 43.8%) and the 1980s ($n = 16$, 16.7%) (Figure 2). Temporal cluster analysis indicated one significant high-count cluster of publications reporting on NTD and meteorological variables between 2011 and 2018 (relative risk = 5.68 and $P = 0.001$), with no low-count clusters detected (Figure 2).

Kenya, Tanzania, and Ethiopia had the highest number of publications. All East African countries meeting the inclusion criteria for review were represented in the literature, although the range of publication frequency was widespread, with 1–31 publications per country (Figures 3A and 4). Seventeen (17.7%) publications reported on multiple countries. Frequency counts indicated three countries to be prominent regions of study: Kenya ($n = 31$, 32.3%), Tanzania ($n = 23$, 24.0%), and Ethiopia ($n = 23$, 24.0%). Zimbabwe ($n = 16$, 16.7%) and Uganda ($n = 15$, 15.6%) had moderate publication counts. Many coastal countries and islands in the West Indian Ocean region had low publication frequencies. Most publications reported exclusively on rural populations ($n = 53$, 55.2%), whereas 38 publications (39.6%) reported on both rural and urban areas, three (3.1%) publications exclusively reported on an urban population, and the population settlement type was undetermined for two (2.1%) publications. Logistic regression analyses did not identify any statistically significant associations between the publication date and country. Spatial clustering analysis results are presented in Supplemental Material S7.

Schistosomiasis, soil-transmitted helminthiasis, and human African trypanosomiasis were the most common in the climate-NTD literature. There was an unequal representation of the 19 WHO-identified NTDs in the literature (Figure 3B). The NTDs reported on with the highest frequency were schistosomiasis ($n = 28$, 29.2%), soil-transmitted helminthiasis ($n = 16$, 16.7%), and human African trypanosomiasis ($n = 14$, 14.6%). There were no included publications reporting on Chagas disease, echinococcosis, or taeniasis/cysticercosis. Of the 96 included publications, 68 (70.8%) reported ≥ 1 vector-borne NTD. There was a moderate increase in the odds of studies reporting on dengue over time (odds ratio [OR] = 1.54, 95% CI = 1.04–2.29). Logistic regression analyses did not reveal any statistically significant association of the publication date with any other NTD.

FIGURE 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses flow chart diagram outlining publication selection of articles relating climatic factors and neglected tropical diseases (NTDs) in East Africa (1956–2018).

Most studies examined precipitation and temperature associations with NTDs, and changing climate emerged as a recent focus. Precipitation was the most frequently reported ($n = 91$, 94.8%) meteorological variable examined in relation to NTD metrics (i.e., incidence, prevalence, rate, and/or risk of disease), and temperature was also highly represented in the literature ($n = 54$, 56.3%) (Figure 3C). Over half ($n = 49$, 51.0%) of publications reported on both precipitation and temperature. Drought ($n = 10$, 10.4%), humidity ($n = 9$, 9.4%), and flood ($n = 4$, 4.2%) impacts were each investigated infrequently. Eleven publications (11.5%) explicitly discussed impacts of changing climate on NTD metrics, all published between 2011 and 2018. There was a minor increase in the odds of studies examining changing climate over time (OR = 1.15, 95% CI = 1.01–1.30). There were no statistically significant changes in the odds of studies examining other individual meteorological variables over time.

Consideration of social determinants of health was frequent but declined over time. Of the included publications, 73 (76.0%) considered at least one demographic or social indicator with regard to an NTD. Of the specific indicators examined (i.e., sex, gender, Indigenous identity,

age, and socioeconomic status), age and sex considerations were most frequently reported (Figure 3D). The odds of articles considering at least one social determinant of health decreased over time (OR = 0.961, 95% CI = 0.931–0.992). For the specific indicators, the odds of articles including Indigenous identity (OR = 0.934, 95% CI = 0.899–0.970) and age (OR = 0.968, 95% CI = 0.944–0.992) in analyses slightly decreased over time, whereas the odds slightly increased for the inclusion of socioeconomic factors (OR = 1.04, 95% CI = 1.01–1.08) (Figure 5). There was no statistically significant change over time for consideration of sex or gender factors. A total of 21 publications had regional or national disease mapping and/or modeling as a major focus (all published between 2005 and 2016), and of these, only 12 (57.1%) considered a demographic or social indicator, compared with 81.3% of non-mapping and/or modeling publications.

DISCUSSION

Publication trends over time. Publication frequency over time was unsteady, with periods of higher counts potentially

FIGURE 2. Publication frequency of articles relating climatic factors and NTDs in East Africa over time (1956–2018). Years included in significant high-count clusters from temporal cluster analysis have bolded bars. NTDs = neglected tropical diseases; IPCC = Intergovernmental Panel on Climate Change; UN SDGs = United Nations Sustainable Development Goals. This figure appears in color at www.ajtmh.org.

attributable to funding and interest of the public and scientific communities. The first notable increase in the publication count was observed between 1987 and 1989, a time when a surging global focus on climate change was developing, culminating in the formation of the International Panel on Climate Change in 1988. There was a significant high-count temporal cluster identified between 2011 and 2018, coinciding with the release of several important publications and declarations on the NTDs, including *Global Plan to Combat NTDs*,¹¹ *Working to Overcome the Global Impact of NTDs: First WHO Report on NTDs*,⁷ *Accelerating Work to Overcome the Global Impact of NTDs: A Roadmap for Implementation*,¹⁰ and the *London Declaration on NTDs*.⁴¹ The United Nations Sustainable Development Goals may also have contributed to increased publications in recent years, as it places emphasis on climate change mitigation and adaptation, and NTD management.⁴² Although the increased publications on climate associations with NTDs is encouraging, their collective calls for further research and investment indicate the need for continued work to understand how NTDs are affected by climate in East Africa.

Regional distribution of publications. Most publications focused on rural populations, which tend to be at a greater risk for NTDs due to a combination of often limited access to health care and increased exposure to certain disease vectors.^{5,7,11} The countries with the highest publication counts (i.e., Kenya, Tanzania, and Ethiopia) were the top three countries in East Africa by GDP from 1998 to 2018 and net official development assistance and official aid received from 2011 to 2018.^{43,44} By contrast, the cluster of countries in the vicinity of the Western Indian Ocean which had low counts of publications (i.e., Comoros, Madagascar, Malawi, Mauritius, Mozambique, and Seychelles) had lower GDPs and received less net official development assistance and official aid in 2016.^{43,44} These data are unavailable for Mayotte and Réunion as they are French regions, not independent countries. The lack of climate–NTD research in countries bordering the Western Indian Ocean represents an important regional

research gap, especially considering the substantial impact of climate change anticipated for small island states.^{12,45} Furthermore, there is a need to ensure that countries with lesser financial income and international economic assistance benefit from research to understand the status of NTDs within their borders.^{46,47} This is especially important for lower income countries because they can be at a higher risk for negative consequences of both disease and climate change due to the lack of financial resources to manage outbreaks and limited adaptive capacity to respond to climate change.^{3,12} As such, it is important to work toward more equitable regional representation in research that examines climatic factors and NTDs, otherwise we risk exacerbating existing sensitivities to climate change in currently underrepresented populations.

Publication distribution across NTDs. The considerable variation in representation of the 19 WHO-identified NTDs in the literature is likely due to a combination of varying climatic sensitivity, funding, and geographical relevance. The high proportion of publications reporting on vector-borne NTDs may be due to the fact that climate conditions tend to have great impacts on this group of diseases; the lifecycle of vectors and transmission of pathogens are dependent on environmental conditions, meaning the deviation of climatic variables from regional norms can have a considerable impact on the geographical range and incidence of disease.^{2,48} Also, climate-related studies on parasitic infections (e.g., schistosomiasis and soil-transmitted helminthiasis), which are sensitive to climate conditions, were frequently published because parasitic habitats and life cycles are regulated by environmental conditions.⁴⁹ The moderate increase in odds of studies reporting on dengue over time may be explained in part by the increasing dengue epidemic in East Africa.^{50,51} Between 1960 and 2010, 20 dengue outbreaks were laboratory confirmed in 15 African countries, most of which were in East Africa, including four of the five largest epidemics (Seychelles, Réunion, Djibouti, and Comoros).⁵⁰ Factors including urbanization, travel, and favorable climatic conditions are thought to be driving the increase.⁵¹

FIGURE 3. Publication frequencies of articles relating climatic factors and neglected tropical diseases (NTDs) in East Africa (1956–2018). (A) Publication frequency by country. (B) Publication frequency by NTD. (C) Publication frequency by climate variable. (D) Publication frequency by demographic and social factors of interest. All indicators were defined as per Supplemental Material S5. †Soil-transmitted helminthiasis, *human African trypanosomiasis, ‡food-borne trematodiasis, ¶NTD, and ¶male/female designation. This figure appears in color at www.ajtmh.org.

Research requires funding, and there may have been differences in the resources available to study certain NTDs, which could have contributed to the variation in publication counts. The burden of disease is a likely contributing factor to research resource allocation. An evaluation of the burden of each NTD relative to the number of publications investigating its association with climate was beyond the scope of this review, as burden of disease is highly multifactorial and changes over time. However, NTDs which may be particularly important for future research are those that exert a high burden of disease in East Africa and are climate sensitive, a combination which heightens their threat to public health in the region. Some NTDs meeting these criteria include schistosomiasis, lymphatic filariasis, and visceral leishmaniasis. For example, there are an estimated 19 million cases of schistosomiasis in Tanzania and 13 million cases in Mozambique.⁵² An estimated 90 million people are at risk of infection with lymphatic filariasis in Tanzania, Kenya, and Ethiopia.¹⁴ Annually in East Africa, visceral leishmaniasis causes at least 4,000 deaths and is associated with an estimated loss of 385,000 disability-adjusted life years (DALYs).⁵³ All three of these NTDs are vector-borne; they are highly sensitive to climate and projected to increase with climate change throughout the African continent.^{54–56} Therefore, these NTDs

would be important candidates for continued research. In addition, lymphatic filariasis and visceral leishmaniasis may need to be prioritized, as they were relatively underrepresented in the literature.

Climatic variables of interest. The high count of studies examining precipitation and temperature associations with NTDs in the included literature is likely explained by the importance of these variables to disease regulation^{3,4,57} and, in some cases, to current climate trends in East Africa.¹² For instance, precipitation has substantial impacts on many NTDs because it can modulate parasite and vector life cycles and also supports aquatic sites of disease transmission, whereas temperature modifies the biological development and transmission patterns of organisms such as mosquitoes and nematodes involved in NTDs.^{57,58} Furthermore, temperature impacts human behavior involved in disease transmission, which can modify exposure to some NTDs.⁵⁹

The increasing trend in studies discussing changing climate and NTDs may be because East Africa has been established as a warming region.^{12,45,60} The nine articles discussing the impacts of a changing climate were all published recently, which could be explained in part by the length of time it has taken to collect the data necessary to identify these long-term

FIGURE 4. Map illustrating the publication frequency of articles relating climatic factors and neglected tropical diseases in East Africa by country (1956–2018). This figure appears in color at www.ajtmh.org.

changes. As our modeling capabilities and data availability grow, we may be able to synthesize more information to understand how climate change is impacting NTDs. Extreme weather events, such as droughts or floods, which can be associated with climate change,⁶¹ were relatively underrepresented in the reviewed literature. These events can impact NTDs, such as increased outbreaks of leishmaniasis during droughts.⁶ Considering the lack of research in this area, additional work investigating associations between extreme weather events and NTDs is needed to have a more complete understanding of the impacts of extreme climate-related events on these diseases, especially as these events pose significant human health risks and are increasing in number because of climatic changes.^{3,61}

Consideration of demographic and social factors in the literature. Local political, social, and economic circumstances

are tied to both the health of the population and the success of interventions to reduce the burden of NTDs and adapt to climate change.⁶² There was high consideration of demographic and social indicators in the included literature overall, which may reflect recognition among health researchers of the strong influence these factors can have on NTD epidemiology. Logistic regression did reveal a minor decrease in consideration of age and Indigenous identity over time, though. Social and demographic variables are important drivers of health that may be associated with NTDs, confound or interact with other risk factors for NTDs, or modify the effect that climate change has on NTDs.⁴⁸ For instance, socioeconomic status has a wide-ranging influence on wellbeing, as it contributes to an individual's ability to access resources, such as health care, and their adaptive capacity to deal with challenges and mitigate risks to health.^{3,4} Markers of low socioeconomic

FIGURE 5. Trends in the proportion of publications relating climatic factors and neglected tropical diseases in East Africa (1956–2018) which considered (A) any social factor, (B) sex (male/female designation), (C) gender, (D) Indigenous identity, (E) age, or (F) socioeconomic status over time. This figure appears in color at www.ajtmh.org.

status, such as lack of income and education, have been associated with a greater likelihood of experiencing ill health in the context of climate change.⁴ Women are often at a greater risk to experience negative impacts of climate change because of gender differences in decision-making roles, undernutrition due to food hierarchies, barriers to health services and family planning, less access to education and economic independence, and high rates of employment in climate-sensitive agriculture work, among other factors.^{3,12} Children and the elderly are also more likely to experience harm due to climate change, in particular via disease and malnutrition sensitivities.^{3,12} In addition to their associations with climate change, age and sex/gender are known to impact the risk of infection for many

NTDs, including human African trypanosomiasis, leishmaniasis, schistosomiasis, soil-transmitted helminthiasis, among others, due to differences in biological susceptibility and gender role-related exposures.⁷ Indigenous peoples³⁹ (Supplemental Material S5) were identified in few publications, yet they often experience negative health impacts of climate change in part because of existing health inequities, institutional racism, and strong connections on the land, which influence adaptive capacity.^{12,63–67} Future research needs to consider the unique challenges faced by Indigenous peoples to gain a comprehensive understanding of the impacts NTDs have within diverse populations in the context of climate change.

An area of lower consideration of social and demographic factors was studies focused on mapping and modeling NTDs

at large regional scales, which has been encouraged by the WHO and other global health partners' initiatives.^{68,69} Mapping and modeling projects are undoubtedly essential to the effective implementation of disease control programs because they allow us to understand and monitor disease on large scales; however, we must identify ways or develop methods that enable the consideration of social and demographic factors known to modify the burden of disease in these analyses, if we are to provide the richest understanding of NTDs in the future,^{70,71} especially in the context of changing climate.

There is a growing body of the literature that calls for increased social science and interdisciplinary research to be undertaken regarding NTDs.^{72–76} A bibliographic review published in a series commissioned by the WHO on the role of social sciences in NTD control found that social science and interdisciplinary research comprised less than 2.1% of all NTD publications.⁷² A contributor to this result could be a disparity in funding; for instance, a 2011 analysis indicated social science research received less funding from the Bill & Melinda Gates Foundation (the second largest funder of NTD research and development) from 1998 to 2008 than non-social science projects.⁷³ As well, the political context surrounding control programs for NTDs may influence the methods by which evidence is produced, analyzed, and reported in some cases.⁷⁴ Although this review did not broadly classify publications as being social or non-social science research, these reports indicate that the present finding of a declining inclusion of some social and demographic factors in NTD-climate publications may be consistent with a broader issue in NTD research. Failure to consistently consider the social and political context surrounding the NTDs is not without consequence. Infectious diseases exist at the intersection of social and cultural contexts with the physical and biological world; when we do not have a strong grasp of how these social and cultural contexts play into the spread of NTDs, we are forced to rely on evidence that does not acknowledge the complex nature of the disease epidemiology, and our management of NTDs will reflect this lack of understanding.⁷²

Study limitations. This review did not consider literature unavailable in English or French. French terms were not included in the search string, which could have excluded some articles not indexed in English. Historical country names were not included in the search string, which may have excluded some older publications whose indexing was not updated to reflect modern classifications. Our search string did pick up several publications that exclusively used historical country names, indicating that the search may have maintained good sensitivity to mitigate this issue.

CONCLUSION

Links between climatic variables and human health and disease are well established, and the NTDs are no exception. The body of research investigating associations between climatic factors and NTDs in East Africa is modest but spans over six decades and is growing; the volume of research indicates this topic has perceived importance by researchers and relevance to current and future public health challenges in the context of climate change, a viewpoint reinforced by the WHO. However, if control, elimination, and/or eradication of NTDs is to be achieved in a world of changing climate,

intensified research on their climate associations should be a priority, especially for the countries and individual diseases that are substantially underrepresented in the current body of the literature. There is also a need for increased consideration of demographic and social indicators in upcoming research, as the effects of social and climatic determinants of health on the burden of disease are strongly intertwined and need to be considered together to accurately predict the future state of NTDs in public health. At a time when we are rapidly beginning to see the impacts of climate change on our global community, there is a heightened demand for research to equip public health institutions with the necessary knowledge to make informed decisions regarding the current management of disease and to properly prepare for future needs of the populations they serve. NTDs historically have had little visibility outside affected populations and many are currently positioned to be markedly impacted by climate change; thus, it is essential that they do not continue to be neglected in crucial research examining how climatic factors influence human health, lest opportunities for adaptation be missed to mitigate the health risks for millions of people.

Received May 15, 2019. Accepted for publication January 23, 2020.

Published online March 30, 2020.

Note: Supplemental materials appear at www.ajtmh.org.

Indigenous Health Adaptation to Climate Change Research Team: Cesar Carcamo, Victoria Edge, James Ford, Patricia Garcia, and Alejandro Llanos.

Acknowledgments: We wish to thank Ali Versluis (open education resources librarian, University of Guelph McLaughlin Library) for her contributions to this review's literature search methods. We also wish to thank Teresa Lewitzky (Data Resource Centre library associate, University of Guelph McLaughlin Library) for her assistance in creating the publication frequency map (Figure 4) in this text. We also thank Nia King and Marta Thorpe for their time spent screening French language publications.

Financial support: Funding for this project was provided by the Canadian Institutes of Health Research (received by S. L. H., L. B. F., S. L., D. B. N., and the IHACC Research Team), a University of Guelph President's Scholarship summer research assistantship stipend (received by J. M. B.), and the Ontario Veterinary College Graduate Research Assistantship Program (received by K. E. B.-W.).

Disclosure: The funders had no role in study design, data collection and analysis, and preparation of the manuscript, nor decision to publish.

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