Distribution of tungiasis in latin America: Identification of areas for potential disease transmission using an ecological niche model

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Summary

Background Tungiasis is a neglected tropical disease (NTD) found in Sub-Saharan Africa and Latin America. Despite the high frequency in marginalized populations, little information is available on the geography and estimates of the population at risk in endemic regions. Here we used a geostatistical model to map the potential geographic distribution of areas suitable for tungiasis transmission in Latin America and estimated the at-risk population.

Methods We developed an ecological niche model (ENM) using tungiasis occurrence records and remotely sensed environmental and socioeconomic data. The potential geographic distribution was then compared to the current population distribution of the region to derive the total population living in urban and rural areas.

Findings We identified a total of 138 records of occurrences of tungiasis in Latin America, ranging from Mexico to Argentina; 27 reports were not included in the modeling, due to missing detailed geographic information. The occurrences with detailed geographic information (n = 112) included 17 countries in Latin America and the Caribbean. The locations were in environments that primarily consisted of forests (29%), croplands (16•5%), and shrublands (10•9%). We predicted environmentally suitable areas for tungiasis transmission in 45 countries. The estimated human population living in these areas is 450,546,547 with urban centers accounting for 347,007,103 and rural areas 103,539,444. Countries with significant ecological suitability and documented occurrences include Brazil, Colombia, Mexico, Argentina, Bolivia, Ecuador, French Guyana, Guatemala, Haiti, Paraguay, Peru, Trinidad and Tobago, and Venezuela.

Interpretation This is the first study mapping the potential distribution of tungiasis in Latin America, evidencing the need for population-based studies and elaboration of integrated control measures.

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Keywords: neglected tropical diseases; tungiasis; geographic information science

Introduction

Tungiasis, a neglected tropical disease (NTD), is a parasitic skin disease caused by the sand flea Tunga penetrans, endemic to resource-poor communities throughout Latin America, sub-Saharan Africa, and the Caribbean. The disease is widespread in Latin America and the Caribbean, but reliable data on disease occurrence are not available on the national level.[1] Several cross-sectional studies have evidenced high prevalence and severe morbidity in underprivileged communities in human and animal populations, such as in Brazil, Colombia, Haiti, and Trinidad and Tobago.[2-6] In endemic areas, the disease occurs focally, predominantly in urban slum areas, rural communities, fishing villages, and indigenous communities.[1,4,7]

The use of geographic information systems (GIS) can provide estimations on the spatial patterns of disease risk to facilitate effective public health interventions at multiple scales of analysis. Although limited in

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Research in context

Evidence before current study

Tungiasis is a neglected tropical disease (NTDs) common among low-socioeconomic status populations with poor access to health resources. Despite the long history of the disease in Latin America, the Caribbean and sub-Saharan Africa, the literature on tungiasis from a geographic perspective is limited. A previous study has mapped and compiled disease occurrence data at a broad scale across sub-Saharan Africa; however, to date, the literature does not include studies applying similar methodologies for Latin America.

Added value of the current study

In total, 138 occurrence records were compiled in Latin America and the Caribbean, and an ecological niche model (ENM) was developed to map the relative suitability of tungiasis in relation to environmental and socioeconomic covariates. 45 countries were identified to harbor environmentally suitable regions for potential tungiasis distribution. The total population living in suitable areas was estimated at 450 million.

Implications of all the available evidence

Delineating areas of high disease transmission risk can facilitate and guide public health interventions and define focus areas for tungiasis studies and disease control.

scope, recent literature incorporating GIS for studies on tungiasis has helped spread awareness of the disease and knowledge of its potential geographic distribution.[8,9] One such method, Ecological Niche Modeling (ENM), is an essential tool to predict potential species distributions in relation to environmental constraints and has gained considerable traction as the primary method employed for disease mapping studies.[10] Previously, the ENM approach has been applied to predict tungiasis distribution on the African continent,[8] but there are no systematic data on suitable areas for tungiasis transmission in Latin America and the Caribbean. To fill this gap, in this study, the potential spatial distribution of tungiasis in Latin America was mapped using occurrence data and a range of environmental and socioeconomic data. In addition to the study from Africa, we included occurrences from additional sources such as grey literature and Masters and Ph.D. theses and considered the date range, as tungiasis distribution and environmental conditions have changed considerably over time.

Methods

Study Area and Occurrence Records

The model calibration region or **M** region[11] included South America, excluding the southern half of the continent, Central America, Mexico, and the Caribbean (Figure 1). The **M** region, based on the **BAM** Framework,[11] represents the hypothesized accessible area available to a T. penetrans during its biogeographic history. There were no occurrence reports from the most southern region of the continent, and given the climatic conditions, tungiasis is not to be expected to occur in this region. Tungiasis occurrence records were collected from literature sources spanning a temporal period from 1896 – 2021(please see supplemental materials). Tungiasis weas defined as the presence of at least one embedded tunga flea. In these records, diagnosis was mostly done clinically, and in some cases histopathological sections were done.

The search of these records was conducted in English, French, Portuguese and Spanish in Google (www.google.com), Google Scholar (https://scholar.google.com/), PubMed (https://pubmed.ncbi.nlm.nih.gov/), Lilacs (https://lilacs.bvsalud.org/en/), Scielo (https://www.scielo.br/) and from regional Masters and Ph.D. theses, grey literature and news reports, including all countries, dependencies and other territories in Latin America and the Caribbean. Search terms included, for example, “tungiasis Brazil”, “tungiasis Peru”, “tungiasis animals”. All types of studies (case reports, case series, population-based studies etc.) were included. No time range or article type limits were applied. Additionally, these data were supplemented with species data for T. penetrans from the Global Biodiversity Information Facility (GBIF) (https://www.gbif.org/).[12] To account for spatial autocorrelation in the occurrence records and to ensure independent records, the SDM toolbox extension[13] in ArcGIS 10·8·1 (ESRI. ArcGIS desktop: release 10.8. Environmental Systems Research Institute, CA, USA) was implemented with a 30-kilometer distance threshold. As a result, the final cleaned dataset featured 91 occurrence locations.

Environmental Data Description and Analysis

Gridded monthly climate and climatic water balance estimates were obtained from the TerraClimate (http://www.climatologylab.org/terraclimate.html) dataset (1981-2010) at a ~4 km resolution.[14] Supplementing the TerraClimate data were mean elevation (~5 km) data[15] and remotely sensed high-resolution cloud cover observations at a ~1 km resolution.[16] These open-source data were obtained from the EarthEnv data repository (https://www.earthenv.org/). In addition, soil coverages representing the distribution of sand, clay, silt, and soil pH were downloaded at a 5-kilometer resolution (5-cm depth, g/100 (w%)) from the International Soil Reference and Information Centre (ISRIC) (https://soilgrids.org/).

Previous studies on the relationship between soil and tungiasis prevalence are limited in scope; however, work from Nagy,[17] Chadee,[6] Winter,[18] and Nyangacha

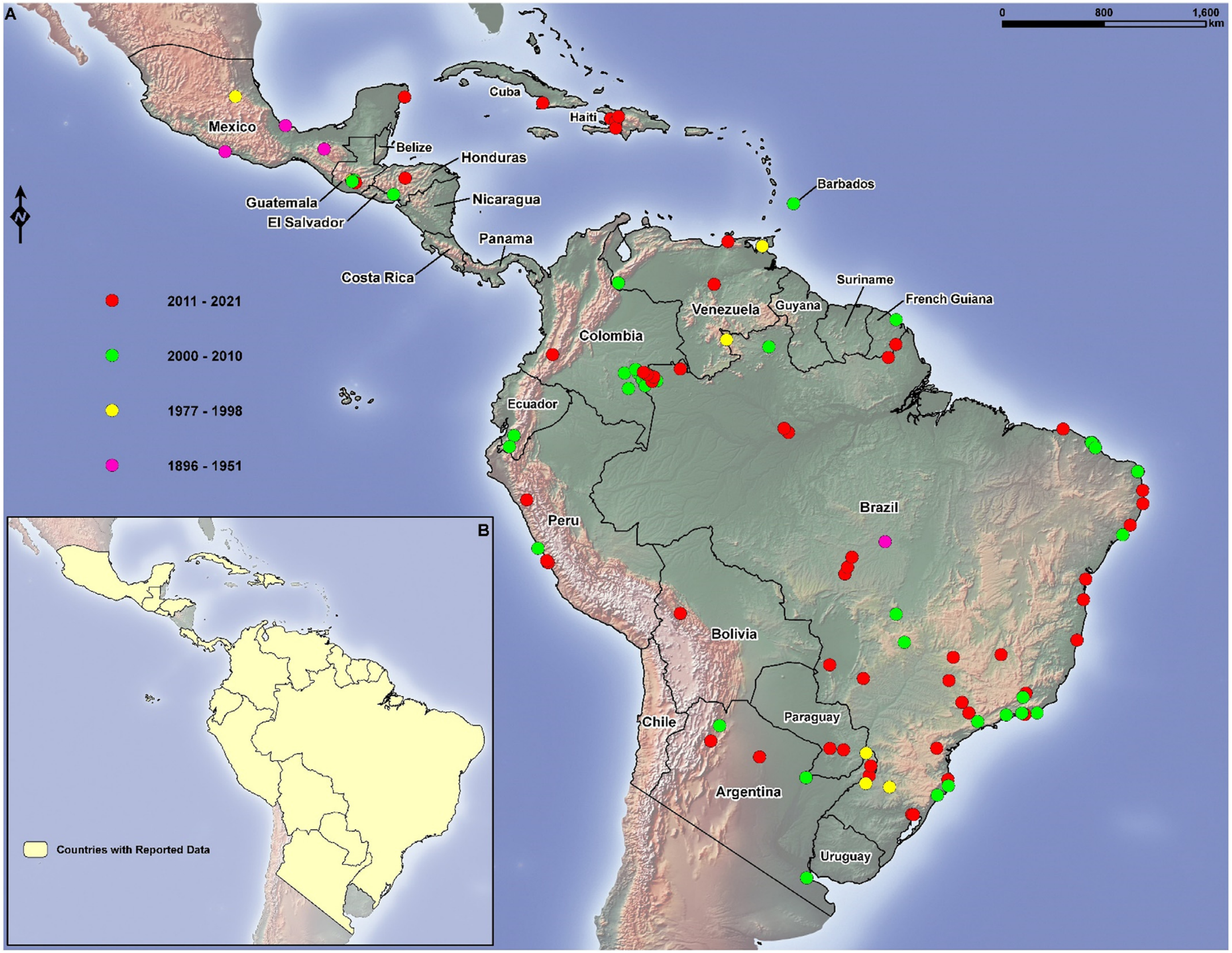

Figure 1. A. Model calibration area (M region) and tungiasis occurrence reports with geographic details identified, stratified by date range (n = 138) (1896-2021). B. Countries with reported data in Latin America and the Caribbean.

and colleagues[9] have documented the apparent association between sandy, clay soils and the depth at which T. penetrans eggs (surface), larvae (2-5 cm) and pupae are found in the soil. Additionally, included were biweekly AVHRR (advanced very-high-resolution radiometer) Normalized Difference Vegetation Index (NDVI) data from 2000 – 2014 at a 1 km resolution from Clark Labs (Clark University) (https://clarklabs.org/), and the 8-day MODIS mean land surface temperature values (LST) (~1 km) (2000-2012) obtained from the WorldGrids data archive.[19] Landcover data representing the distribution of croplands, forests, shrublands, and herbaceous vegetations (~1 km) were obtained from the Global Landcover Network Share database (GLC-Share) (1998-2012) (http://www.fao.org/geonetwork/srv/en/main.home) managed by the Food and Agricultural Organization of the United Nations (FAO). Additionally, to account for distance to water bodies in Latin America, we included a 250-meter resolution raster (https://www.arcgis.com/home/item.html?id=46cbfa5ac94743e4933b6896f1dcecfd).

The density of livestock accounted for the risk to humans in close contact with animals;[20] these were the density of goats,[21] and pigs. [21] These data were obtained from the Food and Agricultural Organization of the United Nations (FAO) Gridded Livestock of the World (v2·01) database at a ~1 km resolution (livestock.geo-wiki.org). Socioeconomic variables included accessibility to cities[22] and nighttime lights satellite imagery, which represented a poverty proxy[23] (https://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html). To ensure a uniform geographic extent and cell size, all variables were resampled at a 4 km resolution. Finally, a principal component analysis (PCA) was carried out in ArcGIS 10·8·1 (ESRI. ArcGIS desktop: release 10.8. Environmental Systems Research Institute, CA, USA), on the selected variables to account for dimensionality and multicollinearity in our dataset. Following the PCA analysis, the first 8 principal components were retained, which summarized 99% of the overall variance. Additionally, a biplot was produced to visually summarize the loadings of the variables (vectors) and their contributions to the first two PC's. (Figure 2) The complete list of covariates (n = 29) is detailed in Table 1.

Maxent Modeling and Population Estimate in Suitable Areas

The potential geographic distribution of tungiasis was modeled with the maximum entropy algorithm implemented (Maxent) with the R package (R Studio team PBC; 2020), 'maxnet' v.0.1.4.[24] Maxent provides an estimate for the geographic extent of a species by identifying the distribution with 'maximum entropy' subject to the constraints from the environmental conditions at the site of occurrence locations.[24]

Before modeling, we tuned our data by varying the level of 'regularization' to the optimal level of model complexity (flexibility of modeled response) with the R package (R Studio team PBC; 2020) ENMeval v·2·0·0[25] found in the ENM application Wallace.[26] Here, we varied our regularization multipliers (RM) from 0·5 to 5·0, at increments of 0·5 (0·5, 1, 1·5, 2, 2·5, 3, 3·5, 4, 4·5, 5) with 5 different feature class (FC) combinations (L, LQ, H, LQH, LQHP; L = linear, Q = Quadratic, H = hinge, and P = product) (total = 50 candidate models; 10 RM × 5 FC), and specified a 'block' spatial partition (k = 4) method. The best combination of FC's and RM's was selected based on the lowest (< 0) corrected Akaike information criterion (AICc) (delta. AICc).[29] Additional settings specified 10,000 background points, cloglog output type (inhomogeneous Poisson process), and the 10th percentile training presence threshold.

The final model was evaluated with the partial receiver operating characteristics (pROC)[27] approach at a 5% error rate (E = 0·05) using the Niche Analyst (NicheA) software[28] (http://nichea.sourceforge.net/). The pROC approach avoids some of the potential downfalls of the traditional AUC (area under the curve) statistic and allows for differential weighting of model omission and commission errors.[27] The total population residing in urban and rural areas was estimated by overlaying the binary raster (10th percentile training presence) with the 2020 WorldPop (https://www.worldpop.org/) gridded population (~1 km resolution) surface, estimating the total number of individuals per pixel value and the Global Rural-Urban Mapping Project (GRUMP) v1 (CIESIN) (https://sedac.ciesin.columbia.edu/data/collection/grump-v1) Columbia University (New York, NY, USA).

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Results

We identified a total of 138 records of occurrences of tungiasis from 22 countries in Latin America and the Caribbean (1896-2021, Figure 1) that were screened for suitability and fully evaluated (see the complete list in supplementary material). A total of 26 reports were not included in the modeling due to missing detailed geographic information, and we ended up for analysis with 112 manuscripts that came from 17 Latin American and Caribbean countries. These included reports from several countries from which no other reports were available, specifically Costa Rica, Dominican Republic, Guyana, Panama, and Suriname. From South America, we identified reports from all countries except for Chile and Uruguay. From 2011 to 2021, 64 locations were georeferenced, with an additional 51 records from 2000-2010. Records from 1896 to 1998, comparatively speaking, were limited, with only 23 documented over

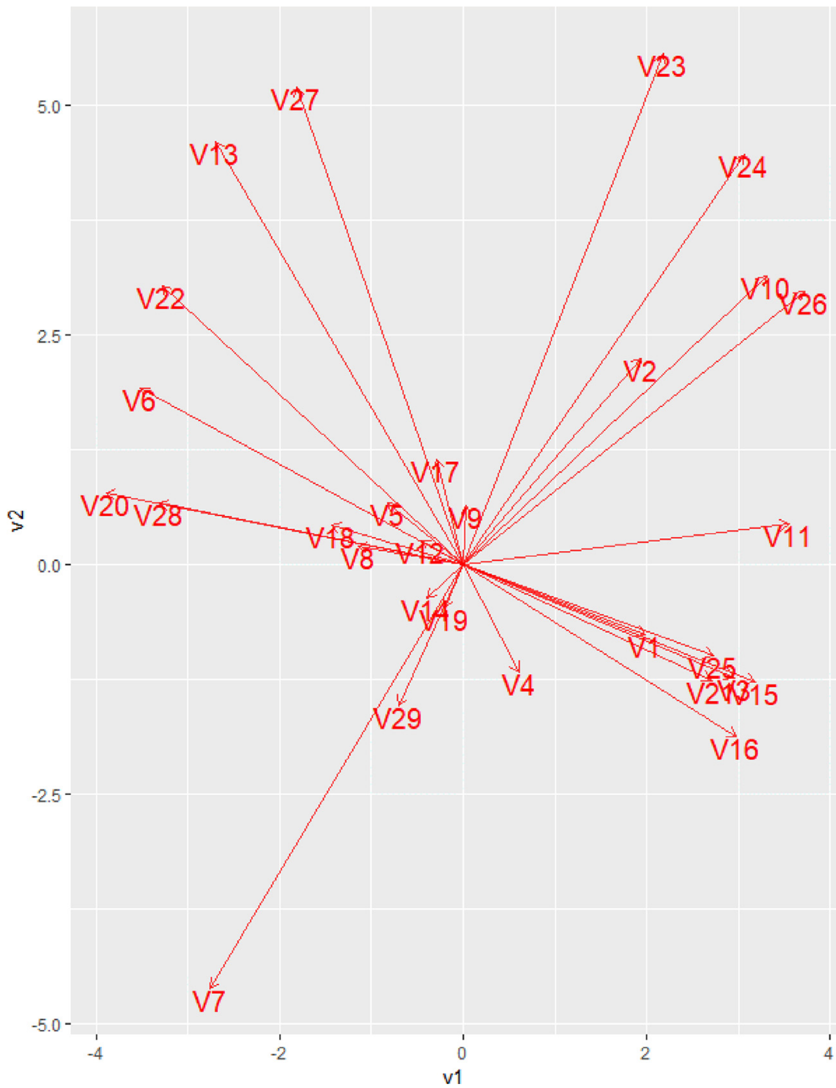

Figure 2. PCA Biplot PC1 (32%); PC2 (14%). Variables of significance to PC1 and PC2 include: maximum temperature (23), minimum temperature (24), vapor pressure (26), land surface temperature (LST), NDVI (11), soil pH (20), wind speed (28), climate water deficit (6), downward surface shortwave radiation (22), potential evapotranspiration (13), vapor pressure deficit (27), precipitation (25), soil moisture (21), tree covered area (13), runoff (15), cloud cover (16). Biplot created with the software, Niche Analyst (NicheA): http://nichea.sourceforge.net/.

102 years. In total, 82% of all records were documented from 2000-2021. Figure 3 depicts the number of records and the temporal range of occurrence records. The majority were documented in Brazil, Colombia, Argentina, Venezuela, Mexico, Paraguay, Guatemala, Peru, and Haiti. The locations were in environments that primarily consisted of forests (29%), croplands (16·47), and shrublands (10·91%) at a mean elevation of 380 meters. The average maximum and minimum temperatures for the month were 29· 8 C° and 19·4 C°, while the average monthly precipitation was 156·76 mm.

The maxent model with the lowest corrected Akaike information criterion (AICc) featured linear (L), quadratic (Q), and hinge (H) features and a RM = 1.5 (delta. AICc = 0) (see appendix for corresponding response plots). The partial ROC test found that the median distribution model performed significantly better than random based on the partial AUC (E = 0·05) of 0·86, and a ratio of observed to null expectations which were above 1 (1·60) (P <0·01)[30]. The potential distribution of tungiasis-suitable areas is presented in Figure 4. A total of 45 countries were identified to harbor environmentally suitable regions for potential tungiasis distribution. Countries with significant ecological suitability and documented occurrences include Brazil, Colombia, Mexico, Argentina, Bolivia, Ecuador, French Guyana, Guatemala, Haiti, Paraguay, Peru, Trinidad and

Variable	Spatial Resolution	Source	Units	Average
Actual Evapotranspiration (aet) (monthly total)	~4 km	TerraClimate	mm	93•13
Climate Water Deficit (def) (monthly total)	~4 km	TerraClimate	mm	23•82
Potential Evapotranspiration (pet) (monthly total)	~4 km	TerraClimate	mm	116•95
Precipitation (ppt) (monthly total)	~4 km	TerraClimate	mm	156•76
Runoff (q) (monthly total)	~4 km	TerraClimate	mm	65•34
Soil Moisture (soil) (total end of the month)	~4 km	TerraClimate	mm	101•25
Downward Surface Shortwave Radiation (srad)	~4 km	TerraClimate	w/m2	194•14
Max Temperature (tmax) (average for the month)	~4 km	TerraClimate	C°	29•8
Min Temperature (tmin) (average for the month)	~4 km	TerraClimate	C°	19•4
Vapor Pressure (vap) (average for the month)	~4 km	TerraClimate	kPa	2•40
Wind Speed (ws) (average for the month)	~4 km	TerraClimate	m/s	2•18
Vapor Pressure Deficit (vpd) average for the month)	~4 km	TerraClimate	kpa	0•84
Cloud Cover (mean annual)	~1 km	EarthEnv	%	6129
Elevation (mean)	~5 km	EarthEnv	Meters	380
Cropland	~1 km	(GLC-SHARE) - FAO	%	16•47
Shrubland	~1 km	(GLC-SHARE) - FAO	%	10•91
Tree Covered Area	~1 km	(GLC-SHARE) - FAO	%	29
Herbaceous	~1 km	(GLC-SHARE) - FAO	%	0•93
Normalized Difference Vegetation Index (NDVI) (2000−2014)	~1 km	Clark Labs (Clark University)	NDVI (.001)	5•6
Land Surface Temperature (LST)	~1 km	WorldGrids	C°	18•77
Sand (0−5 cm)	~5 km	ISRIC	g/100 (w%)	49•19
Silt (0−5 cm)	~5 km	ISRIC	g/100 (w%)	20•66
Clay (0−5 cm)	~5 km	ISRIC	g/100 (w%)	26•04
Soil pH (0−5 cm)	~5 km	ISRIC	g/100 (w%)	5•2
Goat Density	~1 km	FAO	head/km^2	4•37
Pig Density	~1 km	FAO	head/km^2	12•70
Accessibility to Cities	~5 km	Malaria Atlas Project	minutes	710•86
Night-time Lights	~1 km	NOAA	-	-
Distance to Water	250 m	ESRI	km	41•29

***Table 1*: Environmental variables included in ecological niche modeling.**

Tobago, and Venezuela. Areas of high suitability are located virtually along the entire Brazilian coastline, from Fortaleza in the north to the far south cities of Porto Alegre and Curitiba. Inland portions of suitability are present in central and southern Brazil, Peru, Ecuador, subtropical northern Argentina, Uruguay, and lowland regions in Bolivia. Suitability is found throughout the Amazon Basin, particularly in the vicinity of major tributaries of the Amazon River. In Colombia, the Andean natural region and portions of the Caribbean lowlands were identified as potentially suitable. Suitability in Mexico is confined to the Gulf Coastal Plain, the Central Plateau, Southern Sierra Madre region, and the Yucatan Peninsula; Most of the West Indies, particularly Cuba, Jamacia, Haiti, the Dominican Republic, Trinidad and Tobago, and the Lesser Antilles were identified as environmentally suitable, as was Venezuela, Guyana, Suriname, and French Guiana.

The estimated human population living in these environmentally suitable areas is according to the 10th percentile training presence threshold (value = 0.327) is 450,546,547, with urban centers accounting for 347,007,103 and rural areas 103,539,444. The thresholded model omitted all regions in the study area with suitability values lower than values for the lowest 10% of occurrences. Thus, many non-omitted values are found in heavily populated corridors in eastern and southern Brazil, where the bulk of the occurrence data were recorded (Figure 5).

As the environmental and social conditions and urbanization changed significantly over time in the region, we stratified the occurrence records by time range (Figure 6). Thus, the historical records before 1970 included in the model came from Mexico and Brazil − countries with endemic tungiasis still today. Similarly, occurrence reports 1970 -1999 came from endemic countries with recently published occurrences, namely Argentina, Brazil, French Guiana, Paraguay, and Venezuela, except for Costa Rica, which was not included in the model due to missing detailed geographic information, and Trinidad & Tobago with latest reports from 1998.

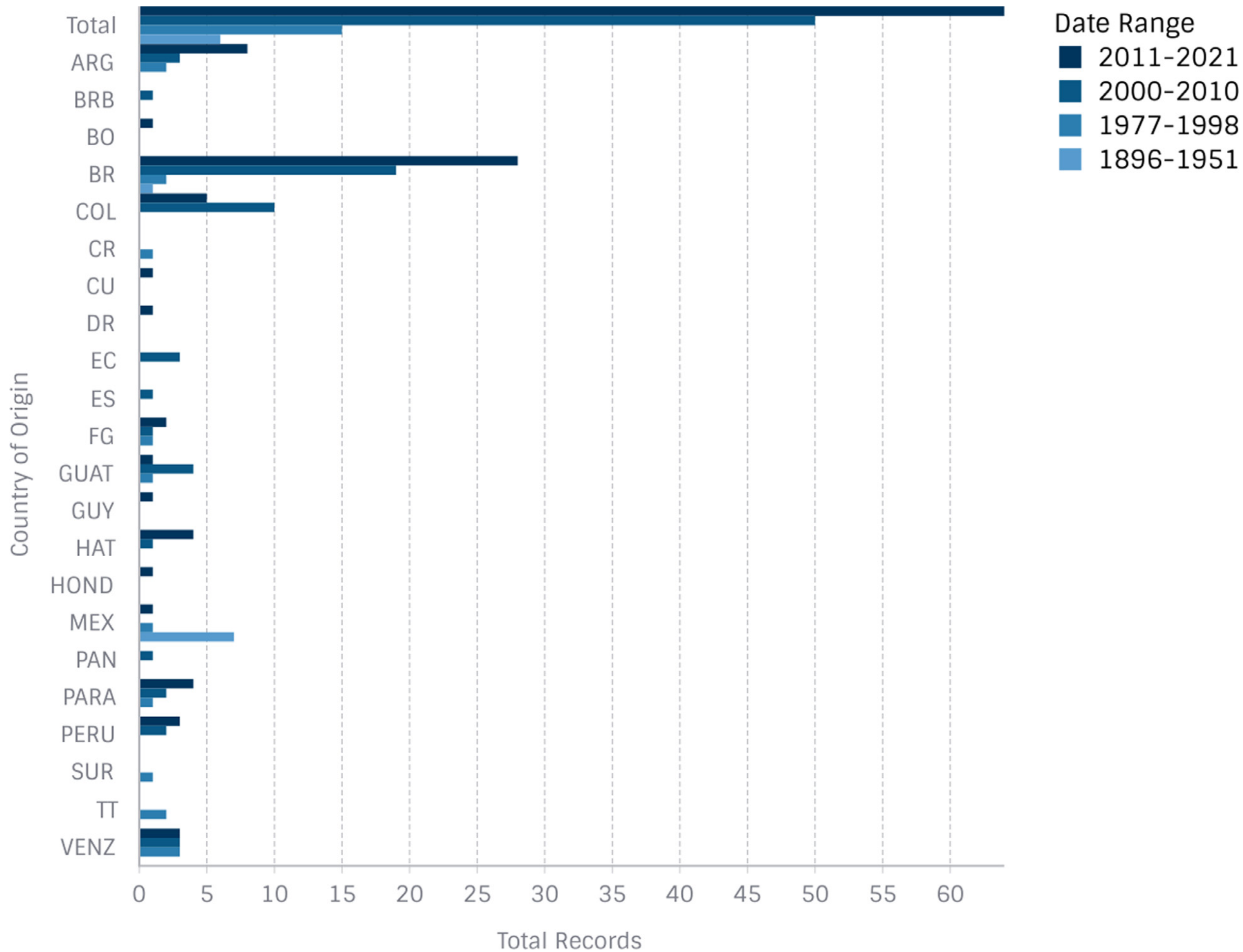

Figure 3. Temporal range of occurrence records (n = 138) (BR = Brazil; COL = Colombia; ARG = Argentina; VENZ = Venezuela; MEX = Mexico; PARA = Paraguay; GUAT = Guatemala; HAT = Haiti; FG = French Guiana; EC = Ecuador; TT = Trinidad and Tobago; SUR = Suriname; PAN = Panama; HOND = Honduras; GUY = Guyana; ES = El Salvador; DR = Dominican Republic; CU = Cuba; CR = Costa Rica; BO = Bolivia; BRB = Barbados)

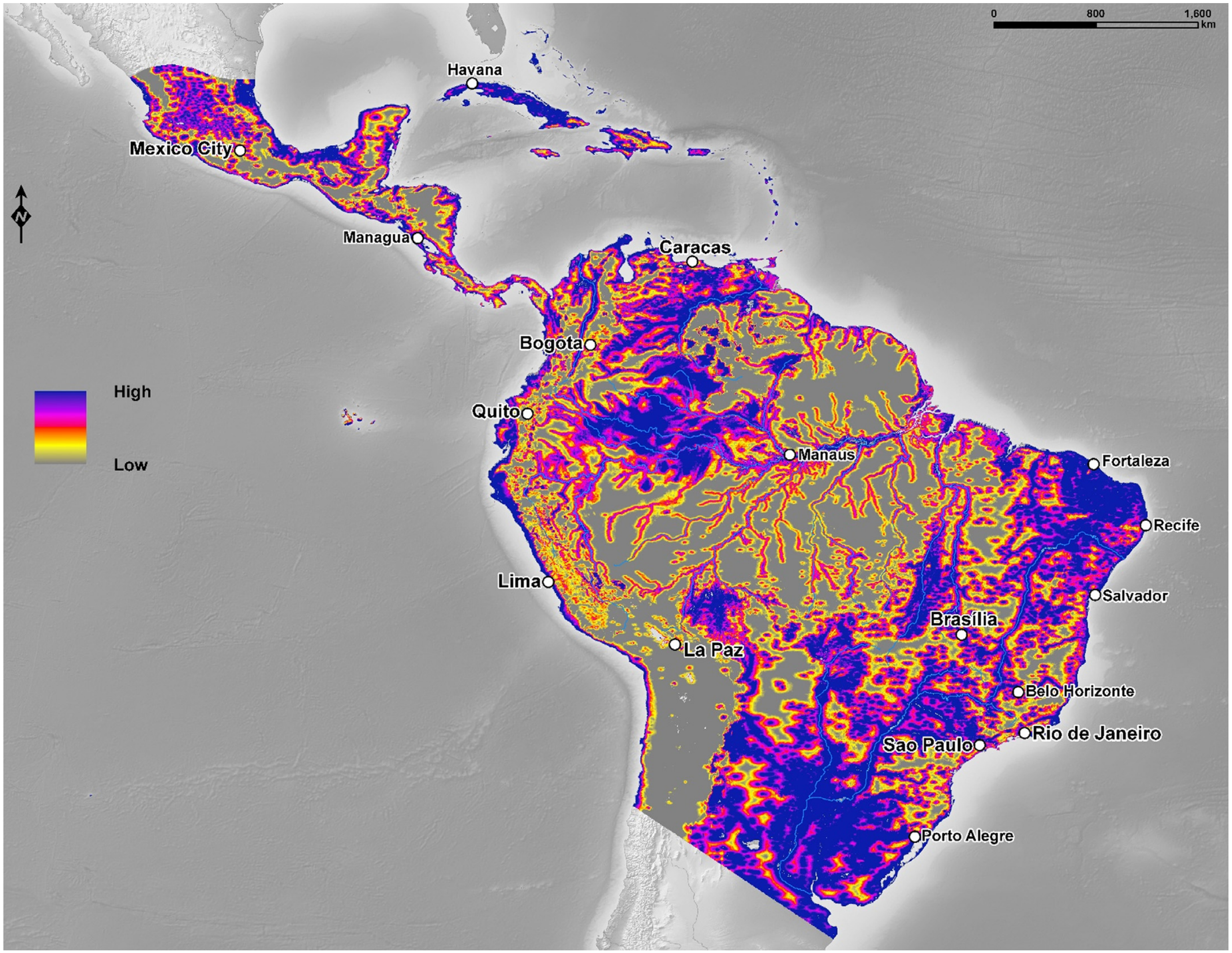

Figure 4. Potential distribution of tungiasis in Latin America (1896-2021) based on a Maxent model with LQH FC's and a RM of 1.5 (delta. AICc = 0).

Discussion

For the first time, this study mapped the potential distribution of tungiasis in Latin America and the Caribbean and delineated potential disease transmission risk areas. We predicted suitability in 45 countries; some have no known documented human or animal cases; these without any reports include Jamaica, Belize, Nicaragua, Puerto Rico, Uruguay, and small island nations and territories in the Lesser Antilles. Interestingly, our model has predicted suitable areas in those countries from which reports were available but not included in the analysis, as no detailed geographic locations of occurrences were available (Costa Rica, Dominican Republic, Guyana, Panama, and Suriname). A total of 450 million people are currently living in suitable areas, 347 million in urban and 103 million in rural areas. However, as tungiasis is a focal disease, not all populations may be at high risk of acquiring the disease, even if residing in environmentally suitable areas. We compiled all available records of occurrences of tungiasis dated 1896-2021. The multiple periods represented here give significant insight into the increased awareness of the disease starting at the beginning of the 21st century from 2000-2010. By the second decade of the century (2011-2021), the number of studies in Latin America increased more than in the previous decade, pointing to again positive steps in recognizing the burden of the disease in the scientific literature. 82% of the data were documented from 2000-2021, accounting for 114 records. Most of the records were in Brazil, Colombia, Argentina, Venezuela, Mexico, Paraguay, Guatemala, Peru, and Haiti, which were identified as having a high degree of relative suitability according to the Maxent model. Our results provided further insights into the large discrepancy in data collection on tungiasis from 1896 – 1998, where only 23 records were documented for 102 years compared to 2011- 2021, when 47% of all data were georeferenced. Despite the tremendous environmental and social changes in Latin America since the last century, we maintained these occurrence records in the model, as they were mainly from rural areas in countries where tungiasis today is still common or from countries with similar characteristics.

This study shows that geographic information systems (GIS) coupled with an ecological niche modeling (ENM) approach can map the spatial relationship between occurrence locations and environmental covariates which can further serve as a foundation for estimating the at-risk population. These approaches coupled with multidisciplinary One Health control strategies under the umbrella of the Pan American Health Organization (PAHO/WHO) may lessen the burden of the disease in communities facing extreme poverty and underdevelopment. Like recent work by Deka[8] in sub-Saharan Africa, this study represents a positive step towards greater awareness of the disease and its impact on human lives and can guide resource allocation and outreach work in at-risk communities throughout Latin America and the Caribbean. In addition to the previous study from sub-Saharan Africa and for the sake of a more complete and robust analysis, here we performed a more comprehensive search of reports of occurrences by investigating additional sources, grey literature, Masters and Ph.D. thesis, and lay media reports, and stratified the data by time period.

Environmental suitability does not necessarily reflect the distribution of disease, as there are many other factors related to transmission and endemicity, such as the presence of resource-poor communities/slums, cultural habits (e.g., walking barefooted in indigenous communities, sitting/resting on the ground, pet holding practices), free-roaming pigs vs. confined pigs, urban vs., rural (e.g., rats and stray dogs as important reservoirs in urban areas, sylvatic/synanthropic animals in rural areas). On the other hand, increasing urbanization may reduce the occurrence of tungiasis considerably, especially in rural areas, as recently described in a long-term follow-up from Nigeria.[7] All these aspects need to be considered for effective control within a One Health Approach to attain sustainable control.[7,29] Furthermore, tungiasis occurrence needs to be differentiated from the occurrence of severe disease leading to significant sequels. For example, in some tourist areas, tungiasis represents a mild concern for travelers, but people suffer greatly from the disease in resource-poor communities in hinterland areas.

Additionally, of concern is the threat of continued climate change, the increased geographic range of vector-borne pathogens, and their diseases. Due to the seasonal variation in the occurrence of T. penetrans, climate change could change transmission dynamics and increase the severity of outbreaks due to prolonged and severe dry seasons in endemic areas. The impacts of climate change will likely significantly impact populations in low-resource settings like those most impacted by NTDs.[30] In addition, increasing contact of populations with sylvatic animals, an important reservoir, must be considered when planning control measures.

Our study has some limitations. First, it is essential to remember that tungiasis has a focal distribution that is strongly linked to poverty, socioeconomic status, and scale. For example, the disease burden may be very high in slums that are only a few hundred meters from upper strata areas of high income, where the disease is entirely unknown. Second, the model presented here does not measure prevalence or incidence and only correlates ecological similarities between occurrence locations; thus, this ecological macro approach does not reflect the risk of the entire population (450 million). Our model incorporated historical and contemporary literature in the data collection process. It needs to be recognized that there are uncertainties associated with these data, especially for the oldest records included in our work, as the relative location only was included instead of more

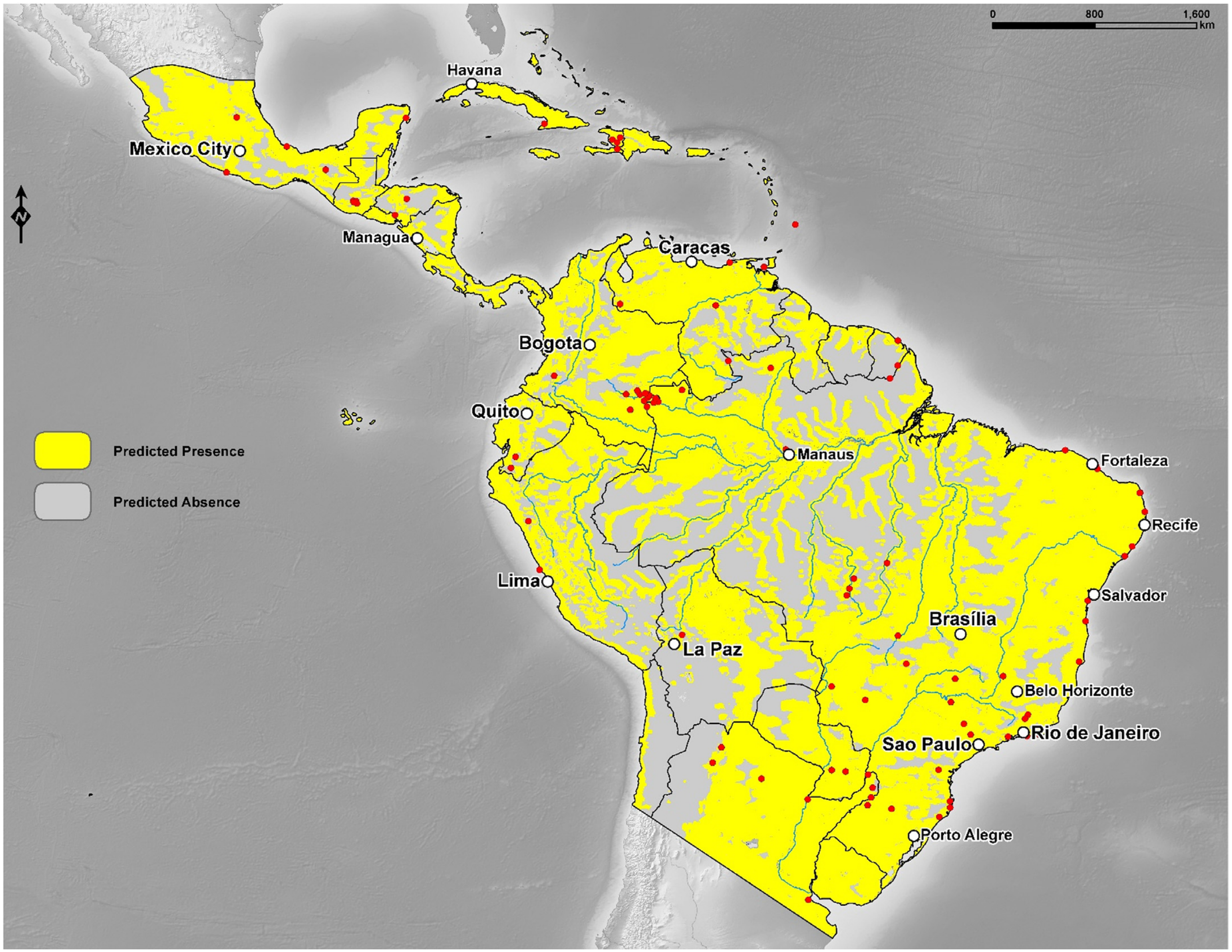

Figure 5. Binary transformation based on the 10th percentile training presence threshold (presence - yellow). Red dots represent the occurrence locations (n = 112) with geographic identifiers.

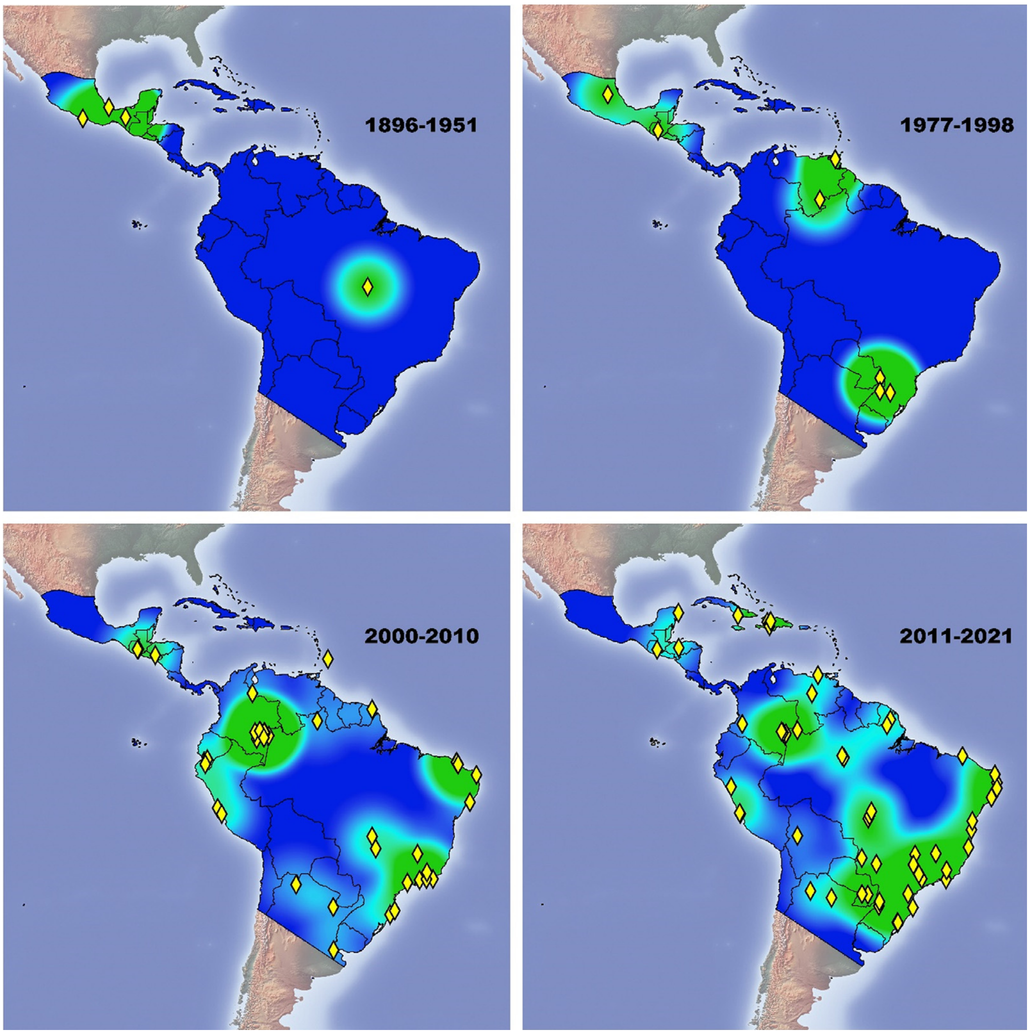

Figure 6. Geographic distribution of occurrence data from 1896-2021, stratified by time period.

accurate geographic coordinates of cities, towns, or villages. There are also probably additional endemic areas that have not been included in our analysis, as no records were available.

In summary, our study provides for the first time an evidence-based approach for mapping the potential environmental distribution of tungiasis in Latin America and the Caribbean, evidencing the need for population-based studies with a focus on the detected suitable areas and elaboration of integrative control measures.

Contributors

MD and JH conceptualized the study. MD and JH contributed to the methodology. MD and JH performed the formal analysis. MD created the graphics and maps. MD and JH prepared the original draft of the manuscript. MD and JH contributed to reviewing and editing the manuscript. MD and JH accessed and checked data underlying the study. Both authors approved the version of the paper for submission.

Data Sharing Statement

Please see the supplementary materials for access to the occurrence data and corresponding literature sources.

Editor disclaimer

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Declaration of Interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The findings and conclusions in this document are those of the authors and do not necessarily represent the views of the Centers for Disease Control and Prevention.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.lana.2021.100080.

References

1 Feldmeier H, Heukelbach J, Ugbomoiko US, et al. Tungiasis—a neglected disease with many challenges for global public health. *PLoS Neglected Tropical Diseases* 2014;**8**(10):e3133.
2 Miller H, Ocampo J, Ayala A, Trujillo J, Feldmeier H. Very severe tungiasis in Amerindians in the Amazon lowland of Colombia: A case series. *PLoS Neglected Tropical Diseases* 2019;**13**(2):e0007068.
3 Louis SJ, Bronsnick T, Louis FJ, Rao B. Tungiasis in Haiti: a case series of 383 patients. *Int J Dermatol* 2014;**53**(8):999–1004.
4 Heukelbach J. *Tungiasis. Rev Inst Med Trop Sao Paulo* 2005;**47**(6):30713.
5 Harvey TV, Heukelbach J, Assuncao MS, Fernandes TM, da Rocha CM, Carlos RS. Canine tungiasis: High prevalence in a tourist region in Bahia state. *Brazil. Prev Vet Med* 2017;**139**(Pt A):76–81.
6 Chadee DD. Tungiasis among five communities in south-western Trinidad. *West Indies. Annals of Tropical Medicine and Parasitology* 1998;**92**(1):10713.
7 Heukelbach J, Ariza L, Adegbola RQ, Ugbomoiko US. Sustainable control of Tungiasis in rural Nigeria: A case for one health. *One Health and Implementation Resarch* 2021;**1**(1):413.
8 Deka MA. Mapping the Geographic Distribution of Tungiasis in Sub-Saharan Africa. *Trop Med Infect Dis* 2020;**5**(3).
9 Nyangacha RM, Odongo D, Oyieke F, et al. Spatial distribution, prevalence and potential risk factors of Tungiasis in Vihiga County, Kenya. *PLoS Neglected Tropical Diseases* 2019;**13**(3):e0007244.
10 Johnson EE, Escobar LE, Zambrana-Torrelio C. An ecological framework for modeling the Geography of disease transmission. *Trends Ecol Evol* 2019;**34**(7):65568.
11 Soberón J, Peterson AT. *Interpretation of models of fundamental ecological niches and species' distributional areas* 2005.
12 *GBIF. GBIF Occurrence Download. 2020* 13 May 2020. https://doi.org/10.15468/dl.xcpprz. accessed.
13 Brown JL, Bennett JR, French CM. SDMtoolbox 2.0: the next generation Python-based GIS toolkit for landscape genetic, biogeographic and species distribution model analyses. *PeerJ* 2017;**5**:e4095.
14 Abatzoglou J, Dobrowski S, Parks S, Hegewisch KC. TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance from 1958—2015. *Sci Data* 2018;**5**(170191).
15 Amatulli G, Domisch S, Tuanmu M-N, et al. A suite of global, cross-scale topographic variables for environmental and biodiversity modeling. *Sci Data* 2018;**5**(1):115.
16 Wilson AM, Jetz W. Remotely sensed high-resolution global cloud dynamics for predicting Ecosystem and Biodiversity distributions. *PLoS biology* 2016;**14**(3):e1002415.
17 Nagy N, Abari E, D'Haese J, et al. Investigations on the life cycle and morphology of Tunga penetrans in Brazil. *Parasitol Res* 2007;**101**(2):23342. Suppl.
18 Winter B, Oliveira FA, Wilcke T, Heukelbach J, Feldmeier H. Tungiasis-related knowledge and treatment practices in two endemic communities in northeast Brazil. *J Infect Dev Ctries* 2009;**3**(6):45866.
19 Hengl T. *WorldGrids archived layers at 1 km to 20 km spatial resolution* 2018. https://zenodo.org/record/1637816 accessed 12 July 2021 2021.
20 Pilger D, Schwalfenberg S, Heukelbach J, et al. Controlling tungiasis in an impoverished community: an intervention study. *PLoS Neglected Tropical Diseases* 2008;**2**(10):e324.
21 Mutebi F, Krucken J, Feldmeier H, et al. Animal reservoirs of Zoonotic Tungiasis in endemic rural villages of Uganda. *PLoS Neglected Tropical Diseases* 2015;**9**(10):e0004126.
22 Weiss DJ, Nelson A, Gibson HS, et al. A global map of travel time to cities to assess inequalities in accessibility in 2015. *Nature* 2018;**553**(7688):3336.
23 Noor AM, Alegana VA, Gething PW, Tatem AJ, Snow RW. Using remotely sensed night-time light as a proxy for poverty in Africa. *Popul Health Metr* 2008;**6**:5.
24 Phillips S, Dudík M, Schapire R. *Maxent software for modeling species niches and distributions (Version 3.4. 1)* 2018: 521. Available in: https://biodiversityinformatics.amnh.org/open_source/maxent/ Accessed on. 2021.
25 Kass JM, Muscarella R, Galante PJ, et al. ENMeval 2.0: Redesigned for customizable and reproducible modeling of species' niches and distributions. *Methods in Ecology and Evolution* 2021. n/a(n/a).
26 Kass JM, Vilela B, Aiello-Lammens ME, Muscarella R, Merow C, Wallace Anderson RP. A flexible platform for reproducible modeling of species niches and distributions built for community expansion. *Methods in Ecology and Evolution* 2018;**9**(4):11516.
27 Peterson AT, Papeş M, Soberón J. Rethinking receiver operating characteristic analysis applications in ecological niche modeling. *Ecological Modelling* 2008;**213**(1):6372.
28 Qiao H, Peterson AT, Campbell LP, Soberón J, Ji L, Escobar LE. NicheA: creating virtual species and ecological niches in multivariate environmental scenarios. *Ecography* 2016;**39**(8):80513.
29 Heukelbach J. One health & implementation research: Improving health for all. *One Health Implement Res* 2021;**1**(1):13.
30 Bryson JM, Bishop-Williams KE, Berrang-Ford L, et al. Neglected tropical diseases in the context of climate change in East Africa: A systematic scoping review. *The American journal of tropical medicine and hygiene* 2020;**102**(6):144354.