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Reviewing Evidence and Research Trends on Climate Change and Infectious Disease

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Abstract: The Intergovernmental Panel on Climate Change (IPCC) has expressed high confidence in the amplification of health threats worldwide due to climate change, a sentiment supported by the close linkage between the life cycles of many infectious agents and climate variables. Various studies have demonstrated that fluctuations in temperature, precipitation, and humidity exert significant influence on the transmission and distribution of infectious diseases. However, the precise magnitude, direction, and strength of this impact on infectious disease transmission remain ambiguous. To elucidate the necessary avenues for advancing research in this area, it is often imperative to synthesize existing literature. This retrospective, systematic analysis of literature within a specific field, commonly known as a systematic review, serves as a popular and effective method for identifying trends and gaps in ongoing research. Findings from systematic reviews, along with scoping studies that map the availability of literature on a particular topic, are instrumental in guiding future research directions and policy decisions, particularly in rapidly evolving scientific fields like epidemiology.

Despite their effectiveness, systematic reviews are notably scarce in the domain of anthropogenic climate change research, particularly concerning its impact on infectious diseases. Therefore, there exists a pressing need for a systematic synthesis of recent empirical research assessing the disease impacts of climate change. In this context, we aim to present a synthesis of scientific literature on the nexus between climate change and infectious diseases from recent years. Our overarching objective is to discern the trends in recent empirical research concerning the impacts of climate change on infectious diseases and to identify any geographic, topical, or taxonomic trends within this research landscape. We intend to evaluate the geographic regions where the intersection of climate change and disease transmission has been understudied, considering both the study area and the affiliations of the first authors to identify geographical and bibliometric signals. Additionally, we will assess the taxa of hosts and transmission types of pathogens studied. Ultimately, our endeavor is to provide insights that can inform future research directions, policies, and practices based on the trends and impacts identified within the literature.

Keywords: Climate Change, infectious diseases, infection, transmission, infestation, chytridiomycosis.

Methodology

Search Strategy, Inclusion Criteria, Exclusion Criteria

Our search strategy involved retrieving articles from literary repositories such as Web of Science (Clarivate™) and PubMed™ using a keyword search approach. The keywords utilized encompassed terms related to climate change, including "climate change," "global warming," "greenhouse gas*," "world warming," as well as terms associated with infectious diseases such

as "disease," "infectious," "pathogen," "waterborne," "water borne," "food borne," "vector borne," "parasite," and "non-vector borne." Time restrictions were set from January 2015 to December 2020 to capture publications from the most recent five-year period of empirical climate change research preceding the pandemic. This search was limited to journal manuscripts as the focus was on analyzing original peer-reviewed research. Other types of literature such as book chapters, review articles, proceedings papers, or conference abstracts were excluded. Following the retrieval of articles, redundant entries were eliminated using Endnote citation software.

Subsequently, we conducted an initial screening of both article titles and abstracts to identify articles that did not meet the review criteria. The inclusion criteria consisted of: (1) peer-reviewed manuscripts published without retraction, (2) research primarily focused on assessing the impact, repercussions, effects, association, or influences of climate change on disease, infection, transmission, infestation, or illness, (3) original research rather than review articles, (4) descriptive or retrospective research based on real-world systems using non-simulated future-climate data (i.e., present-day and past climate only), (5) utilization of primary data, and (6) the focus on pathogens, parasites, vectors, or diseases impacting either humans, non-human animals, or both. Each article underwent review by at least two independent reviewers, and inclusion or exclusion was determined based on the predefined criteria. In cases where reviewers disagreed on the suitability of an article, a third reviewer provided a decisive evaluation. Studies falling outside the defined inclusion criteria were identified and maintained in a separate database. Additionally, studies on plant diseases were excluded as they were beyond the scope of this study.

Evidence Extraction and Analysis

Following the initial screening process, the remaining publications underwent comprehensive review, and evidence extraction was conducted for each article to facilitate our gap analysis of bibliometric, subject, taxonomic, and geographic trends in research and publication. Descriptive metadata was collected from each article to examine publication details such as year of publication, journal name, title, authors, etc. Authorship demographics were assessed by recording the lead author and senior author's names, pronouns, and institutional affiliations for each publication. Pronouns were recorded based on the personal preferences of each author, as indicated on their institutional or research-affiliated websites, in an effort to be inclusive of all authors' identities while respecting their privacy. In cases where authors did not specify their pronouns publicly, they were recorded as "unknown". Additionally, descriptive metadata on study methods, locations, disease hosts, vectors, pathogens studied, transmission methods, primary taxa of interest, and spatial scales were collected for each article.

To evaluate the quality of the included literature, we synthesized the conclusions drawn by the authors and reported these findings based on the authors' interpretation of their results. Descriptive information on publication funding or support for articles published in the most recent year included in the review (i.e., 2020) was also collected to identify current funding sources for recent climate change and disease publications. Comparison of funding sources with current estimates of country gross domestic product (GDP) from the World Bank World Development Indicators Dataset was performed.

The distribution of categorical topics within the literature was assessed using a Pearson's chi-squared ($\chi 2$) test. Given that approximately 60% of known infectious diseases are zoonotic, we compared this expected proportion with the proportion of literature assessing zoonotic diseases. Similarly, we utilized the $\chi 2$ test to determine if the proportion of host species categories studied (humans, wildlife, and livestock) were equal.

To analyze the geographic distribution of publication demographics, lead authors' institutional affiliations were recorded and assigned to their corresponding countries of origin. Spatial and temporal patterns of study locations and author affiliations were summarized and visualized

using ArcGIS Pro version 2.9.3 and R version 4.1. Population data from the United Nations Population Division for the year 2020 were used to assess per-capita research effort by country.

Results

Demographics of the Literature

Our initial keyword search yielded a total of 10,461 articles retrieved from both PubMed and Web of Science. Among these, 621 research articles (5.9%) met the inclusion criteria for the period spanning 2015 to 2020 and were selected for evidence extraction and gap analysis. Within this subset of publications, researchers identified 109 distinct infectious diseases associated with climate change research. A fraction of the publications (n = 127) examined multiple diseases within the same study. Authors of the reviewed articles indicated that climate change impacted the disease system under examination in 59% of the cases. The majority of articles (83.9%) describing climate change impacts reported an increase in the prevalence, transmission, or suitability for the studied disease, while 11.5% indicated a decrease in these factors. Only 7.7% of the assessed articles reported no discernible effect of climate change on the disease system under investigation. Additionally, the review revealed that 32.7% of the articles concluded that climate change could potentially impact the disease system being studied, with authors not definitively reporting a pattern.

Research Trends

Among the studies analyzed, infectious diseases stemming from cross-species pathogen transmission from animals to humans (i.e., zoonotic diseases) represented the majority (n = 288, 46.4%), significantly outnumbering diseases that do not originate from such transmission (n = 253, 40.7%) ($\chi 2 = 9.97$, P = 0.002). Infectious diseases impacting humans were well-represented in the literature (n = 406) ($\chi 2 = 114.3$, P = 0.0001), whereas those affecting livestock were less common (n = 152). Only 116 publications assessed diseases affecting wildlife.

The most frequently studied conditions included vector-borne diseases (Fig. 1), such as malaria (n = 58), dengue fever (n = 37), and Lyme disease (n = 22) (Fig. 1). Among the vectors studied, mosquitoes were the most prevalent (n = 174), followed by ticks (n = 51), and flies (n = 14) (Fig. 1). Other frequently studied environmentally transmitted conditions encompassed food and water-borne diseases, such as diarrheal diseases (n = 18) and chytridiomycosis (n = 10) (Fig. 1). Additionally, research focused on diseases hosted by arthropods (n = 189) and humans (n = 185) (Fig. 1). The third most studied host taxonomic group consisted of non-human mammals (n = 47), followed by amphibians (n = 19) and birds (n = 17) (Fig. 1). In terms of study scale, research was predominantly conducted at the local, regional, or country levels, with fewer efforts directed towards global-level studies (Fig. 2).

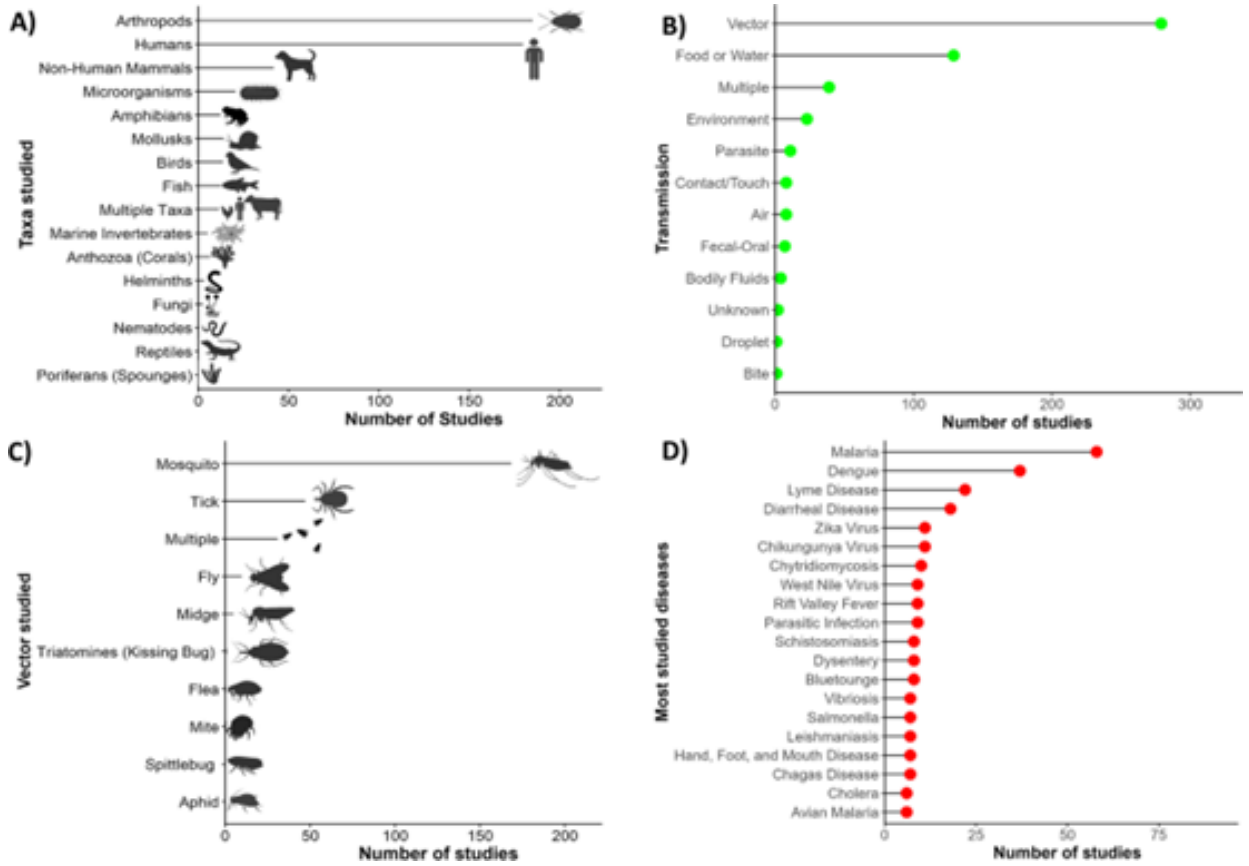

Figure 1 Trends in climate change and disease research. Number of publications (x-axis) from 2015–2020 according to A taxa of host species studied, B transmission type of diseases studied, C vector species studied, and D top 20 most studied diseases from over 100 different diseases studied. Multiple: multiple diseases with multiple transmission types studied in a single article

Publication Trends

In terms of publication demographics, the bibliometric analysis revealed a predominant usage of he/him pronouns for both first and senior authors (Fig. 3). Notably, we did not encounter any instances of they/them or other non-binary pronouns among the first or senior authors in the reviewed articles. Additionally, our analysis indicated that lead authors' affiliations and study areas were most frequently located in the United States, China, the United Kingdom, Canada, and Australia (Figs. 4, 5). When considering research efforts relative to the population size of each country, countries such as Norway, Australia, and Canada exhibited a comparatively higher research output (Fig. 4). The majority of lead author affiliations were affiliated with higher education institutions, primarily universities or colleges, with fewer publications originating from governmental organizations or independent research institutions (Fig. 2). Noteworthy university affiliations were often found in the United States (e.g., the University of California, Colorado State University, University of Florida) and in China (e.g., Shandong University) (Fig. 5). Regarding funding sources for papers published in 2020, the majority of funding was derived from federal or national institutions (53.3% of articles) or a combination of federal and academic institutions (26.7% of articles), predominantly originating from high-income countries such as the United States, Canada, Germany, and the United Kingdom (Supplementary Fig. 1). Information regarding funding sources from lower-income countries was limited, with only one country (Greece) having a GDP ranking below the top 50 among reported countries based on World Bank estimates [21]. Non-governmental organizations and local agencies constituted a modest proportion of funding sources for the total articles published (20%).

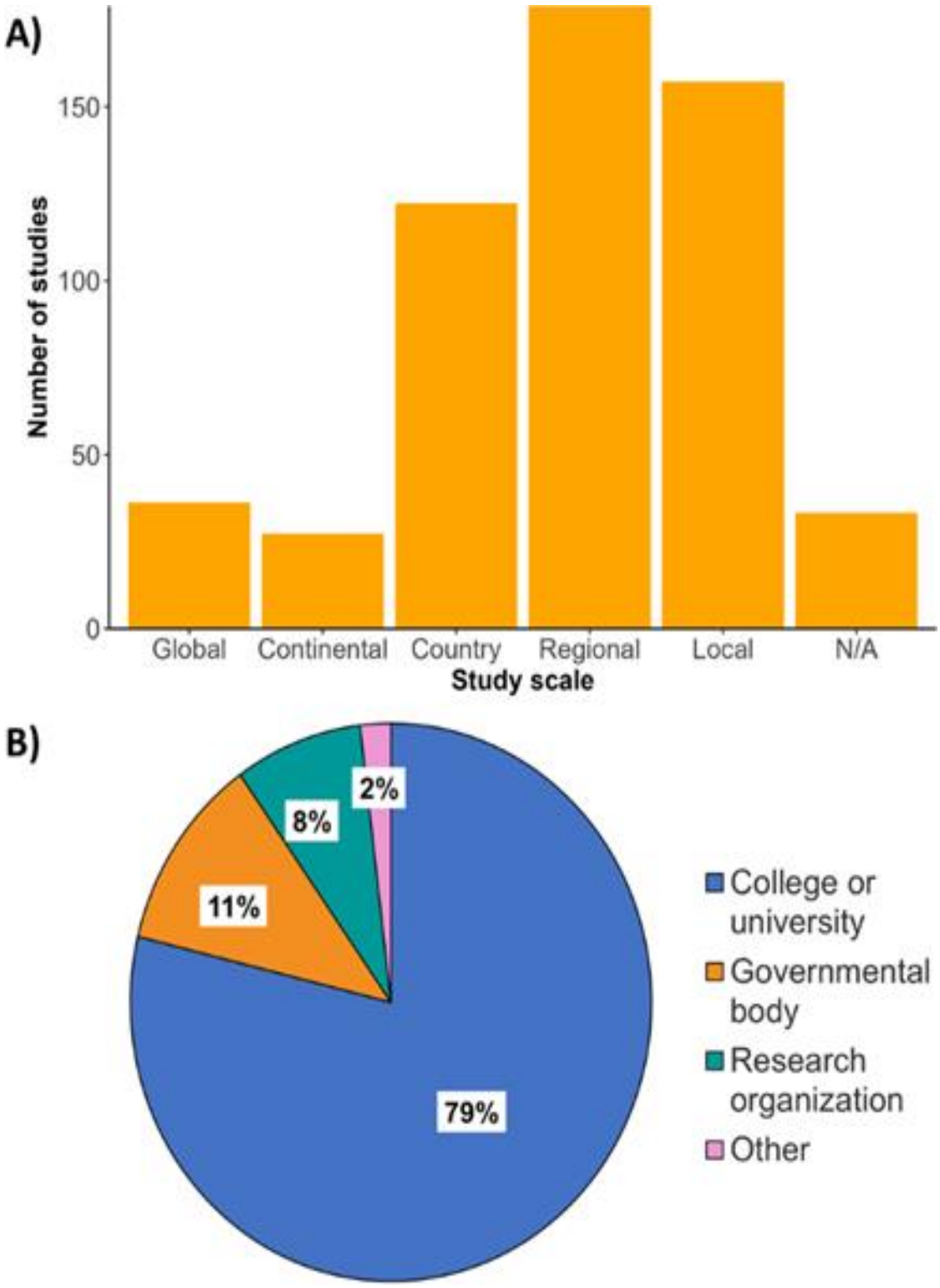

Figure 2 Bibliometric demographics. A Number of publications (x-axis) from 2015–2020 when delimited by scale of study. N/A: Studies for which a spatial scale was not applicable (e.g., laboratory-based studies) or for which scale was not specified. B Percentile breakdown of lead author affiliations collated into categories based on the institution's description (i.e., college or university, governmental organizations or research organization). Other: lead author affiliation institutions which do not fit one of these categories including non-governmental organizations, independent researchers, or private companies not otherwise specified

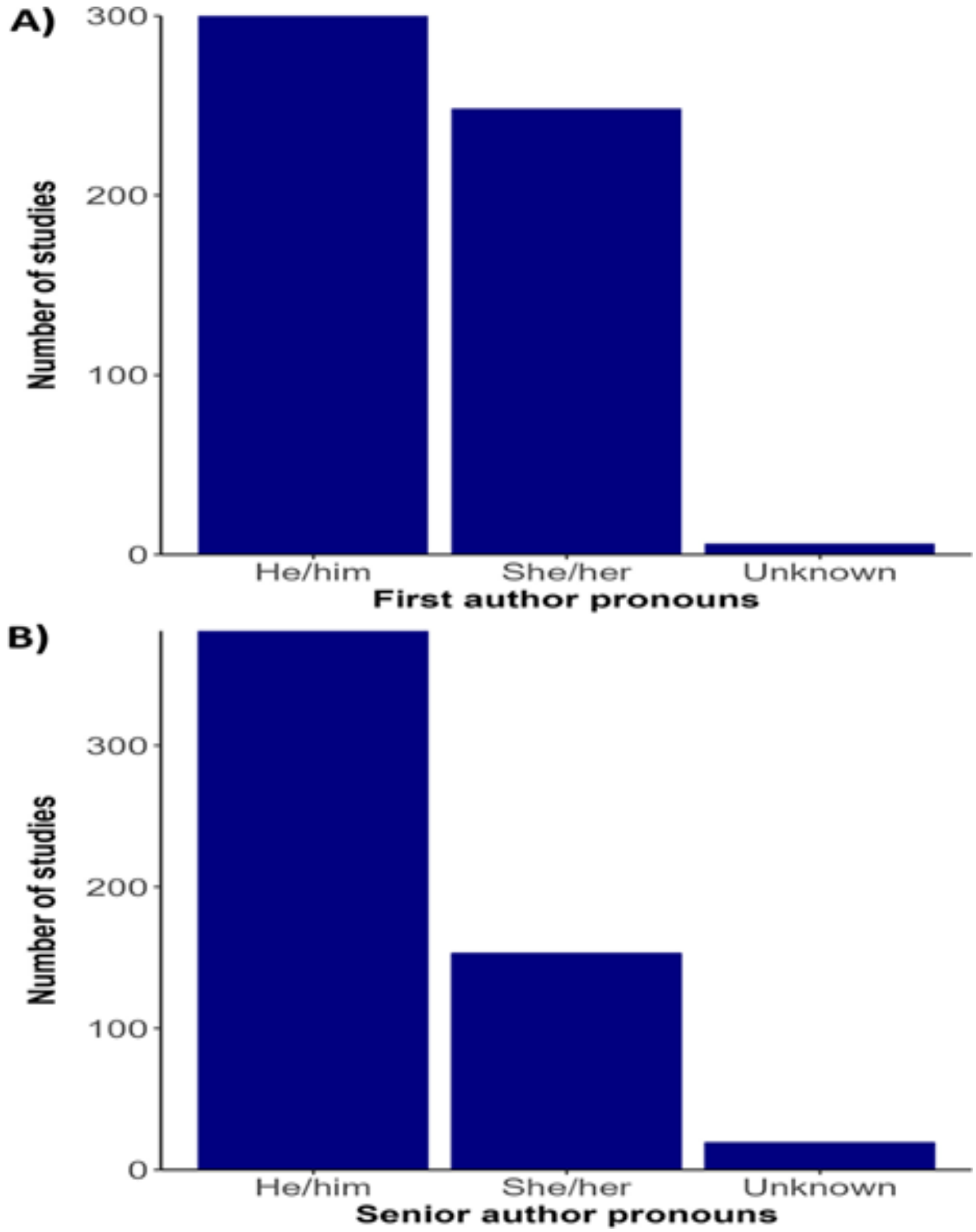

Figure 3 Author pronouns on climate change and infectious disease research. The self-identified pronouns of A first authors and B last (senior) authors of articles on climate change and disease from 2015 to 2020. The disparity between he/him pronoun usage over other pronouns was pronounced for senior authors. Authors' pronoun usage in public settings may vary from their gender identities.

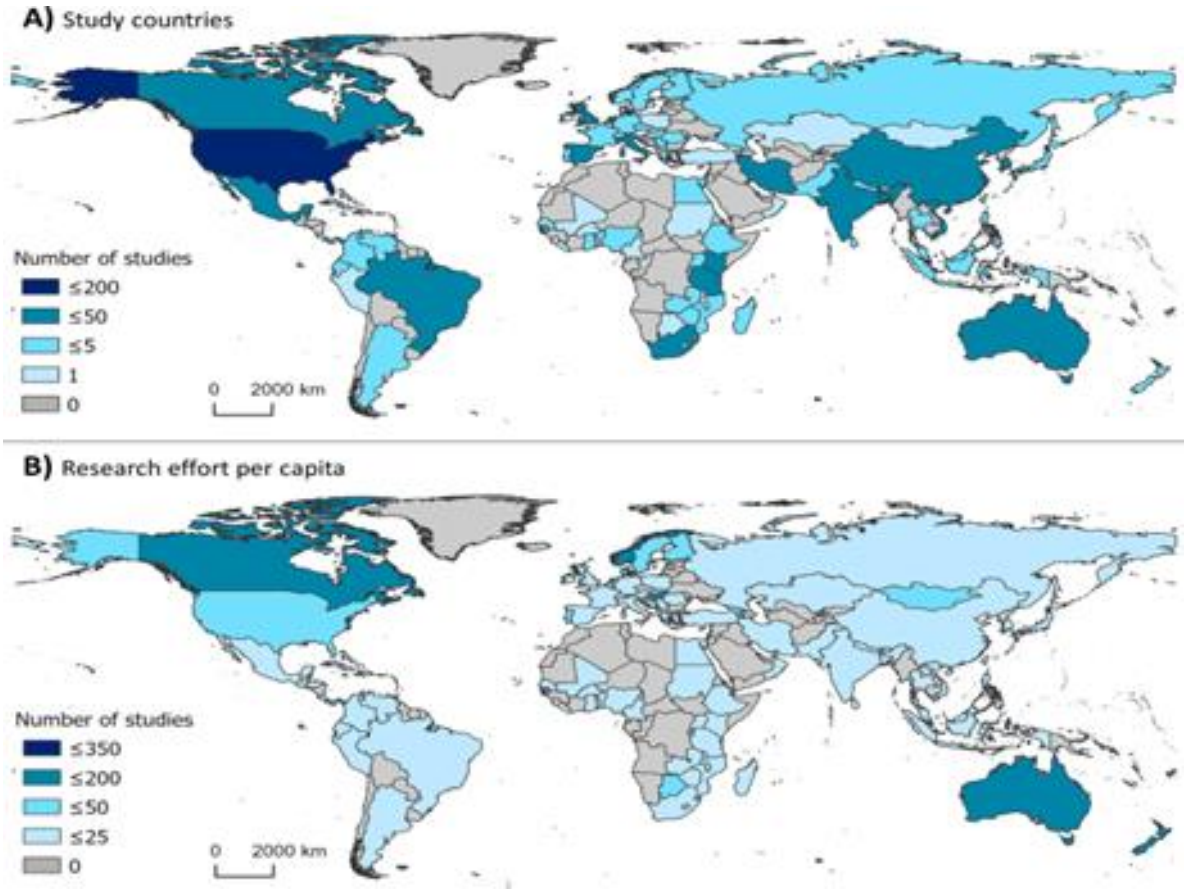

Figure 4 Map of study locations by country. A The geographic representation of where studies were conducted (i.e., country where the data analyzed in the study originated) from 2015–2020 on climate change and infectious disease and B publications that fit the inclusion criteria as a proportion of human population in 2020 (per one million individuals). Population data were collected from the United Nations Population Division [26]. Darker color represents more publications conducted in or on the corresponding country. Grey indicates that no studies which fit the inclusion criteria were conducted in or on the corresponding countries. Shape file for map creation sourced from DIVA-GIS

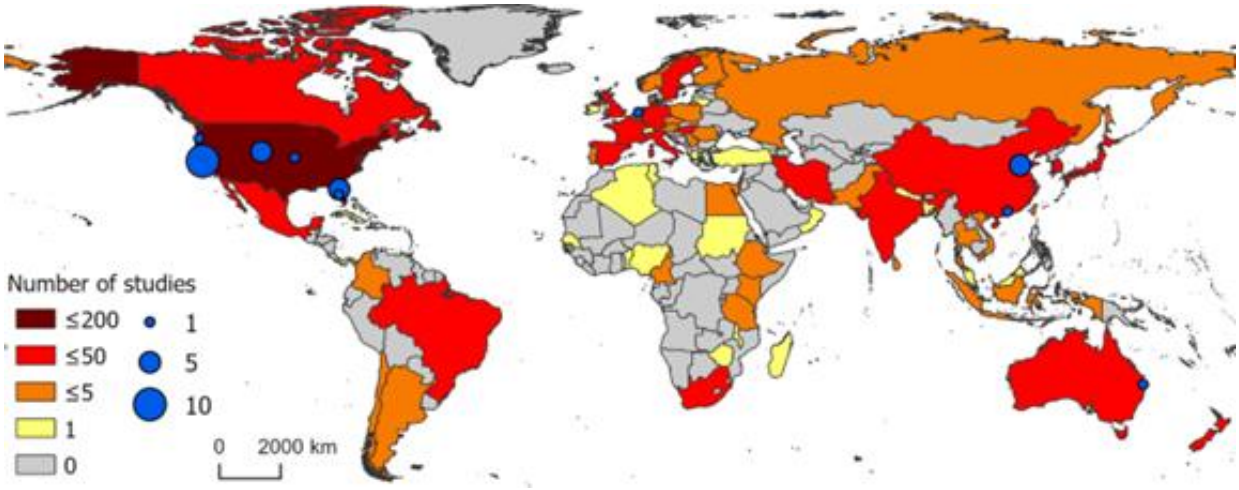

Figure 5 Map of lead author affiliation origins. The geographic representation of lead author affiliation origins for research on climate change and disease from 2015 to 2020. Darker color represents more publications originating from the corresponding country. Grey indicates that no studies which fit the inclusion criteria were conducted by authors affiliated with the corresponding countries. Blue points indicate the top ten publishing institutions globally for climate change and disease. Shape file for map creation sourced from DIVA-GIS

Discussion

This study presents an overview of the prevailing trends in current literature concerning the intersection of climate change and infectious diseases. Our analysis reveals notable biases in both the thematic focus and geographic distribution of research in this field. Particularly, we observed a significant emphasis on diseases affecting humans and those transmitted by arthropods. Taxonomic biases, which refer to the disproportionate focus on specific organisms, have been previously noted in biodiversity and conservation research. Our findings underscore similar biases towards mammalian hosts and arthropod-borne pathogens within the realm of climate change and infectious disease research. Such biases could potentially divert attention and resources away from less studied taxa, thereby impeding a comprehensive understanding of disease dynamics across ecosystems.

The emphasis on vector-borne diseases, which pose a substantial burden on human health with an estimated annual toll of approximately 700,000 lives, aligns with the overarching focus on human health within research agendas. This inclination towards human-centric investigations may stem from various factors, including public health priorities and funding allocations, which often prioritize research with direct relevance to human well-being. Additionally, societal pressures may contribute to the skew towards human-centric and zoonotic diseases, reflecting broader concerns about disease transmission and public health preparedness.

However, despite the anthropocentric tendencies evident in our findings, certain taxa, such as amphibians, birds, and aquatic invertebrates, face heightened risks of extinction due to infectious diseases. The dearth of research on these lesser-studied groups raises concerns about our ability to understand and mitigate disease threats in vulnerable ecosystems. Moreover, neglecting wildlife diseases may hinder our understanding of disease emergence and transmission dynamics, potentially leading to unforeseen public health consequences through spillover events and ecological imbalances.

Our analysis also highlights a predominance of lead authors affiliated with higher education institutions, indicating a bias towards academic-based research. While academia plays a crucial role in generating knowledge and fostering scientific inquiry, this imbalance suggests limited involvement of stakeholders from governmental and independent research institutions in shaping research agendas. Such disparities in participation may hinder progress in formulating comprehensive policy responses to the complex challenges posed by climate change and infectious diseases.

Furthermore, while federal or national institutions emerged as the primary funding sources for recent research publications, the influence of funding agencies on research priorities and outcomes cannot be overlooked. Notably, corporate funding has been associated with the politicization of climate change-related topics, underscoring the importance of diverse and transparent funding sources in promoting unbiased scientific inquiry. Increasing government funding for climate change and infectious disease research, with a focus on environmental justice considerations, could help address existing inequities in research funding and foster more inclusive and impactful research efforts. Additionally, greater investment in the social science dimensions of climate change could facilitate broader societal engagement and enhance the legitimacy of climate change research as a global imperative.

We observed a prevalent use of he/him pronouns among lead and senior authors in the reviewed articles, indicating a higher representation of male or male-identified authors compared to female or female-identified authors (Fig. 3). This gender disparity was more pronounced among senior authors, aligning with a broader pattern of gender inequity in academic authorship, despite recent increases in female authorship. Historically, women or female-identified researchers have been underrepresented in science, a trend likely to persist for the foreseeable future. Such gender disparities in authorship are particularly concerning in the context of climate change and infectious disease research, given the field's societal implications. Women are expected to bear a

disproportionate burden of climate change and health impacts due to socio-economic factors and cultural discrimination. Thus, it is imperative to ensure the representation of women's viewpoints and experiences in scientific literature to inform more inclusive and effective policies for climate change adaptation and mitigation.

Regarding geographic scale and location, our analysis revealed that the majority of climate change and infectious disease research focused on regional and local scales, suggesting a prevalence of fine-scale studies shaping our understanding of climate change's impact on human and animal health. Moreover, research efforts were concentrated in temperate regions such as North America and Europe, rather than tropical areas like sub-Saharan Africa, Latin America, and Pacific Southeast Asia, even after adjusting for country population. This spatial bias is concerning, given that tropical regions are most susceptible to the impacts of emerging infectious diseases and climate change. Notably, areas with limited research effort included regions expected to experience significant climate change effects and disease emergence, such as Latin America, Northern and West Africa, and the Indo-pacific. Efforts to elucidate emerging infectious diseases in these regions are crucial for mitigating risks associated with disease emergence.

Additionally, the underrepresentation of extremely cold Arctic or Subarctic regions, despite recent outbreaks of avian influenza and the potential threat posed by melting permafrost, underscores the need for concerted research efforts in these areas. The intersection of susceptibility to climate change impacts and infectious diseases highlights the importance of addressing research gaps in underrepresented regions to mitigate disease risks effectively. Moreover, the underrepresentation of countries and communities already vulnerable to infectious diseases exacerbates social inequities.

However, our assessment may be subject to several limitations. Publications from lower-income or developing countries may not have been adequately represented in the analyzed data repositories due to publication barriers such as language or lack of equitable partnerships. This potential misrepresentation could perpetuate inequities in global health research and exclude relevant discoveries from the global health agenda. Moreover, publication bias may have influenced our results, as positive or significant findings are often prioritized for publication, potentially skewing the conclusions drawn from the sample. These limitations underscore the need for continued efforts to address inequities in scientific research and ensure diverse and inclusive representation in academia.

In conclusion, our analysis revealed distinct geographic and taxonomic trends in recent studies investigating the intersection of climate change and infectious diseases. The predominant focus was on vector-borne pathogens, primarily conducted in well-developed, high-income countries with temperate climates, thereby overlooking directly-transmitted diseases prevalent in tropical regions. This anthropocentric bias in research may contribute to a limited understanding of climate change impacts on wildlife systems. The underrepresentation of certain taxonomic groups of pathogens and hosts, transmission types, and geographic areas raises significant global health concerns, as neglected areas and diseases may serve as sources of emerging zoonotic diseases. Adopting an ecosystem-based approach to studying disease responses to climate change could help mitigate the identified topical and taxonomic biases.

Recent outbreaks of viral zoonoses in underrepresented regions like Madagascar, Saudi Arabia, and Indonesia, resulting in widespread human epidemics of diseases such as plague, Middle East respiratory syndrome, and cholera, underscore the critical need for increased research in these marginalized areas. The COVID-19 pandemic further emphasizes the necessity for comprehensive research on directly transmitted pathogens circulating in wildlife. Moreover, there is a pressing need to examine the relationship between patterns of research funding and climate change and infectious disease studies. Understanding the funding landscape, including agencies' prioritization of specific regions, diseases, and topics, could shed light on research bias, equity, and allocation of resources.

The mutual influence of climate change research and intergovernmental policy is increasingly evident and actionable. Both funding agencies and the scientific community should prioritize policy changes to address the identified biases, including the diseases studied, geographical areas, and the representation of leading authors. Policy interventions could involve prioritizing infectious disease research and surveillance at the human-wildlife interface within the climate change context, allocating funds to scientists from minority groups and neglected geographic regions. Addressing research inequities will enhance human capacity, surveillance, and scientific infrastructure, strengthening the global health response to climate change threats.

Moreover, research foundations in high-income countries should embrace inclusive collaboration practices to recognize and value contributions by local scientists from underrepresented countries, thereby advancing research equity and effectively preventing future emerging diseases at their sources. Garnering political and social support for climate change and infectious disease research is crucial given the anticipated rates of climatic variation in the near future. In summary, urgent action is needed to bolster research efforts for neglected disease systems and geographies while reassessing environmental justice aspects from scientists leading these studies to local beneficiaries, thereby advancing infectious diseases research in the context of climate change.

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