Spatial and temporal distribution of soil-transmitted helminth infection in sub-Saharan Africa: a systematic review and geostatistical meta-analysis

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Summary

Background **Interest is growing in predictive risk mapping for neglected tropical diseases (NTDs), particularly to scale up preventive chemotherapy, surveillance, and elimination efforts. Soil-transmitted helminths (hookworm, *Ascaris lumbricoides*, and *Trichuris trichiura*) are the most widespread NTDs, but broad geographical analyses are scarce. We aimed to predict the spatial and temporal distribution of soil-transmitted helminth infections, including the number of infected people and treatment needs, across sub-Saharan Africa.**

Methods **We systematically searched PubMed, Web of Knowledge, and African Journal Online from inception to Dec 31, 2013, without language restrictions, to identify georeferenced surveys. We extracted data from household surveys on sources of drinking water, sanitation, and women's level of education. Bayesian geostatistical models were used to align the data in space and estimate risk of with hookworm, *A lumbricoides*, and *T trichiura* over a grid of roughly 1 million pixels at a spatial resolution of 5×5 km. We calculated anthelmintic treatment needs on the basis of WHO guidelines (treatment of all school-aged children once per year where prevalence in this population is 20–50% or twice per year if prevalence is greater than 50%).**

Findings **We identified 459 relevant survey reports that referenced 6040 unique locations. We estimate that the prevalence of hookworm, *A lumbricoides*, and *T trichiura* among school-aged children from 2000 onwards was 16·5%, 6·6%, and 4·4%. These estimates are between 52% and 74% lower than those in surveys done before 2000, and have become similar to values for the entire communities. We estimated that 126 million doses of anthelmintic treatments are required per year.**

Interpretation **Patterns of soil-transmitted helminth infection in sub-Saharan Africa have changed and the prevalence of infection has declined substantially in this millennium, probably due to socioeconomic development and large-scale deworming programmes. The global control strategy should be reassessed, with emphasis given also to adults to progress towards local elimination.**

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Introduction

Over the past 10 years, interest has grown in better understanding the extent of neglected tropical diseases (NTDs).[1–4] Spatially explicit information on the distribution of NTDs is crucial to improve control and elimination efforts.[5,6] Advances have been made with spatial modelling, including risk profiling of leishmaniasis at the district level,[7] predictive risk mapping of loiasis at the national level,[8] cross-national models of schistosomiasis,[9–11] a subcontinental map of soil-transmitted helminth infection,[12] and a continental future projection of lymphatic filariasis.[13] Additionally, the modelling results have enabled estimation of the number of infected people at different geographical scales, which facilitates calculation of treatment and other intervention needs and their costs.[14]

For human helminthiases, which account for the largest burden of NTDs,[3,15,16] WHO recommends periodic administration of anthelmintic drugs on the basis of prevalence of infection at a given location to control morbidity.[17] Predictions of infection risk in areas where prevalence data are lacking can be supplied by spatial statistical models. Studies have provided model-based risk maps and estimates over large scales in South America[12] and China.[18] The authors constructed gridded estimates of population-adjusted prevalence and identified high-risk areas that should be prioritised for control interventions. The work also highlighted the need for doing surveys in areas where data are unavailable or extremely scarce.

Sub-Saharan Africa is among the regions with the highest prevalence of soil-transmitted helminth infections, but progress to reduce the burden has been slower there than in any other region of the world.[19,20] Country-wide analyses of soil-transmitted helminthiasis risk have been done.[21] However, a cross-national geostatistical analysis to estimate spatiotemporal patterns and provide country-specific infection estimates at high spatial resolution across sub-Saharan Africa has not yet been done.[22] A Bayesian geostatistical analysis of the number of people infected with soil-transmitted helminths in sub-Saharan Africa was done as a part of the Global Burden of Disease

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2010 study,[15] using data from the Global Atlas of Helminth Infection.[23,24] Risk maps have been provided by the Global Atlas of Helminth Infection. The Global Neglected Tropical Diseases (GNTD) database compiles open-access geographically referenced prevalence data for soil-transmitted helminth infections and other NTDs that can be used by researchers and control managers to obtain spatially and temporally explicit estimates of at-risk areas.[25,26]

We did a systematic review and extracted data from geographically referenced surveys that reported prevalence of hookworm, *Ascaris lumbricoides*, and *Trichuris trichiura* infections in sub-Saharan Africa. We did a meta-analysis of the data with Bayesian geostatistical models and provided high-resolution risk maps. We also assessed the potentials of education attainment, water, and sanitation-related indicators to increase the predictive ability of the models. Additionally, we estimated the annual treatment needs across the region according to WHO guidelines for preventive chemotherapy.[17]

Methods

Systematic review

We did a systematic review in accordance with the PRISMA guidelines.[27] We systematically searched PubMed, Web of Knowledge, and African Journal Online from inception to Dec 31, 2013, with no restrictions applied for date of survey or language of publication. We included 43 sub-Saharan African countries (appendix). We used the following search terms: "angola* (OR benin*, OR botswana, OR burkina faso, OR upper volta, OR burundi, OR côte d'ivoire, OR cote d'ivoire, OR ivory coast, OR cameroon, OR camerun, OR kamerun, OR central african republic, OR chad, OR congo, OR zaire, OR djibouti, OR equatorial guinea, OR eritrea, OR ethiopia, OR gabon, OR gambia, OR guinea, OR guinea-bissau, OR kenya, OR lesotho, OR liberia, OR malawi, OR mali, OR mauritania, OR mozambique, OR namibia, OR niger*, OR rwanda, OR senegal, OR sierra leone, OR somalia, OR south africa, OR south sudan, OR sudan, OR swaziland, OR tanzania, OR togo, OR uganda, OR zambia, OR zimbabwe, OR rhodesia) AND helminth* (OR ascari*, OR trichur*, OR hookworm*, OR necator, OR ankylostom*, OR ancylostom*, OR strongy*, OR hymenolepis, OR toxocara, OR enterobius*, OR geohelminth*, OR nematode*)". We also searched the grey literature, including personal collections and reports from control programmes and ministries of health.

See Online for appendix

Data extraction

We adapted the protocol by Chammartin and colleagues[12] to extract the data. We initially reviewed titles and abstracts, if available, and excluded studies of animals, plants, and genetics, case reports, in-vitro studies, and those that did not mention surveys of soil-transmitted helminthiasis. Quality assessment of retrieved items was based on 30% of articles selected at random. Full-text articles were excluded if they did not report prevalence data, were based on a specific group of patients (eg, hospital patients, those infected with HIV, neonates, etc), were case-control studies, clinical trials, or pharmacological studies (except control groups without anthelmintic intervention), were done in displaced populations (eg, travellers, military), and if the population had undergone deworming in the past 12 months. Extracted data were systematically entered into the GNTD database and geographically referenced with information provided in the reports and various online map and travel guide resources (eg, Wikimapia, Google Maps, iGuide Interactive Travel Guide). We assigned centroids for administrative units on the basis of administrative boundaries in the Database of Global Administrative Areas (version 2).

Relevant prevalence data were extracted and entered in the GNTD database with information on the source (authors, journal, publication date), survey (date, type of survey), location (coordinates, name, administrative unit), and parasitology (species, number of people positive or examined, prevalence, age, diagnostic tool). If information was missing and papers had been published in the past 20 years, we contacted the authors. Quality of prevalence data extraction was assessed[12] and all coordinates were double-checked in Google Maps. We included surveys in the meta-analysis if the sample size was greater than ten individuals. If the date of the survey was missing, we used date of publication instead. Data were screened by location to check for duplicates, in which case the survey with the greater amount of information was used for analysis.

Environmental, socioeconomic, and population data

We consulted WorldClim—Global Climate Data to obtain data on the proxies of temperature, precipitation, and altitude. Soil moisture and acidity values were downloaded from the Nelson Institute Center for Sustainability and the Global Environment.

Household data were compiled from readily available demographic and health surveys, multiple indicator cluster surveys, world health surveys, and living standards measurement study on sources of drinking and non-drinking water, sanitation facilities, and educational level of women. We used the classification of the Joint Monitoring Programme for Water Supply and Sanitation of WHO and UNICEF[28] to identify households with access to improved drinking-water sources and sanitation. By aggregating household indicators at village level, we constructed proxies of socioeconomic status: the percentage of households with access to improved drinking-water sources, the percentage of households with access to improved sanitation, and the percentage of women who had attended at least primary school.

Locations were classified as rural or urban, according to data downloaded from the Center for International Earth Science Information Network.[29] We obtained population densities in 2000 and 2010 from Worldpop and country-specific percentages of the population younger than 20 years from the United States Census Bureau International Database.[30] For Sudan and South Sudan,

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percentages of the population aged younger than 20 years in 2008 were used instead of values from 2000 because this was the year with the earliest available data. Links to the databases and resources used in this study are provided in the appendix.

Statistical analysis

In the Bayesian binomial geostatistical analysis, the number of infected people among those surveyed was used as the outcome and environmental and socioeconomic proxies were used as predictors. Additionally, we applied Bayesian binomial geostatistical models to obtain percentages for the socioeconomic proxies (improved drinking-water source, improved sanitation, and women's educational attainment). We used integrated nested Laplace approximations (INLA)[31] and the stochastic partial differential equations approach[32] to do fast approximate Bayesian inference. Analyses were done in R (version 3.1.1) and the INLA package. Details for implementing geostatistical models with INLA are provided elsewhere[32–34]

Socioeconomic indicators were not available at epidemiological survey locations. To align the data, we used Bayesian geostatistical models and obtained high-resolution estimates for the indicators, with the urban classification as a predictor. Climatic predictors were highly correlated. To avoid collinearity, we specified groups of highly correlated covariates (Pearson's correlation coefficient greater than 0·9). Within each group we selected the variable and its functional form that best predicted the data according to the (leave-one-out) cross-validated logarithmic score[35,36] calculated from a bivariate Bayesian geostatistical logistic regression model. The functional forms assessed were linear and categorical (three or four categories, dependent on the quantiles of each variable's distribution). Non-linear effects were modelled by spline approximations with random walk processes of order one and two.[37] If a random walk was selected and the effect resembled a known functional form, it was substituted by the specific function to ease computations. The variable and form with the lowest mean logarithmic scores were selected from each group. To identify the set of most important environmental and socioeconomic covariates, we fitted geostatistical models with all possible combinations of covariates and selected those with the best mean logarithmic scores.

All models included survey period as a binary covariate (before 2000 or from 2000 onwards), and interactions were assessed with survey type (school-based, defined as surveys done in schools or those focusing on populations younger than 20 years, or community-based). To incorporate the uncertainty of the socioeconomic indicators' predictive value, we fitted a joint model of the indicator and prevalence if the best model included any socioeconomic predictor. The joint model uses the local mean adjustment of the socioeconomic indicator at the epidemiological survey locations, estimated from the posterior predictive distribution of its spatial process. Furthermore, we fitted models with period-specific socioeconomic proxies obtained from geostatistical models, each with a single (continent-specific) temporal trend and a common spatial process for both periods. To take into account that the distance between two locations on the Earth is not a straight line, we used a distance measure that is defined on the sphere's surface.[32]

The models were used to predict the risk of species-specific soil-transmitted helminth infection on a 5×5 km grid of 960 132 pixels. By overlaying the predicted risk surfaces with the population density grids and the census-based population percentages, we calculated population-adjusted prevalence by country and subregion (southern, western, eastern, and middle, as defined by the United Nations Statistics Division,[38] and modified to include Sudan in the eastern subregion). A set of 300 random samples, simulated from the joint posterior predictive distribution, was used to estimate infection risk and number of people infected and for uncertainty calculations.

We based our calculation of anthelmintic treatment needs on the WHO guidelines,[17] which suggest treating all school-aged children once per year in communities where the infection prevalence in the school-aged population is

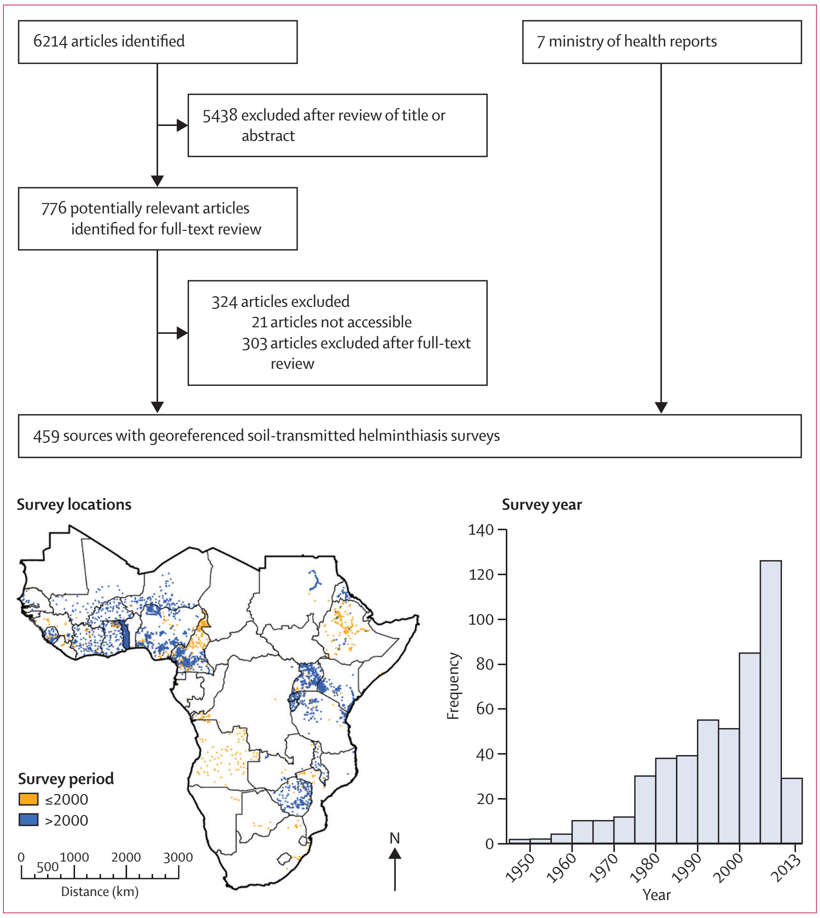

Figure 1: **Literature search and selection, survey locations, and survey years**

20–50% or twice per year if prevalence is greater than 50%. For each predicted pixel-level prevalence that was higher than 20% or 50%, the treatment needs were equal to one or two times the school-aged population within that pixel, respectively.[14] We used the WHO definition of school-aged population (age 5–14 years) and values were obtained from the United States Census Bureau International Database.[30]

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to all the data and had final responsibility for the decision to submit for publication.

Results

Of 6221 identified data sources, we extracted information from 459 (figure 1; appendix). 51% of surveys were done before 2000. The total number of unique survey locations was 6040, of which 785 (13%) corresponded to urban settlements. Raw observed data for prevalence of species-specific soil-transmitted helminth infections are shown in figure 2. Most data were derived from national surveys done in Cameroon, Kenya, Nigeria, and Togo. No data were available for Democratic Republic of the Congo (DR Congo), Djibouti, Lesotho, South Sudan, or Swaziland.

Raw socioeconomic and population data were available for 32 618 locations (appendix). The medians of the percentage of households with access to improved drinking-water sources and use of improved sanitation were 80% and 12%, respectively (appendix). All three socioeconomic variables were positively associated with the urban classification (data not shown). Five countries had no geographically referenced data for the socio-economic proxies. Of the remaining 38, only 12 had data from both survey periods (appendix). Hence, our geo-

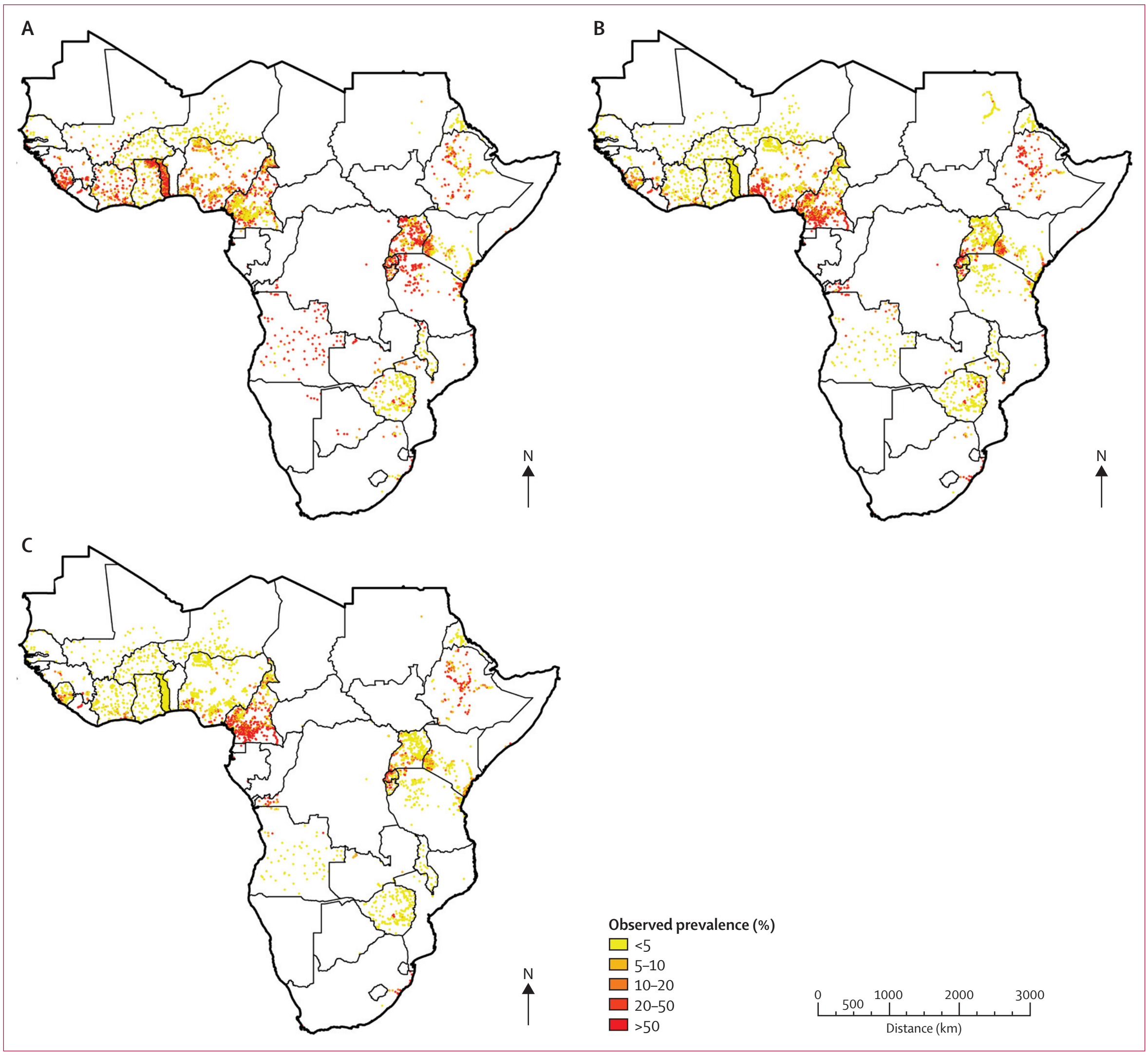

***Figure 2*: Raw observed prevalence of soil-transmitted helminth infections in sub-Saharan Africa**
(A) Hookworm. (B) *Ascaris lumbricoides*. (C) *Trichuris trichiura*.

statistical models could only yield period-specific estimates for socioeconomic proxies and allowed assessment of only continent-level rather than country-level temporal trends. Exploratory analysis, however, suggested that some countries had positive changes and others had negative changes (appendix).

After taking into account highly correlated predictors and identifying their best functional form from bivariate Bayesian geostatistical models, we fitted all possible combinations of around 12 predictors per helminth species, which gave rise to 4096 models. The best predictive model and the estimated parameters of the predictors for each species are shown in table 1. The socioeconomic proxy improved drinking-water source was included in the best model for hookworm. Negative trends were found for surveys done from 2000 onwards for all three soil-transmitted helminth species. Surveys of school-aged children revealed higher prevalence for *A lumbricoides* and *T trichiura* than community-based surveys done before 2000, whereas the survey type had no effect on the prevalence of hookworm infection. Hookworm was negatively associated with urban settlements and locations with high percentages of improved drinking-water sources. Non-linearity of the soil moisture resembled a parabolic function, indicating that extreme dry or wet soils are associated with the absence of hookworm infection. Low variations in temperature and precipitation in the warmest quarter were associated with increased prevalence of *A lumbricoides*. The factors associated with increased risk of *T trichiura* infection were high precipitation in the warmest quarter, high temperature in the coldest quarter, and low variation in precipitation.

Period-specific socioeconomic predictors did not change model-based estimates of covariate effects and predictions of infection risk compared with constant socioeconomic predictors. Hence, we report predictions of infection risk based on models with common socioeconomic predictors for the two time periods (figure 3). Hookworm risk was high in western and middle Africa, with the highest-risk areas being in Sierra Leone, Togo, and around Lake Victoria. *A lumbricoides* and *T trichiura* followed similar

	Median estimate (95% CI)
Hookworm*	
Urban-rural classification	
Rural	..
Urban	–0·43 (–0·59 to –0·27)
Survey period (year)	
Before 2000	..
From 2000 onwards	–1·44 (–1·52 to –1·35)
Survey type	
Community-based	..
School-based	–0·04 (–0·08 to 0·00)
Survey period × survey type	–0·02 (–0·10 to 0·06)
Mean adjustment of improved drinking–water sources	–0·07 (–0·11 to –0·02)
Spatial variance†	5·06 (4·74 to 5·45)
Spatial range (km)†	29·2 (27·6 to 31·0)
Ascaris lumbricoides	
Isothermality (%)	
<66·9	..
66·9–74·5	1·28 (0·99 to 1·58)
>74·5	1·57 (1·24 to 1·90)
Precipitation of warmest quarter (mm)	
<173	..
173–277	1·34 (1·06 to 1·63)
277–1151	1·94 (1·62 to 2·27)
>1151	2·07 (1·75 to 2·40)
Survey period (year)	
Before 2000	..
From 2000 onwards	–1·41 (–1·54 to –1·28)
Survey type	
Community-based	..
School-based	0·53 (0·47 to 0·59)
Survey period × survey type	–0·63 (–0·76 to –0·50)
Spatial variance†	6·39 (5·90 to 6·93)
Spatial range (km)†	40·2 (36·8 to 42·8)
(Continued from previous column)	
Trichuris trichiura	
Mean temperature of coldest quarter (°C)	
<21·4	..
21·4–23·6	0·12 (–0·10 to 0·33)
23·6–25·1	0·08 (–0·19 to 0·35)
>25·1	0·22 (–0·15 to 0·58)
Precipitation of warmest quarter (mm)	
<175	..
175–279	1·29 (0·84 to 1·74)
279–1051	1·23 (0·77 to 1·69)
>1051	1·48 (1·02 to 1·94)
Soil acidity (pH)	
<5·6	..
5·6–6·1	–1·06 (–1·42 to –0·71)
>6·1	0·18 (–0·22 to 0·58)
Precipitation seasonality	–0·04 (–0·04 to –0·03)
Survey period (year)	
Before 2000	..
From 2000 onwards	–1·57 (–1·72 to –1·42)
Survey type	
Community-based	..
School-based	0·75 (0·68 to 0·83)
Survey period × survey type	–0·88 (–1·03 to –0·73)
Spatial variance†	7·59 (6·90 to 8·34)
Spatial range (km)†	46·8 (43·3 to 51·0)

(Table 1 continues in next column)

*See appendix for effects of soil moisture. †Parameters of the spatial process.

***Table 1:* Posterior estimates of the final geostatistical models for risk of species-specific soil-transmitted helminth infection in sub-Saharan Africa**

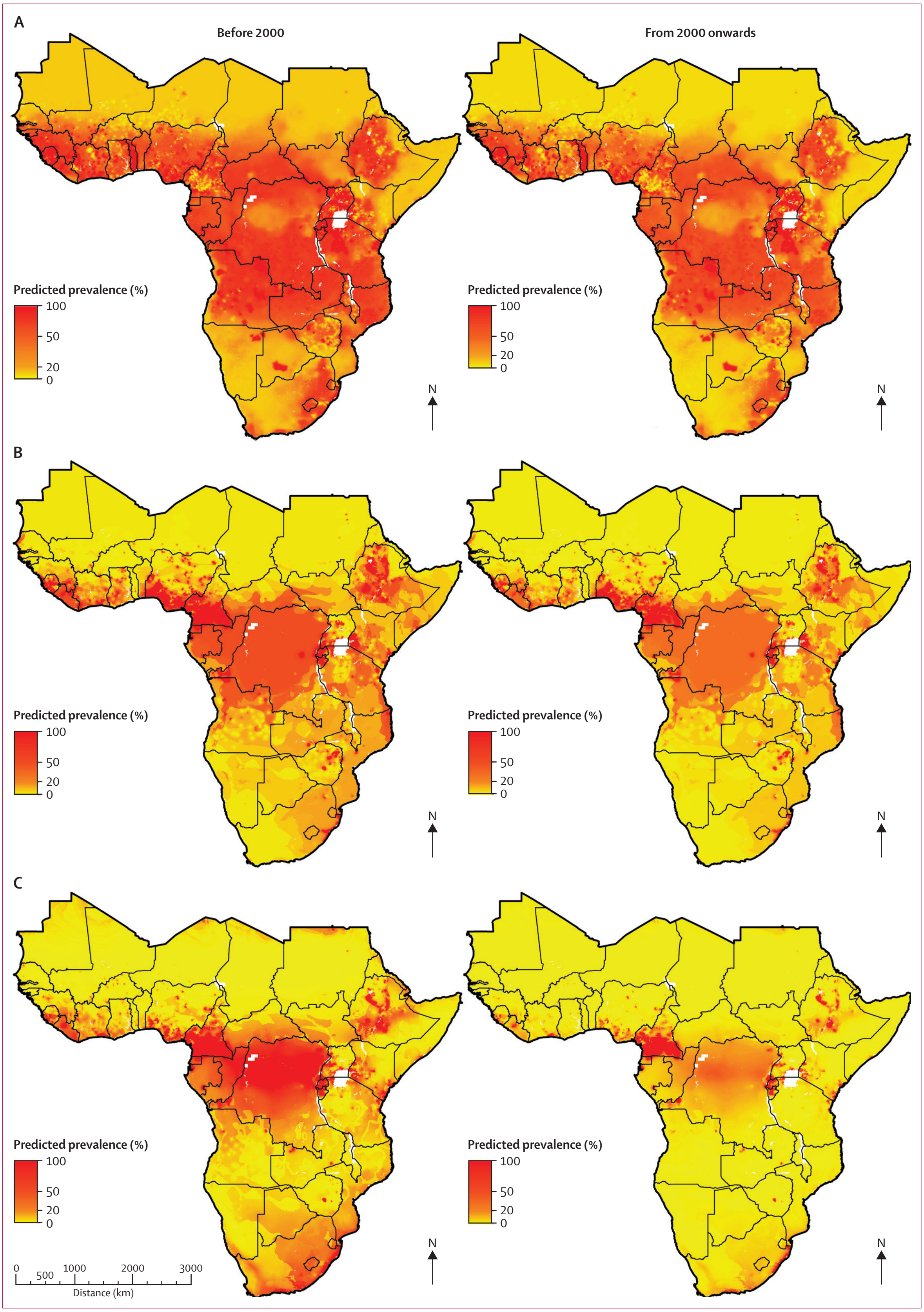

Figure 3: **Median predicted risk estimates for soil-transmitted helminth infections in sub-Saharan Africa before 2000 and from 2000 onwards**
(A) Hookworm. (B) *Ascaris lumbricoides*. (C) *Trichuris trichiura*.

spatial patterns with high prevalence seen in Cameroon, Ethiopia, and at the borders of Burundi, DR Congo, and Rwanda. A high-resolution map of the percentage of households with access to improved drinking-water sources is provided in the appendix.

Population-adjusted prevalence of infection for each of the three soil-transmitted helminth species was stratified by country and subregion (tables 2, 3). The highest prevalence of soil-transmitted helminth infection was predicted in western Africa, followed by eastern, southern,

	Population aged <20 years (1000s)	Prevalence of hookworm (%)	Prevalence of *Ascaris lumbricoides* (%)	Prevalence of *Trichuris trichiura* (%)	Prevalence of all soil-transmitted helminths (%)*	Number of anthelmintic doses for school-aged children (1000s)†
Angola	7872	15·9 (13·5–20·5)	3·4 (2·4–5·1)	1·8 (1·1–2·9)	20·1 (17·3–25·1)	1835 (1477–2388)
Benin	3953	18·3 (12·3–26·8)	4·3 (1·7–9·7)	1·4 (0·4–4·7)	23·5 (17·0–32·4)	1086 (670–1602)
Botswana	929	4·4 (3·4–6·2)	1·4 (0·8–3·3)	2·0 (1·0–4·8)	7·8 (6·0–11·0)	49 (27–95)
Burkina Faso	9122	9·9 (7·0–15·7)	0·4 (0·3–1·0)	0·4 (0·2–1·1)	10·7 (7·9–16·6)	902 (540–1711)
Burundi	4826	30·4 (23·1–38·9)	16·2 (13·9–18·8)	13·5 (11·1–17·1)	49·0 (43·1–55·3)	3079 (2684–3438)
Cameroon	9199	9·9 (8·3–11·3)	10·4 (9·5–11·6)	12·5 (11·7–13·4)	28·0 (26·3–29·5)	3340 (3094–3550)
Central African Republic	2037	15·5 (12·1–19·9)	4·0 (2·7–5·8)	4·0 (2·6–6·4)	22·0 (18·7–26·4)	512 (388–660)
Chad	6405	7·4 (5·6–10·2)	1·2 (0·7–2·6)	0·3 (0·2–0·8)	9·0 (7·0–11·9)	415 (214–689)
Congo	1869	12·9 (7·6–34·5)	4·8 (2·1–24·5)	5·0 (2·2–15·4)	24·8 (14·7–46·1)	461 (203–942)
Côte d'Ivoire	9537	23·7 (19·8–27·6)	4·4 (3·5–5·4)	5·6 (4·6–7·0)	30·0 (26·9–33·2)	3617 (3197–4162)
Djibouti	135	3·4 (1·0–10·6)	0·5 (0·1–2·2)	2·6 (0·6–12·4)	6·9 (2·8–17·4)	5 (0–26)
DR Congo	37 088	17·9 (15·5–21·3)	9·2 (7·4–11·3)	10·5 (8·8–13·2)	33·0 (30·0–36·5)	15 551 (13 586–17 628)
Equatorial Guinea	273	11·2 (6·0–21·1)	14·6 (7·5–28·0)	17·6 (9·5–32·1)	37·0 (26·5–51·2)	125 (82–188)
Eritrea	2693	3·3 (1·8–5·9)	0·7 (0·3–1·6)	0·5 (0·2–1·2)	4·5 (2·9–7·7)	58 (15–159)
Ethiopia	44 433	17·7 (15·1–20·0)	8·5 (7·1–10·2)	6·1 (4·7–7·9)	28·8 (25·7–31·2)	15 592 (13 586–17 237)
Gabon	592	26·0 (12·9–40·6)	14·4 (6·0–31·8)	26·0 (12·5–36·4)	47·8 (36·2–57·9)	347 (262–420)
Gambia	984	20·3 (7·3–44·6)	1·6 (0·5–13·8)	0·1 (0·0–1·7)	22·7 (9·5–46·0)	276 (46–614)
Ghana	11 641	14·4 (11·7–19·3)	4·3 (2·8–8·7)	1·5 (0·8–3·0)	19·8 (16·1–24·8)	2468 (1775–3431)
Guinea	4502	21·9 (17·3–26·9)	3·8 (2·6–6·0)	1·7 (1·0–3·9)	26·2 (21·9–31·4)	1452 (1174–1789)
Guinea-Bissau	466	14·0 (7·3–27·2)	0·8 (0·2–3·0)	0·1 (0·0–0·7)	15·3 (8·3–28·4)	65 (16–170)
Kenya	20 188	16·9 (14·3–20·0)	11·5 (9·9–13·4)	5·0 (4·0–6·8)	29·2 (26·1–32·4)	7376 (6502–8330)
Lesotho	1011	21·3 (10·8–35·6)	2·4 (0·6–9·9)	5·7 (1·3–18·4)	29·3 (17·9–43·1)	360 (190–551)
Liberia	1410	21·9 (16·4–28·8)	8·6 (5·3–13·6)	6·6 (3·5–11·8)	33·4 (27·4–40·7)	636 (504–790)
Malawi	8475	14·9 (10·9–20·0)	2·1 (1·2–3·9)	0·6 (0·2–1·7)	17·3 (13·1–22·4)	1578 (1075–2184)
Mali	8986	10·4 (8·4–12·8)	0·6 (0·4–0·9)	0·3 (0·2–0·6)	11·2 (9·1–13·4)	1012 (712–1307)
Mauritania	1938	2·8 (1·5–12·2)	0·5 (0·3–1·2)	0·2 (0·2–0·7)	3·7 (2·3–12·9)	20 (7–291)
Mozambique	12 417	15·6 (12·5–19·5)	3·8 (2·6–6·3)	3·4 (2·2–5·2)	21·9 (18·5–25·8)	3162 (2503–3935)
Namibia	973	7·2 (4·0–13·7)	1·1 (0·5–2·8)	0·9 (0·4–3·0)	9·4 (5·6–15·6)	82 (31–175)
Niger	8878	4·0 (2·7–5·7)	0·5 (0·3–0·9)	0·1 (0·1–0·3)	4·6 (3·3–6·4)	237 (114–459)
Nigeria	81 508	16·9 (14·7–19·2)	9·8 (8·1–11·3)	3·0 (2·2–4·6)	26·7 (24·1–28·9)	26 290 (23 258–28 907)
Rwanda	5477	31·9 (24·2–39·6)	31·7 (28·1–37·4)	23·3 (20·9–27·2)	62·6 (56·3–68·5)	4243 (3826–4598)
Senegal	6632	8·2 (5·1–15·2)	2·7 (1·6–6·3)	0·4 (0·2–1·2)	11·6 (8·0–17·9)	664 (326–1410)
Sierra Leone	2461	34·3 (29·1–40·6)	6·3 (4·8–8·1)	2·5 (1·8–4·0)	39·9 (34·9–45·7)	1288 (1091–1484)
Somalia	4091	5·5 (4·2–8·0)	2·4 (1·6–4·5)	4·2 (2·8–6·5)	11·7 (9·4–15·0)	496 (394–708)
South Africa	18 219	11·6 (8·8–16·0)	5·7 (4·2–8·1)	8·1 (6·0–13·8)	22·9 (19·5–29·0)	4653 (3744–6378)
South Sudan	5617	8·6 (6·8–10·8)	2·2 (1·6–3·2)	1·9 (1·3–3·1)	12·3 (10·3–15·0)	549 (391–785)
Sudan	19 292	2·4 (1·8–3·2)	0·6 (0·4–1·2)	0·2 (0·1–0·6)	3·3 (2·6–4·4)	110 (51–296)
Swaziland	631	18·4 (7·7–38·8)	2·3 (0·4–12·3)	2·9 (0·4–14·5)	24·7 (11·9–45·1)	185 (67–358)
Tanzania	23 633	24·3 (21·6–27·7)	3·8 (2·9–4·8)	2·0 (1·4–3·9)	28·6 (25·6–32·9)	8296 (7300–9688)
Togo	2838	34·4 (31·3–38·4)	0·7 (0·4–1·5)	0·4 (0·2–0·9)	35·3 (32·0–39·1)	1280 (1131–1495)
Uganda	20 639	31·0 (27·5–33·8)	4·5 (3·5–5·8)	3·7 (2·9–5·1)	36·6 (33·4–39·3)	9457 (8556–10 306)
Zambia	7478	18·2 (13·9–27·5)	2·6 (1·7–6·7)	1·0 (0·6–2·1)	21·7 (16·7–30·2)	1839 (1238–2763)
Zimbabwe	6875	10·4 (7·7–14·7)	2·7 (2·0–4·1)	0·7 (0·4–1·4)	13·4 (10·8–17·8)	933 (664–1395)
Total	428 222	16·5 (15·6–17·6)	6·6 (6·1–7·0)	4·4 (4·1–4·9)	24·7 (23·7–25·7)	126 466(120 241–132 307)

Data area median (95% credible interval) except for number aged <20 years. DR Congo=Democratic Republic of the Congo. *Overall prevalence was calculated under the assumption that the three species of soil-transmitted helminths are independent. †WHO definition, age 5–14 years.

***Table 2*: Population-adjusted prevalence of soil-transmitted helminth infections from 2000 onwards and annual anthelmintic treatment needs**

	Before 2000				From 2000 onwards			
	Population	Prevalence of hookworm (%)	Prevalence of *Ascaris lumbricoides* (%)	Prevalence of *Trichuris trichiura* (%)	Population	Prevalence of hookworm (%)	Prevalence of *Ascaris lumbricoides* (%)	Prevalence of *Trichuris trichiura* (%)
Population aged <20 years								
Eastern	121 340 394	34·3 (32·9–35·7)	19·7 (18·9–20·7)	18·1 (17·1–19·2)	150 202 927	16·5 (15·6–17·6)	6·7 (6·3–7·3)	4·7 (4·3–5·2)
Middle	64 945 309	34·5 (33·0–36·0)	18·5 (17·5–19·6)	16·4 (15·3–17·4)	81 824 674	16·7 (15·6–18·0)	6·3 (5·7–7·0)	4·1 (3·7–4·8)
Southern	38 987 696	34·2 (32·7–35·6)	18·9 (17·9–20·2)	17·5 (16·4–18·6)	48 847 355	16·6 (15·3–17·8)	6·4 (5·9–7·0)	4·2 (3·8–4·7)
Western	119 268 659	34·1 (32·7–35·5)	19·7 (18·9–20·7)	17·6 (16·7–18·6)	147 346 980	16·4 (15·5–17·5)	6·6 (6·1–7·1)	4·4 (4·0–4·9)
Population aged >20 years								
Eastern	98 948 578	34·6 (32·9–36·0)	16·0 (15·2–16·8)	12·9 (12·2–13·8)	127 312 077	16·7 (15·8–17·8)	7·2 (6·6–7·8)	5·3 (4·8–5·9)
Middle	52 856 357	34·7 (33·1–36·3)	15·1 (14·1–16·2)	11·4 (10·5–12·4)	69 305 534	17·0 (16·0–18·3)	6·6 (6·0–7·4)	4·6 (4·1–5·3)
Southern	31 878 914	34·3 (32·5–36·0)	15·4 (14·5–16·4)	12·3 (11·3–13·4)	41 601 143	16·8 (15·7–17·9)	6·8 (6·3–7·5)	4·8 (4·2–5·4)
Western	97 017 768	34·4 (32·8–35·9)	15·8 (15·0–16·5)	12·3 (11·5–13·1)	124 494 350	16·7 (15·7–17·9)	7·1 (6·5–7·7)	4·9 (4·5–5·5)

Data area median (95% credible interval) except for population. Eastern=Burundi, Djibouti, Eritrea, Ethiopia, Kenya, Malawi, Mozambique, Rwanda, Somalia, South Sudan, Sudan, Tanzania, Uganda, Zambia, and Zimbabwe. Middle=Angola, Cameroon, Central African Republic, Chad, Congo, Democratic Republic of the Congo, Equatorial Guinea, and Gabon. Southern=Botswana, Lesotho, Namibia, South Africa, and Swaziland. Western=Benin, Burkina Faso, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, and Togo.

***Table 3*: Population-adjusted prevalence of species-specific soil-transmitted helminth infections by survey period and subregion**

and middle Africa. Sierra Leone and Togo were predicted to have the highest hookworm prevalence. Gabon and Rwanda had the highest risks of infection with *A lumbricoides* and *T trichiura*. Overall, we estimated that among the roughly 800 million people in the 43 countries of sub-Saharan Africa 130 million, 53 million, and 37 million people were infected with hookworm, *A lumbricoides*, and *T trichiura*, respectively. Overall annual treatment needs were estimated to be nearly 126 million doses, and the total number of school-aged children needing treatment was estimated to be 91 million. More than 15 million treatments would be needed for DR Congo, Ethiopia, and Nigeria, which corresponds to roughly 12%, 12%, and 20% of the total treatment needs, respectively.

Discussion

We did a systematic review and a geostatistical meta-analysis of surveys of soil-transmitted helminth infections in sub-Saharan Africa. Analyses based on geostatistical models are the most rigorous approaches for risk profiling of NTDs at different geographical scales. Our models included temporal terms, socioeconomic proxies, and environmental predictors. By exhaustive fitting of all possible Bayesian geostatistical models, we identified one for each soil-transmitted helminth species that was used to predict infection risk at high spatial resolution. A decrease in prevalence from 2000 onwards is predicted for sub-Saharan Africa, which matches the findings from other regions, such as Cambodia,[39] China,[18] and South America.[6]

The use of environmental and socioeconomic factors allowed us to predict the infection risk in areas where no surveys have been done. We predicted moderate prevalence in regions where data are scarce. For instance, the risk of infection is high for all three soil-transmitted helminth species in DR Congo and extends into Gabon for hookworm and *A lumbricoides*. Surveys are warranted in areas with sparse data to update predictions and models. Model-based estimates should in turn be iteratively updated[40] to support monitoring and surveillance efforts.

Our analyses revealed several insights that are noteworthy. First, the predicted prevalence for all three soil-transmitted helminth species in southern Africa was much lower than previously reported.[24] The previous estimates were based on only 45 survey locations across southern Africa, including Zimbabwe. Our analysis is based on more than 200 unique survey locations in this subregion, most of which had survey data obtained after 2008. Hence, the risk of soil-transmitted helminth infection in southern Africa might previously have been overestimated. Second, in eastern Africa (excluding Madagascar), our estimated prevalence was lower than that predicted before but the higher value might have been driven by high prevalence of soil-transmitted helminth infection in Madagascar.[41] Third, in western Africa, we retrieved roughly double the amount of point prevalence measures and predicted lower prevalence for *A lumbricoides* than did Pullan and colleagues.[24] Fourth, in middle Africa (excluding Cameroon), only few geographically referenced surveys were available for inclusion in our analyses and, therefore, our estimates are prone to notable uncertainty.

The risk of infection with all three soil-transmitted helminth species declined from 2000 onwards, probably due to socioeconomic development[42] and intensified control measures.[43] We excluded surveys done within 12 months after deworming to avoid potential bias from the direct effect of anthelmintic treatment. Within 1 year of treatment, prevalence of *A lumbricoides* and *T trichiura* approach pretreatment levels, whereas the prevalence of hookworm infection remains reduced by about half.[44] Hence, a negative temporal trend is expected to relate to deworming, other interventions, and socioeconomic development. In sub-Saharan Africa, a slight increase in the prevalence of soil-transmitted helminth infections was reported after a comparison of data from 1994 and 2003, but prevalence decreased in all other regions worldwide in the same period.[19] A later analysis by Pullan and colleagues,[24] however, showed no temporal trend for soil-transmitted helminth infection.

Poverty and socioeconomic status can be measured through many indices. We used readily available household data and standard classifications to construct proxies for drinking water and sanitation, but we did not detect strong associations. Other possible proxies, such as use of treated water or access to sanitation,[45] might improve prediction, as associations with soil-transmitted helminth infections have been noted in assessments of individual-level data. The aggregation of socioeconomic factors at village level and their spatial misalignment with the data for soil-transmitted helminth infections resulted in substantial variation within and between villages, which renders the identification of any effects difficult.[39] This heterogeneity might also explain why period-specific socioeconomic predictors did not improve prediction of risk of infection.

Since 2000, ministries of health, WHO, and other national, international, and non-governmental organisations have stepped up control against soil-transmitted helminthiasis and other NTDs, emphasising preventive chemotherapy. According to data reported by WHO, in 2010–12, the total of children younger than 15 years in sub-Saharan Africa who were treated once with albendazole or mebendazole was more than 70 million in each year.[46] In 2012, the subcontinental preventive chemotherapy coverage reached 26%. Initiation of major control interventions, however, has differed between countries, and not all have reported administered treatments to WHO. Therefore, we cannot take into account treatment coverage at the national or subnational level. Apart control programmes for soil-transmitted helminthiasis, the Global Program to Eliminate Lymphatic Filariasis (GPELF) and the African Programme for Onchocerciasis Control (APOC) have administered hundreds of millions of tablets of albendazole, mebendazole, and ivermectin treatments in the past decade (appendix).[47,48] Although albendazole and mebendazole are not as efficacious against *T trichiura*, as against hookworm and *A lumbricoides*, combination of either of these drugs with ivermectin results in reasonable efficacy against *T trichiura*.[49–52] Since its establishment, APOC has administered more than 80 million doses of ivermectin[47] and GPELF has widely administered combination therapy with albendazole and ivermectin among other treatments.[53] WHO estimates that, in 2011, the number of Africans covered by preventive chemotherapy for at least one disease was higher than 200 million.[48] Since not all treatments are reported to WHO, the true number of people receiving anthelmintic treatment might be substantially greater.[43,54]

Our lower prevalence, compared with values reported previously, and the achieved coverage estimates (for the African region) of the WHO progress report in 2012,[55] suggest that the 2020 target set by WHO of preventive chemotherapy reaching at least 75% coverage in all countries is on track. Additionally, our estimation of 91 million school-aged children needing treatment is less than that reported by WHO for the African region in 2011. We calculated the estimated treatment needs at pixel level under two assumptions: infections with the three different species are independent, and the prevalence for the age groups younger than 20 years and 5–14 years are the same. Nevertheless, these estimates provide important baseline information for decision-makers for initiating and designing control interventions.

Risk predictions for *A lumbricoides* and *T trichiura* among the school-aged population were substantially higher before 2000 than from 2000 onwards. The interaction between trend and survey type might be indicative of the school-based deworming efforts that were intensified since World Health Assembly resolution 54.19 was put forward in May, 2001.[56] The difference in the prevalence of soil-transmitted helminth infections, according to survey type, has become negligible from 2000 onwards. This finding suggests that prevalence in the school-aged population dropped to a level that matches the entire community. Thus, the emphasis on school-based deworming is worthy of reassessment. More aggressive targeting of the other populations defined by WHO as eligible for intervention (preschool-aged children, women of childbearing age, and adults, particularly those with high occupational exposure)[17] might be necessary. Similar suggestions have been made by Anderson and colleagues,[57] who suggested that school-based deworming could have time-limited benefits for the greater community. The proposal of new treatment guidelines will need additional studies to assess how changes in the prevalence an intensity of infection depend on different treatment schedules for different subgroups of the population at specific prevalence levels.[58]

Data compilation and meta-analyses are prone to bias. We adhered to a predefined data extraction protocol to limit potential sources of bias in our analyses. Several methodological improvements have been discussed elsewhere[6,12] and relate to incorporating diagnostic sensitivity and the relation between age and prevalence into geostatistical modelling.

We assumed that the relation between prevalence and the predictors and the considered interactions were constant across sub-Saharan Africa. The study area, however, is large and the relation between the predictors and infection risk might vary in space because, for instance, unmeasured factors, such as intervention levels or health-system performance, vary in space. We did not model varying covariate effects across space.[59] We did, however, fit models incorporating smooth changes of spatial process parameters in space (ie, non-stationary models), and these did not improve predictive performance.

We are aware of large-scale surveys done in African countries that could not be included in this analysis because the data were not readily available in geographically referenced forms. In Mozambique and Burkina Faso, for example, two surveys done after 2005 included 1275 and 130 schools, respectively.[60,61] In Côte d'Ivoire, a health and demographic surveillance system has been established in the Taabo area in the south-central part of the country, and has been used to construct a household-level database in 2008.[62] Another two surveys in Côte d'Ivoire included more than 80 schools.[63,64] The data from these surveys will be important to incorporate in future model-based predictions. Furthermore, some surveys from the peer-reviewed literature were excluded from our analysis due to incomplete information. The need to report complete survey information should be emphasised to assist spatial analysis of aggregated survey data.[22,26]

High-resolution spatially explicit risk predictions and maps can assist control programmes to select treatment strategies based on endemicity levels and to design future surveys. Estimated numbers of infected people can help international funding agencies to allocate resources to the countries. Information on the number of required treatments can be useful to drug producers and drug donors. Our findings contribute to the international efforts to reach the WHO-defined milestone of mapping soil-transmitted helminth infections to identify areas requiring preventive chemotherapy, and to monitor programmes aimed at achieving the 2020 target of control and elimination of NTDs.[55] Together with the analysis by Chammartin and colleagues in South America,[12] and Lai and colleagues in China,[18] a global stepping stone towards model-based soil-transmitted helminth infection risk estimates has now been built.

Contributors

D-AK-V processed and analysed the data, interpreted the results, and wrote the manuscript. D-AK-V, PB, and EL contributed to the systematic review and data extraction. PV extracted the data on water supply, sanitation, and education and processed these data with D-AK-V. D-AK-V, JU, and PV developed the protocol and search strategy for the systematic review. UFE, AG, EM, NM, PM, AMP, GR, MS, IT, LATT, ST, and MSW provided substantial data. PV assisted in the meta-analysis. JU and PV conceptualised the project and revised the manuscript. All authors approved the final version of the manuscript before submission.

Declaration of interests

We declare no competing interests.

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