



Schistosomes, snails and climate change: Current trends and future expectations

Anna-Sofie Stensgaard^{a,*}, Penelope Vounatsou^{b,c}, Mita E. Sengupta^a, Jürg Utzinger^{b,c}

^a Center for Macroecology, Evolution and Climate, The Natural History Museum of Denmark, University of Copenhagen, Copenhagen, Denmark

^b Swiss Tropical and Public Health Institute, Basel, Switzerland

^c University of Basel, Basel, Switzerland

ARTICLE INFO

Keywords:

Schistosomiasis
Parasites
Intermediate host snails
Climate change
Global warming
Temperature
Africa

ABSTRACT

The exact impact of climate change on schistosomiasis, a disease caused by a blood fluke that affects more than 250 million people mainly in tropical and subtropical countries, is currently unknown, but likely to vary with the snail-parasite species' specific ecologies and the spatio-temporal scale of investigation. Here, by means of a systematic review to identify studies reporting on impacts of climate change on the agents of schistosomiasis, we provide an updated synthesis of the current knowledge about the climate change-schistosomiasis relation. We found that, despite a recent increase in scientific studies that discuss the potential impact of climate change on schistosomiasis, only a handful of reports have applied modelling and predictive forecasting that provide a quantitative estimate of potential outcomes. The volume and type of evidence associated with climate change responses were found to be variable across geographical regions and snail-parasite taxonomic groups. Indeed, the strongest evidence stems from the People's Republic of China pertaining to *Schistosoma japonicum*. Some evidence is also available from eastern Africa, mainly for *Schistosoma mansoni*. While studies focused on the northern and southern range margins for schistosomiasis indicate an increase in transmission range as the most likely outcome, there was less agreement about the direction of outcomes from the central and eastern parts of Africa. The current lack of consensus suggests that climate change is more likely to *shift* than to *expand* the geographic ranges of schistosomiasis. A comparison between the current geographical distributions and the thermo-physiological limitations of the two main African schistosome species (*Schistosoma haematobium* and *S. mansoni*) offered additional insights, and showed that both species already exist near their thermo-physiological niche boundaries. The African species both stand to move considerably out of their "thermal comfort zone" in a future, warmer Africa, but *S. haematobium* in particular is likely to experience less favourable climatic temperatures. The consequences for schistosomiasis transmission will, to a large extent, depend on the parasites and snails ability to adapt or move. Based on the identified geographical trends and knowledge gaps about the climate change-schistosomiasis relation, we propose to align efforts to close the current knowledge gaps and focus on areas considered to be the most vulnerable to climate change.

1. Introduction

Shifts in patterns of precipitation, a rise in temperature and an increase in the frequency and severity of extreme climate events (e.g. droughts and flooding) are three major components of ongoing climate change (IPCC, 2013). Numerous studies have documented how climate change is already changing plant and animal species' distribution and phenology as they attempt to adapt or track their climatic optima (Walther et al., 2002). Climate change is also affecting many infectious disease agents, particularly those transmitted via an ectotherm or

poikilotherm invertebrate vector or intermediate host, whose distribution and development are inextricably linked with climate (Campbell-Lendrum et al., 2015). Yet, determining the exact effects of climate change on specific human infectious diseases, despite a growing interest from the scientific community, has proven difficult and the debate about the potential health impacts remains polarized (Lafferty and Mordecai, 2016).

This is also the case for snail-borne schistosomiasis that affects more than 250 million people worldwide, particularly in countries of the tropics and subtropics (Hotez et al., 2014). Climate-induced shifts in

* Corresponding author at: Center for Macroecology, Evolution and Climate, The Natural History Museum of Denmark, University of Copenhagen, Universitetsparken 15, DK-2100 Copenhagen, Denmark.

E-mail address: asstensgaard@snm.ku.dk (A.-S. Stensgaard).

<https://doi.org/10.1016/j.actatropica.2018.09.013>

Received 6 July 2018; Received in revised form 19 September 2018; Accepted 20 September 2018

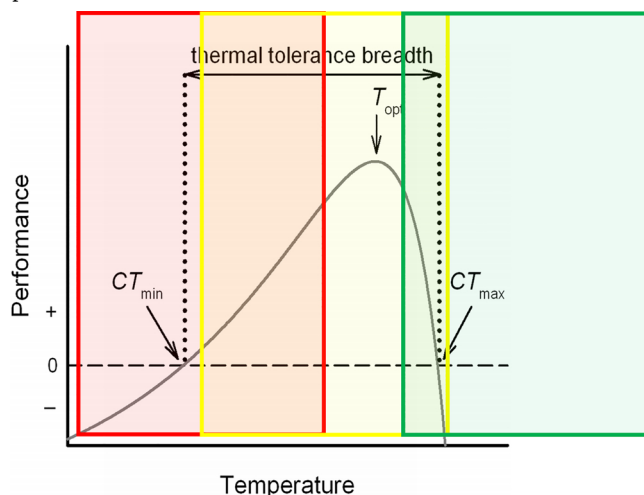
Available online 24 September 2018

0001-706X/ © 2018 Elsevier B.V. All rights reserved.

phenology and geographical range of both schistosomes and intermediate host snails are likely to affect disease dynamics. Of prospective scenarios, snails and parasites could be introduced into currently non-endemic areas as environmental conditions become more suitable (Gautret et al., 2015). Hence, accurate predictions of these outcomes and their geographical location play an essential role in alerting health authorities to potential future risks, and have important implications for the feasibility of schistosomiasis control and elimination efforts. A sound knowledge of the functional relationship between the biology and ecology of the parasites, their intermediate hosts and the major climatic drivers is pivotal to build accurate models of climate change impact on schistosomiasis. However, the social-ecological context and multi-factorial nature of schistosomiasis (Utzinger et al., 2011; McManus et al., 2018) make it difficult to detect climate-mediated changes, and it is currently unclear what the dominant outcome and net effect of climate change on schistosomiasis distribution and transmission will be.

Hence, there is a pressing need to review our current understanding of the potential effects of climate change, particularly global warming, on schistosomiasis and our capacity to predict future impacts. To this end, we systematically reviewed and summarised the principal findings of climate change-schistosomiasis research published in the peer-reviewed literature to date. Specifically, our review was motivated by asking the following questions. First, what is the current scientific consensus/evidence (if any) about the effect and direction of climate on schistosomiasis? Second, do outcomes vary across geographical location, modelling methods and parasite-snail species? Third, can we use our current understanding of the intra-specific variation in schistosome-snail species' thermotolerances, ecology and climatic niches to inform our expectations about future scenarios for the main *Schistosoma* species affecting humans?

Our piece consists of two main parts: we begin by reviewing and summarising the principal findings and specificities of studies investigating the effect of climate change on the three main human *Schistosoma* species (i.e. *Schistosoma haematobium*, *S. japonicum* and *S. mansoni*) and their specific intermediate host snail species, to determine how many studies, and if any trends (taxonomically, geographically or methodologically) are prevalent. Then, focusing on the impacts of global warming, we synthesise experimental evidence about the effect of temperature on the performance of these schistosome species to look for differences in thermal tolerances, by identifying key points on each species thermal performance curves (Box 1). We compare these findings with empirical data on their geographical distribution and climatic niches to identify any differences that could provide new insights into schistosome species' specific responses to the rising, global temperatures.



Box 1: Generalized thermal performance curve of a hypothetical

ectotherm.

The relationship between environmental temperature and an organism's performance (measured, for example, as fecundity, growth and metabolic rate) can be expressed as a thermal performance curve (TPC) (grey line). The optimum temperature (T_{opt}) specifies the temperature at maximum performance. The ecophysiological key characteristics, critical thermal minimum (CT_{min}) and maximum (CT_{max}), delimit an organism's thermal tolerance. The shape and range of TPCs most likely vary between species of parasites and intermediate host snail species, and determine where climatic suitability for transmission and snail proliferation will increase or decrease with climate warming. The colored squares represent different climatic scenarios in a given location: red: prevailing/current climatic conditions that is suboptimal for the given species; yellow: warming scenario that give optimal conditions for the species in that geographical location, and green: warming scenario where temperatures become too hot.

2. Methods

2.1. Search strategy and selection criteria

We systematically reviewed the peer-reviewed literature to identify relevant publications pertaining to climate change and schistosomiasis. A systematic search of the extant literature on PubMed and Web of Science databases was conducted on all available published literature up to 31 December 2017 using the following search terms in various combinations and Boolean operators (OR, AND): *Schistosom**, *Bulinus*, *Biomphalaria*, *Oncomelania*, *Climat** change, warming. Identified articles were screened by reading through the titles and abstracts. In addition, reference lists of the identified articles were screened for any additional relevant studies for inclusion. Full text articles were retrieved and managed in EndNote reference manager version X7 (Clarivate Analytics; Philadelphia, PA, USA). Two reviewers (ASS and MES) independently examined the full text of publications included for qualitative review ($n = 103$) to extract information about the reported direction of climate change on schistosomiasis and intermediate host snails (i.e. overall positive, negative or uncertain/both directions possible).

2.2. Comparison of geographical distributions, climatic variability and thermotolerances of the schistosome species

In addition to reviewing climate change-schistosomiasis research with an emphasis on a potential impact of climate change, we also synthesised current knowledge about the thermo-physiological performance/tolerance of the three most important human schistosome species. We compared this information with empirical observations of schistosomiasis to look for any intraspecific differences between species that might impact future patterns (i.e. assess for any difference with regards to their sensitivity to warming), or explain discrepancies between the direction of impacts found in our literature review.

To do so, we downloaded geographically referenced point-based prevalence data for *S. haematobium* and *S. mansoni* from the Global Neglected Tropical Disease (GNTD) database (Hürlimann et al., 2011); restricting our search spatially to Africa. At present, more than 10,000 unique survey locations (mainly on *S. mansoni* and *S. haematobium* in Africa) are included in the GNTD database (www.gntd.org). For each survey point with at least 5% prevalence (chosen as the cut-off value to represent locations with endemic transmission), we extracted both current and future bioclimatic temperatures. All bioclimatic data were acquired from the Worldclim dataset (www.worldclim.org) (Hijmans et al., 2005). Future temperatures were based on downscaled climatic conditions for the time period 2070 (average 2061–2080) for RCP 8.5, readily obtained from the Coupled Model Intercomparison Project phase 5 (CMIP5), as presented by the Intergovernmental Panel on Climate Change (IPCC, 2013).

3. Trends in climate change-schistosomiasis research over two decades

Our systematic review identified 386 peer-reviewed publications. These were narrowed down to 183 relevant studies referring to climate change and schistosomiasis. Eighty of these studies were excluded, since they lacked any direction of the change. The remaining 103 studies were included in the qualitative review synthesis, while 20 of these studies were retained for the final review (Fig. 1).

The oldest published articles referring to the topic of climate change impacts on schistosomiasis were published in the early and mid-1990s. Subsequently, an exponential increase in articles pertaining to climate change and schistosomiasis occurred. In 2015 and 2016, there were 19 papers in each year focussing on climate change and schistosomiasis, while this number slightly decreased in 2017. About half of the published papers constitute original research articles, the rest being reviews, commentaries, editorials and the likes (Fig. 2).

Martens and colleagues were the first to apply a global modelling approach to the study of impact of climate change on schistosomiasis (Martens et al., 1995, 1997). In their first study, they linked global circulation model-based scenarios of climate change with a model of the relationship between climate variables (temperature and precipitation) and the parasite's basic reproduction rate (R_0). They found that the world's population at risk of schistosomiasis might increase by 0.7–3.3%, due to expanding ranges of schistosomiasis into higher latitudes (North and South) and higher altitudes. However, in a follow-up study published two years later, using a slightly different modelling

approach, they concluded that schistosomiasis transmission potential is likely to decrease by 11–17% by 2050. Yet, they emphasised that transmission of schistosomiasis in countries in which, until recently, pockets of transmission occurred (e.g. Japan and southern European countries) are likely to increase, a scenario that came true with the outbreak of urogenital schistosomiasis in Corsica in 2015 (Boissier et al., 2015).

About a decade later, researchers from the People's Republic of China put forth a series of publication pertaining to climate change and *S. japonicum* (Yang et al., 2005, 2006; Zhou et al., 2008). In a first study (Yang et al., 2005), it was shown that the historical isotherm (freezing line), considered to be the approximate northern limit of *S. japonicum* transmission in the People's Republic of China, had shifted from 33°15' N latitude to 33°41' N, expanding the potential transmission area by 41,335 km², which corresponds to approximately the size of Switzerland. This translated to an additional 20.7 million people at risk of schistosomiasis in the People's Republic of China. Subsequently, using a growing degree day (GDD) modelling approach, the authors hypothesised that the number of *S. japonicum* parasite generations, as measured by GDDs summed over a year (i.e. annual growing degree day, AGDD in short) would increase in the future by speeding up their development in longer growing seasons and extending the current area where both parasites and intermediate host snail can proliferate (Yang et al., 2006). GDD is a unit used to express the amount of heat energy an organism can accumulate, and AGDD is an important aggregate measure that has been found to correlate with the distributional patterns of many living organisms (Malone and Zukowski, 1992). The approach is based on the

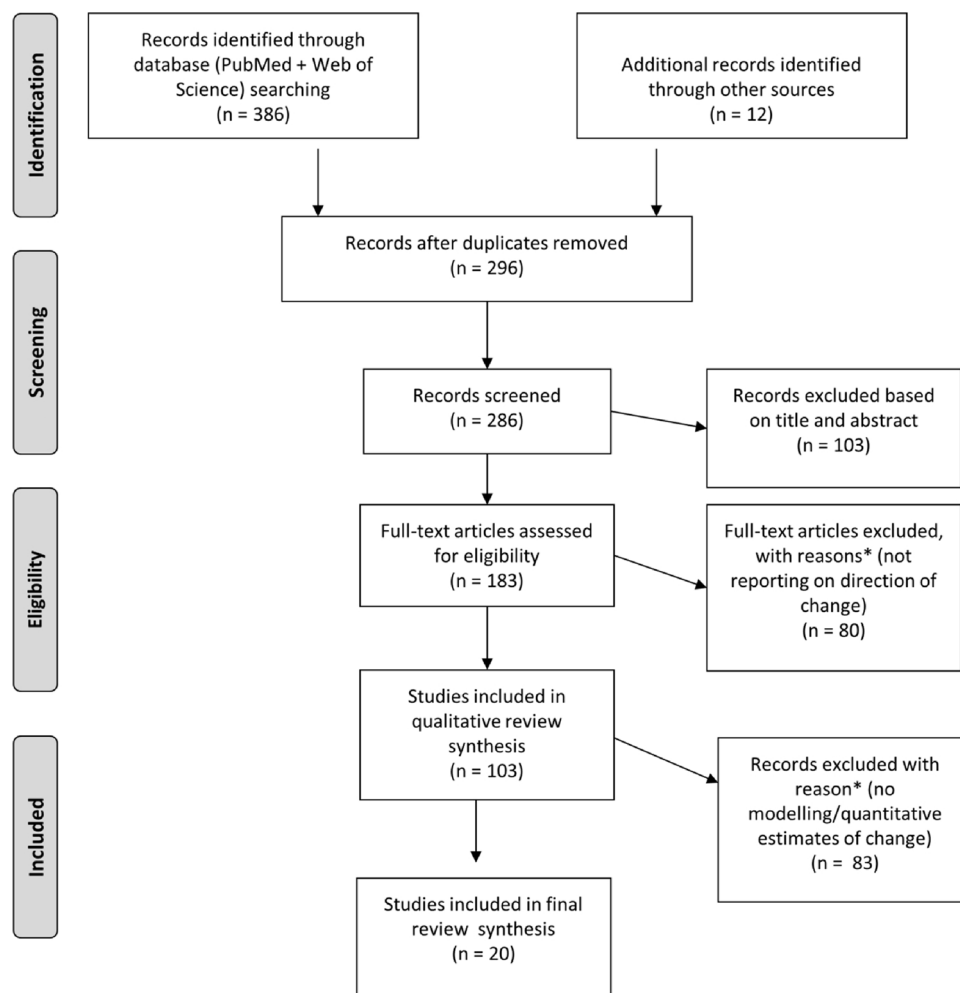


Fig. 1. PRISMA diagram of the literature search process.

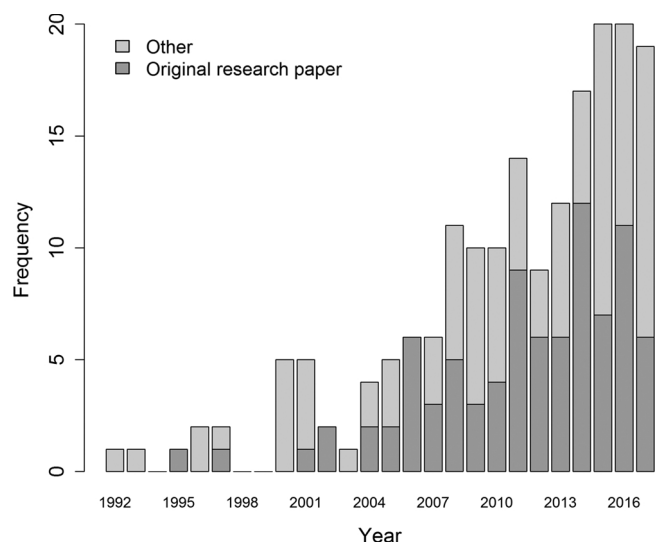


Fig. 2. No. of publications reporting/referring to/on the impact of climate change and/or climate change on schistosomiasis from 1992 to 2017 ($n = 183$) broken down by original research papers (light-grey), and in dark-grey “other” (reviews, editorials, commentaries and reports).

assumption that a snail only develops when the environmental temperature is higher than a certain minimal threshold and that the thermal total energy required for development is constant (Malone et al., 2006). This was then confirmed by Zhou et al. in 2008, who forecasted an expansion of schistosomiasis transmission into currently non-endemic areas in the northern part of the People’s Republic of China, with an additional risk area of 783,883 km² by 2050 (Zhou et al., 2008).

The first decade in the new millennium saw an increased publication output, particularly with regard to reviews and commentaries, highlighting the sensitivity of infectious and vector-borne diseases in general. Referring to schistosomiasis (i.e. Sutherst, 2004; Kelly-Hope, 2008; Mas-Coma et al., 2008, 2009), many of them concluded that the most likely scenario of a future warmer world would be that of expanded schistosomiasis transmission.

Next, a suite of statistical modelling papers focusing on Africa emerged, initiated by Stensgaard and colleagues (2013). The authors combined GDD models for *S. mansoni* with snail habitat suitability models for several intermediate host snail species and showed that, overall, conditions for most of the *S. mansoni* intermediate host snails

could decrease (by as much as 43% for *Biomphalaria pfeifferi*, the most important intermediate host snail for *S. mansoni* in Africa) under future climate change scenarios for the African continent. The study also highlighted the importance of accounting for other environmental factors relating to the snail habitats, such as environmental modifications, land use and water availability. Most studies published by then, in particular those applying dynamic, mathematical modelling, primarily employed temperature as the only driving factor (see, for example, Mangal et al., 2008) without accounting for other potential modifiers. Additionally, the studies lacked species specificity (Fig. 3 left), particularly with regard to intermediate host snails.

An overview of the identified 20 papers that apply quantitative analysis and/or modelling to predict a potential impact of climate change on schistosomiasis is given in Table 1.

3.1. Species trends: are some species more in focus than others?

Most human schistosomiasis cases are caused by infection with any one of the three species *S. mansoni* (Africa, Brazil and the Caribbean), *S. haematobium* (Africa and the Middle East) or *S. japonicum* (People’s Republic of China and The Philippines). Snails of the genera *Biomphalaria*, *Bulinus* and *Oncomelania* act as intermediate hosts for *S. mansoni*, *S. haematobium* and *S. japonicum*, respectively. Within each genus, there are several species of snails capable of acting as an intermediate host for schistosomes. For instance, there are as many as 12 suitable *Biomphalaria* host species for *S. mansoni* in Africa alone, and these different snail species all have different ecological requirements (Brown, 1994). Given their different habitat preferences, it is therefore not unlikely that these snails will be affected differently by changing climatic conditions. This was, for instance, evident from a study on climate change impacts on *S. mansoni* and intermediate host snails in Africa (Stensgaard et al., 2013), showing that the expected effects of climate change will lead to a reduction in suitable habitats for four out of five species of intermediate host snails for the parasite, as current living areas become too hot for the snails. This study underlined the importance of including biological knowledge of different intermediate host snail species in the models to gain a deeper insight of how rising temperatures might govern schistosomiasis transmission.

However, our review revealed that a considerable number of studies on the climate change-schistosomiasis nexus do not even differentiate between the parasite species, but merely refer to impacts on schistosomiasis (Fig. 3). Of the relatively few studies that do focus on specific species, there was an overweight of studies concerned with *S. japonicum* and its intermediate host snail species, *Oncomelania hupensis*. This observation is explained by the fact that most climate change-schistosomiasis studies thus far were conducted in the People’s Republic of China

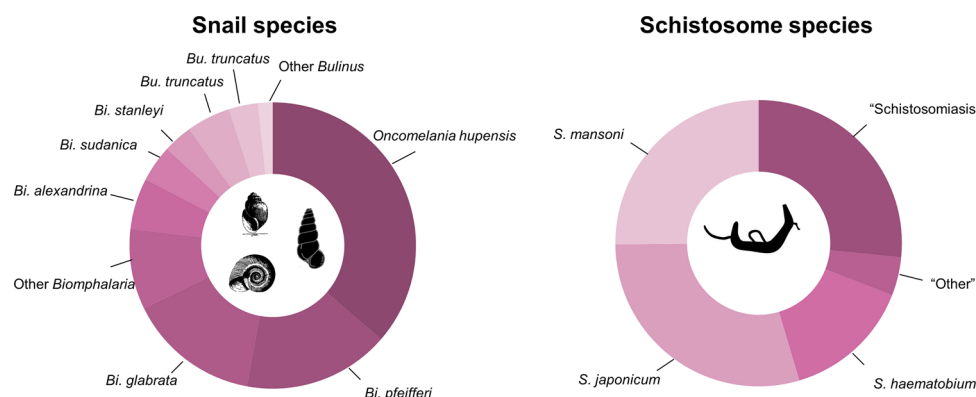


Fig. 3. Papers broken down by species referred to in the 183 identified papers pertaining to climate change and/or global warming and one or several agents involved in the schistome life cycle.

Table 1
Summary of published studies that assessed the effect of climate change on schistosomiasis between 1992 and 2017, using quantitative/analytical approaches to determine/back-up the concluded outcome.

Study	Place	Parasite species	Snail species	Response type investigated	Main factors drivers/predictors	Method	Time period (model)	Results	Overall outcome
Martens et al. (1995)	Global	Non-specific schistosome species	-	Geographical risk areas and number of people at risk	Temp + precip	Mathematical model	2050/2100 relative to 1990 (UKMOGCM & ECHAM1-A-GCM)	Predicted extension of areas conducive to schistosomiasis transmission. Overall increase in populations at risk of schistosomiasis	↑
Martens et al. (1997)	Global	Non-specific schistosome species	-	Epidemic potential (EP)	Temp + precip	Mathematical model	2050 relative to 1931–1980 (GFDL89, UKTR, ECHAM1-A)	Predicted decrease in overall epidemic potential.	↓
Yang et al. (2005)	People's Republic of China	<i>S. japonicum</i>	<i>O. hupensis</i>	Geographical area suitable for snail and number of people at risk	Temp only	Trend analysis and kriging of temperature surfaces	1971–2000 relative to 1961–1990 (meteorological station data)	Predicted expansion of potential transmission area. Increase in number of people at risk	↑
Yang et al. (2006)	People's Republic of China (Jiangsu province)	<i>S. japonicum</i>	<i>O. hupensis</i>	Change in AGDD	Temp only	Growing degree day model (GDD)	2006 relative to 2003	Predicted increase in AGDD	↑
Zhou et al. (2008)	People's Republic of China	<i>S. japonicum</i>	<i>O. hupensis</i>	Potential transmission index (PTI)	Temp only	Growing degree day model (GDD)	2050 relative to 2000	Predicted expansion of schistosomiasis transmission area (north)	↑
Mangal et al. (2008)	-	<i>S. mansoni</i>	Non specific <i>Biomphalaria</i> spp.	Parasite prevalence and abundance	Temp only	Mathematical model	No specified time period	Observed altitudinal change in transmission risk areas (above 1400 m)	↔
John et al. (2008)	Uganda	<i>S. mansoni</i>	-	Altitudinal transmission risk area	Hum (parasitological data) only	Epidemiological survey	2008 (compared to 1998–2002)	Predicted decrease in PTI with up to 19% overall	↓
Stensgaard et al. (2013)	Sub-Saharan Africa	<i>S. mansoni</i>	(in <i>Bi. pfeifferi</i>)	Potential transmission index (PTI)	Temp + precip + env + hum	Hybrid (GDD + SDM model)	2070–2099 relative to 1950/1990 (HADCM3)	Predicted decrease in suitable snail habitat with up to 43%	↓
	-	-	<i>Bi. pfeifferi</i>	Range size/suitable snail habitat	Temp + precip + env + hum	SDM	2070–2099 relative to 1950/1990 (HADCM3)	Predicted increase in suitable snail habitat with up to 14%	↑
	-	-	<i>Bi. sudanica</i>	Range size/suitable snail habitat	Temp + precip + env + hum	SDM	2070–2099 relative to 1950/1990 (HADCM3)	Predicted decrease in suitable snail habitat with up to 15%	↓
	-	-	<i>Bi. alexandrina</i>	Range size/suitable snail habitat	Temp + precip + env + hum	SDM	2070–2099 relative to 1950/1990 (HADCM3)	Predicted decrease in suitable snail habitat with up to 45%	↓
	-	-	<i>Bi. choanomphala</i>	Range size/suitable snail habitat	Temp + precip + env + hum	SDM	2070–2099 relative to 1950/1990 (HADCM3)	Predicted potential increase in schistosomiasis risk in flowing water in cooler areas, but decrease in infection risk may increase dramatically with small increases in temperature in areas at/near the currents limits of schistosome transmission	↔
McCreesh et al. (2014a)	Africa	<i>S. mansoni</i>	<i>Bi. pfeifferi</i>	Infection risk	Temp only	Mathematical model (agent-based)	No specified time period	In most areas where <i>Bi. pfeifferi</i> is the host, infection risk is likely to decrease	↓
McCreesh and Booth (2014b)	Africa	<i>S. mansoni</i>	<i>Bi. glabrata</i>	Infection risk	Temp only	Mathematical model (agent-based)	No specified time period	Predicted reduction in area suitable for snail habitat	↓
Pedersen et al. (2014a)	Zimbabwe	-	<i>Bu. globosus</i>	Area of suitable snail habitat	Clim + env	SDM	2050 + 2100 vs present (HIRHAM RCM & GCM)	Predicted increase in areas of suitable habitat in 2055, but decline towards 2100	↔
	-	-	<i>Bi. pfeifferi</i>	Area of suitable snail habitat	Clim + env	SDM	2050 and 2100 vs present (HIRHAM RCM & GCM?)	Predicted decrease in favourable	↓
Pedersen et al. (2014b)	Zimbabwe	-	<i>Bu. globosus</i>	Area of suitable snail habitat	Clim + env	SDM	2012 relative to 1988	Predicted decrease in favourable	↓
	-	-	<i>Bi. pfeifferi</i>	Area of suitable snail habitat	Clim + env	SDM	2012 relative to 1988	Predicted decrease in favourable	↓

(continued on next page)

Table 1 (continued)

Study	Place	Parasite species	Snail species	Response type investigated	Main factors drivers/predictors	Method	Time period (model)	Results	Overall outcome
McCreesh et al. (2015)	Eastern Africa	<i>S. mansoni</i>	<i>Bi. pfeifferi</i>	Infection risk	Temp only	Mathematical (agent-based) model	2026–2035 & 2056–2065 relative to baseline 2006–2015 (RCM: RCA 4 & AOGCM – EC-EARTH)	Predicted increase in <i>S. mansoni</i> transmission over much of eastern Africa	↑
Stensgaard et al. (2016)	Eastern Africa	<i>S. mansoni</i>	<i>Bi. pfeifferi</i>	Infection risk and snail habitat suitability	Temp + precip + env + hum	Hybrid (SDM + agent-based model)	2026–2035 & 2056–2065 relative to baseline 2006–2015 (RCM: RCA 4 & AOGCM – EC-EARTH)	Predicted increase in overall risk areas in 63% of total area vs predicted decrease risk in 37% of the total area in eastern Africa	↔
Pedersen et al. (2017)	Zimbabwe	<i>S. mansoni</i>	-	Overall prevalence	Temp + precip + env + hum	Geostatistical model	2010 relative to 1981	Observed decline in overall prevalence (9.4% in 1981 to 5.1% in 2010)	↓
		<i>S. haematobium</i>	-	Overall prevalence	Temp + precip + env + hum	Geostatistical model	2010 relative to 1981	Observed decline in overall prevalence (41.5% in 1981 to 17.3% in 2010)	↓
Casimiro et al. (2006)	Portugal	<i>S. haematobium</i>	-	Percentage of days/year within favourable temperature range for parasite survival	Temp only	Ecologic scenarios based on temperature thresholds	2040–2049 & 2080–2100 (HadRM2 and PROMES)	Increased percentage of days/year within favourable temperature range for parasite survival	↑
Wang et al. (2015)	Anhui province, People's Republic of China	<i>S. japonicum</i>	-	Relative Sensitivity	Temp + precip + humidity	Statistical indicator/model	No specific time-period	Increased sensitivity	↑
Zhu et al. (2017)	People's Republic of China	-	<i>O. hupensis</i> (+ subspecies)	Potential snail distribution	Temp + precip	SDM	2050/2060 and 2080/2090	Predicted future expansions in snail suitable areas	↑
		<i>S. japonicum</i>	-	Future potential transmission potential	Temp + precip	Estimated based on modelled future snail species distribution (above)	2050/2060 and 2080/2090	Predicted northwards expansion of transmission areas	↑
Stanton et al. (2017)	Uganda	<i>S. mansoni</i>	<i>Biomphalaria</i> spp.	Altitudinal transmission risk area	None	Empirical observations (parasitological and malacological surveys)	Present	Observed natural transmission of intestinal schistosomiasis	↑
Poulin (2006)	-	<i>Schistosoma</i> spp.	Non-specific intermediate host species	Cercarial output	Temp only	Computed Q10 for cercarial production rates	No specific time-period	Predicted increase in cercarial output with increases in environmental temperatures	↑

Abbreviations: Env, other environmental factors; GDD, growing degree day (model); Hum, human; Precip, precipitation; SDM, species distribution model; Temp, temperature.

(Fig. 4). The second most important set of studies pertained to climate change and its potential impact on *S. mansoni*, including the most important intermediate host snail species *Bi. pfeifferi* and *Bi. glabrata* with 35 out of 103 studies that conclude on the direction of impacts of climate change on schistosomiasis. The outcomes of these studies were distributed approximately equally among the categories “positive”, “negative” and “uncertain/both outcomes likely” scenarios. Far fewer studies dealt with *S. haematobium*, and in particular studies looking at potential impacts on *Bulinus*, are currently heavily underrepresented (Fig. 3). Indeed, only two out of 20 modelling studies (Table 1) have dealt with *S. haematobium*: the first from Portugal indicated an increased potential for *S. haematobium* under future climatic conditions in Europe (Casimiro et al., 2006). The second study was conducted in Zimbabwe, and observed a decline in the overall prevalence of urogenital schistosomiasis over the last three decades (41.5% in 1981; 17.3% in 2010), in a period with an increasingly drier and warmer climate (Pedersen et al., 2017)

only one study from South America touched upon the possible effect of climate change for schistosomiasis (Palasio et al., 2015). The authors discussed linkages between the distribution of the intermediate host snail *Bi. straminea* and climate change in Sao Paulo, Brazil. However, there is a complete absence of modelling/prediction studies from the Southern Americas.

The observed geographical variation may in part be explained by climate change-ecological theory. Indeed, for many species, in addition to shifts in the timing of species' life cycles, there is a general trend to shift their ranges poleward or up in elevation with climate change as species attempt to track their climatic optima (Parmesan, 2006). Climate impacts could also cause losses from parts of a species' trailing range margins, that is, the area from where they contract (Sinervo et al., 2010), even though this rarely observed (Sunday et al., 2012). The response will, to a large extent, depend on the particular species' traits, such as heat or cold tolerance that reflect shared evolutionary history and climatic origins.

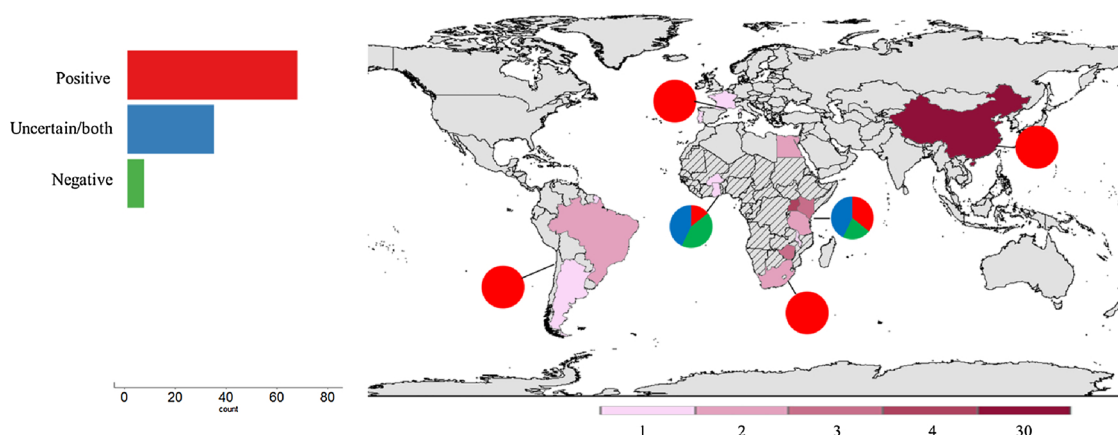


Fig. 4. Global distribution of climate change-schistosomiasis research, as revealed in a systematic review from the peer-reviewed literature. The figure shows the distribution of studies on climate change and schistosomiasis that conclude on the direction of the outcome but not necessarily through quantitatively modelling and prediction ($n = 103$) by country and by direction/outcome. Green: negative (less schistosomiasis as a consequence of climate change); red: positive (more schistosomiasis as a consequence of climate change); and blue: both directions highlighted (or uncertain/ inconclusive). One continental scale modelling study (covering sub-Saharan Africa) is shown in hatch, whereas non-country specific, global and continental scale studies (i.e. reviews, theoretical papers with a global scope, or experimental/mathematical modelling studies) are not shown on the map by country. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Geographical trends in climate change-schistosomiasis research and outcomes

As pointed out, most studies identified in the current review focussed on the People's Republic of China, and hence, *S. japonicum*. These studies ($n = 30$, Fig. 4), consistently point to an increased risk of schistosomiasis with climate change. This, however, is not reflected in the current situation in the country, as the estimated number of people infected with *S. japonicum* decreased from more than 10 million in the mid-1950s to 1.52 million in the 1980s (Chen and Feng, 1999), a period that has experienced general global warming (IPCC, 2013). The decrease in schistosomiasis is attributed to a sustained, large-scale, multifaceted control programme carried out in endemic provinces (Zhou et al., 2007). This highlights the importance of accounting for human/societal factors in combination with environmental drivers when attempting to predict realistic outcomes of climate change impacts.

On the African continent, a total of 23 studies were identified, approximately equally divided with regards to the direction of the predicted outcome (positive, negative and uncertain). Breaking these studies down by region in Africa, revealed that particular studies from low-latitude countries/areas showed little consensus with regards to the direction of the predicted outcome of climate change on schistosomiasis, whereas the studies from i.e. South Africa point towards a negative outcome (increased risk with climate change) (Fig. 4). Finally,

Thus, if schistosomiasis is currently constrained in range at the northern range margin (i.e. People's Republic of China and Europe) and southern range margin (i.e. southern Africa), also referred to as the leading edges of distribution, due to unfavourable climatic conditions (i.e. too cold), we would expect schistosomiasis to expand pole-ward in face of rising temperature. This is in accordance with the observed pattern of studies in Fig. 4, but also with a recent outbreak of urogenital schistosomiasis in Corsica (Boissier et al., 2015).

3.3. Modelling trends in climate change-schistosomiasis research

Currently, two broad types of approach for predicting the impact of climate change on vector-borne diseases in general, and schistosomiasis in particular, can be distinguished. First, empirical-statistical (correlative) approaches that use statistical models of relationships between snail and/or parasite distribution and environmental factors. Second, process-based (mechanistic) approaches that seek to simulate detailed biophysical/epidemiological processes by explicitly incorporating associations between environmental conditions and organismal performance estimated independently of current distributions (Kearney and Porter, 2009; Dormann et al., 2012; Stensgaard et al., 2016). However, both approaches have strengths and limitations, and value in assessing the response of both parasite snail species to climate change (Purse and Golding, 2015; Stensgaard et al., 2016).

In the present review, after eliminating scientific articles that do not

apply quantitatively modelling and/or prediction, a total of 20 studies on the impact of climate change of either schistosomiasis or intermediate host snail species remained. The main features, including the choice of modelling of these studies, are summarised in Table 1.

Of the modelling papers, 10 used a correlative modelling approach based on empirically observed data on snail and/or parasite current/historical distributions (hereof six studies that used a species distribution modelling (SDM) approach) and eight used a process-based modelling approach (i.e. temperature-driven mathematical or GDD model), while only three studies also used a combination/hybrid modelling approach (Table 1, Fig. 5).

The trend that emerges from Fig. 5 and Table 1 is a tendency for correlative modelling studies (typically applying species distribution models to intermediate host snail distributions) to predict negative outcomes (i.e. shrinking suitable snail habitats as in Stensgaard et al. (2013) and Pedersen et al. (2014a,b) more often than positive outcomes. The opposite seem to apply to the process-based models (i.e. temperature driven mathematical models such as in McCreesh et al. (2015).

SDMs are among the most widely applied modelling approach used in conservation biology. The approach benefits from straightforward pairing of distribution data with readily available climate data, but can have weak predictive power when projected to novel climates and give little insight into the causal mechanisms that underlie changes in species ranges (Dormann et al., 2012). Hence, there have been recent calls to improve this methodology (Fordham et al., 2013; Pacifici et al., 2015) and appeals to incorporate more physiology-based knowledge (i.e. species thermotolerances) as a means to increase the accuracy of SDMs (Buckley et al., 2011; Huey et al., 2012; Sunday et al., 2014).

On the other hand, mathematical models that have temperature as the only environmental driver, while able to capture the complex and non-linear relationship between the full spectrums of life cycle stages and temperature in great detail (i.e. McCreesh et al., 2015), run the risk of over-simplification. This can also explain the observed differences in outcomes between the models reviewed in the current study: by far the majority of the process-based studies reviewed focus primarily on ambient temperature as the main environmental explanatory factor, and thus fail to incorporate other important (climatic and non-climatic) environmental drivers that may impact and even limit the distribution of the intermediate host snails (e.g. land cover, soil properties and water availability). Ignoring rainfall and the absolute necessity of appropriate aquatic habitats for the intermediate host snails will arguably lead to unrealistic (overly “optimistic”) predictions about the ability of the parasite to establish itself in areas unsuitable for the survival and proliferation of the intermediate host snail species.

In the climate change-schistosomiasis field, only a few studies have attempted to take advantage of the full spectrum of models, i.e. in “hybrid modelling” (Stensgaard et al., 2013, 2016), that combine SDMs with physiology-driven mechanistic models. Studies using this modelling approach indicate that climate change seems more likely to shift than to expand the geographic ranges of schistosomiasis, compared with models at the extremes on the correlative–process model

continuum (Fig. 5), which may be a more realistic scenario (Lafferty, 2009; Purse and Golding, 2015). In fact, Stensgaard et al. (2016) showed that combining a mathematical agent-based model of the temperature-sensitive stages of the *S. mansoni* and intermediate host snail lifecycles, with a snail species distribution model for eastern Africa, significantly improved model predictions for current conditions. The functional relationship between the biology of schistosomes, snails and temperature form a fundamental part of such process-based niche models.

4. Thermotolerances, geographical distributions and climatic niche space of the schistosome species

The physiological processes of the free-living and intra-molluscan stages of the schistosome parasites are highly sensitive to temperature, and upper/lower thermal thresholds (Box 1) determine their ability to remain active, infective and survive under extreme climatic conditions. Hence, detailed, species-specific information about the relationship between the biology of the various life cycle stages of the parasites and the different intermediate host snails and temperature is adamant to develop more accurate prediction models (i.e. McCreesh and Booth, 2013; Stensgaard et al., 2013; McCreesh et al., 2015). Furthermore, any differences in thermo-tolerances may hint at which *Schistoma*-snail species that may stand to “lose or gain” in a warming world and may offer clarifying insights into the seemingly contradictory results from climate change-schistosomiasis studies from Africa especially. To this end, we here summarise experimental evidence about the effect of temperature on the performance of the main human schistosome species to highlight key points on each species’ thermal performance curves (Box 1).

4.1. Experimentally established effects of temperature on schistosome life history stages

In the schistosome life cycle there are several stages that are sensitive to temperatures in the environment, such as the miracidia and cercariae as these are free living stages, and will be exposed directly to ambient temperature changes. Furthermore, all intra-molluscan stages are sensitive to environmental temperatures, as the snail intermediate hosts are poikilotherms and their internal temperature therefore follows the environmental temperatures.

Numerous experimental studies have been performed to investigate the effect of temperature on the different stages of the *Schistosoma* life cycle. Temperature can influence the performance of all the different stages of the *Schistosoma* life cycle: from the survival of the free-swimming miracidia larvae, the speed of development into mature cercariae inside the molluscan intermediate host, the number of released cercariae and the survival and infectivity of the free-swimming cercariae once shed from the snail. Finally, temperature influences the intermediate host snails’ growth, fecundity and survival, as recently reviewed and synthesised by Kalinda et al. (2017).

However, one of the most important effects of temperature

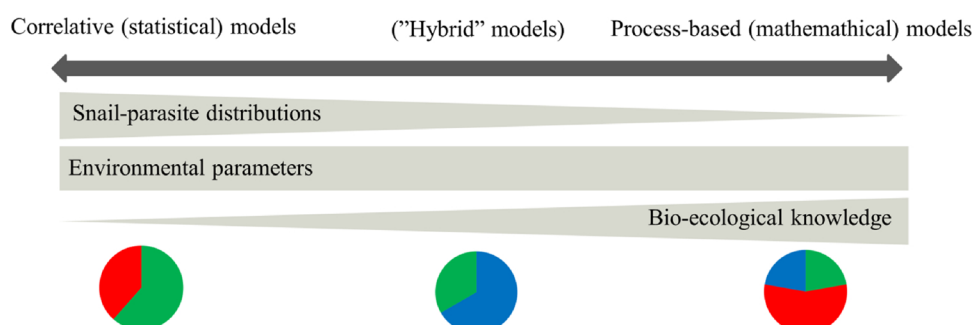


Fig. 5. Methodological trends in climate change impact modelling studies. The distribution of studies that used modelling in the study of climate change impacts on schistosomiasis ($n = 20$) and their main predicted outcome (green, negative; red, positive and blue, uncertain/non-linear/both outcomes predicted) along the correlative–process model continuum. Figure modified after Dormann et al. (2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2

Experimentally observed critical thermal thresholds for parasite intra-molluscan development for the three main species of human schistosomes.

Parasite species	Development in molluscan host	MinDDT (°C) ^a	OptDDT (°C) ^b	MaxDDT (°C) ^c	Thermal tolerance breadth (°C)	Reference(s)
<i>S. mansoni</i>	<i>Bi. glabrata</i>	14.2	32–33	> 34–35	20.8	Pflüger (1980, 1981)
	<i>Bi. pfeifferi</i>	< 16	32–33	> 34–35	> 19	Gordon et al. (1934), Foster (1964)
<i>S. haematobium</i>	<i>Bu. truncatus</i>	15.3	30–32	33	17.7	Pflüger et al. (1984)
	<i>Bu. globosus</i>	15.5	31	> 34–35	19.5	Gordon et al. (1934), Kalinda et al. (2017)
<i>S. japonicum</i>	<i>O. hupensis</i>	15.3	30	–	–	Yang et al. (2006)

^a MinDDT, the minimum development temperature threshold for intra-molluscan parasite development (“developmental null point”).^b OptDDT, temperature where development speed peaks (shortest prepatent period).^c MaxDDT, temperature above which development is inhibited or starts to slow down significantly.

pertaining to intra-molluscan larval stages is the length of the so-called prepatent period, which is the time it takes from miracidia infection of the snail until cercarial shedding. The effect of temperature on the prepatent period has been investigated by experimental manipulation of the snail-parasite system by many researchers. In Table 2, we summarised some of the main findings of these studies for the three main human schistosome species, focusing on establishing the lower temperature threshold (MinDDT), optimum temperature (OptDDT) and maximum temperature/onset of slowdown of parasite development (MaxDDT) for intra-molluscan *Schistosoma* parasite development.

Gordon et al. (1934) for instance, infected *Bi. pfeifferi* with *S. mansoni* at a range of temperatures from 14 °C to 37 °C, and found that increased temperatures up to 32–33 °C shortened the prepatent period to 15 days, from 31 to 35 days at 20–22 °C. However, a further increase of temperature to 34–35 °C was associated with a slowed development speed. Some of these results were further confirmed by Foster in 1964, and Pflüger in 1980 and 1981 (Foster, 1964; Pflüger, 1980, 1981). Moreover, Pflüger (1980) showed that the development speed peaks at 32–33 °C and starts to slow down at 34–35 °C for *S. mansoni* in *Bi. glabrata*. The effect of temperature on *S. haematobium* development shows the same pattern with shorter prepatent periods at higher temperatures. For *S. haematobium* in *Bu. globosus*, Gordon and colleagues reported that temperatures of 20–22 °C resulted in a prepatent period of 66–68 days, while considerably shorter durations (22–27 days) were observed at higher temperatures (34–35 °C) (Gordon et al., 1934). Pflüger et al. reported that the relationship between *S. haematobium* development speed and temperature was linear between 18 °C and 32 °C in *Bu. truncatus* (Pflüger et al., 1984). With a prepatent period of 106–113 days at 18 °C and 17–20 days at 32 °C, the results show that the overall prepatent period is longer for *S. haematobium* compared to *S. mansoni*. Furthermore, combining the results from Gordon et al. (1934) and Pflüger (1984), their data indicate that the development speed peaks around 32–33 °C for *S. haematobium*.

4.2. Link between thermophysiological limitations and geographical distribution of schistosome species in Africa

To compare the climatic niche space of the two main African schistosome species under current and future climatic conditions, we plotted the summarised, experimentally established thermo-physiological lower and upper thresholds of the individual species of schistosomes against bioclimatic temperature data extracted from georeferenced prevalence points with known endemic transmission of schistosomiasis (Fig. 6). We used the mean temperature of the warmest and coldest quarter (bioclim 10 and bioclim 11, respectively) to represent the maximum and minimum temperatures currently experienced by the schistosome species.

Interestingly, we observe that under current temperature regimes, both species are very close to their upper thermal threshold for parasite development. *S. haematobium*, however, seem to occur in slightly warmer areas, and even somewhat above (according to the 95% ellipse). Since the parasites have quite similar physiological thermal

performance values, the difference in their climatic epidemiology must be strongly related to differences in their intermediate host snails environmental tolerances and preferences.

Indeed, the emerging picture from Fig. 6 is well in accordance with observations that high temperatures may explain the absence of the main *S. mansoni* intermediate host snail species, *Biomphalaria* spp., from coastal East Africa and the consequent absence of *S. mansoni* transmission in the same areas (Sturrock, 1966). Similarly, high mortality of *Bi. pfeifferi* in South Africa have been linked to periods of continuous high temperatures (Appleton, 1977). Other studies have shown that there can be great variability in how well the *Bulinus* intermediate host snails of *S. haematobium* can tolerate temperatures. The optimum temperature for growth and reproduction of *Bu. truncatus* and *Bi. alexandrina* has been found to be similar (at 26–28 °C), whereas both were considerably less heat tolerant than the competing snail species *Helisoma duryi* in laboratory investigations (El-Emam and Madsen, 1982). Likewise, the survival of *Bu. africanus* at constant high temperatures is almost identical to that of *Bi. pfeifferi*, whereas, in contrast, *Bu. globosus* can survive up to four times as long at the same elevated temperatures (Joubert et al., 1986). At lower temperatures, both *Bu. africanus* and *Bu. globosus* can survive longer than *Bi. pfeifferi* (Joubert et al., 1984).

The higher tolerance of *Bulinus* snails to high temperatures, and hence, the occurrence of *S. haematobium* in warmer areas than *S. mansoni*, could also be due to the general higher ability of *Bulinus* snails to aestivate (i.e. survive buried in the soil/mud) (Rubaba et al., 2016), highlighting another key parameter that needs to be taken into account: the behavioural ability of the snails to adapt, thus tolerating heat waves and other climate extremes.

As shown in Fig. 6, it is also evident that schistosomiasis transmission is currently taking place somewhat outside the lower thermo-threshold for parasite development. This is, however, not surprising as both snail survival and parasite development are possible at lower, fluctuating temperatures. For instance, with temperature fluctuations of ± 10 °C, *S. mansoni* can complete its life cycle even at very low (11.5 °C) or very high temperatures (40 °C) (Pflüger, 1981). The mapped temperatures (bioclim 10 and bioclim 11) depict averages over a 3-month period, and hence, do not capture these fluctuations.

The fact that *S. haematobium* under the current climate is already found so close to its thermal maximum (even slightly over), could also explain the result of Schur et al. (2013) that indicates a significant decrease in *S. haematobium* infection risk in Africa from the beginning of the 1990s onwards. The authors also note that in the 1950s and 1970s, higher prevalence of *S. haematobium* compared to *S. mansoni* was found in the Lango region of central-northern Uganda, while recent investigations in the same area only detected few *S. haematobium* cases, and that the underlying reasons for this decline is unresolved.

Also, as suggested by the right pane in Fig. 6, the two main schistosome species in Africa will experience temperatures over their MaxDDT under future global warming scenarios. This indicates that future climatic conditions for schistosomiasis might become less suitable with regard to maximum temperatures over large parts of Africa,

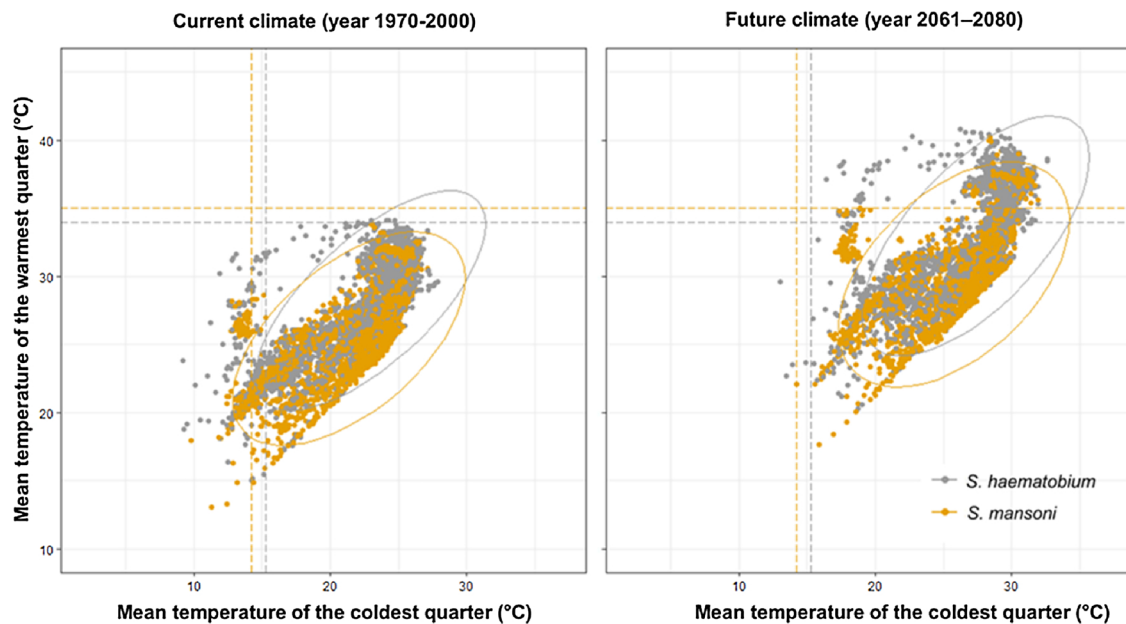


Fig. 6. Climatic (temperature) windows for *Schistosoma mansoni* and *Schistosoma haematobium* on the African continent. The mean temperature (°C) of the warmest quarter and the mean temperature (°C) of the coldest quarter are depicted for each coordinate with parasite presence for *S. mansoni* (orange) and *S. haematobium* (grey). The upper and lower physiological thermal thresholds for parasite development in the intermediate snails host (MDTTmax, horizontal dashed lines; MDTTmin, vertical dashed lines for each species) define the potential maximum thermotolerance range (as described in Table 2). Left: under current climatic conditions; right: under future climatic conditions (prediction for year 2070). Ellipses enclose 95% of the presence data for each parasite species.

particularly for *S. haematobium*. This could indicate that a mean higher impact of climate change on *S. haematobium* compared to *S. mansoni* in Africa. On the other hand, a smaller proportion of schistosomiasis transmission sites will be located in areas with temperatures below the MinDDT, but given the shape of the thermal performance curve (Box 1: note the sharp drop in performance after Topt), the exceedence of the MaxDDT could have a higher impact overall on schistosomiasis transmission.

5. Conclusions and outlook

Scrutinizing more than two decades of research at the climate change-schistosomiasis interface, we note the following: despite a gradual increase in scientific articles that show concern for a potential impact of climate change on schistosomiasis, there are only few original research papers, and even fewer that employ an advanced modelling approach to give a quantitative estimate of the observed or expected impacts. We found that most research efforts focused on the People's Republic of China, despite the fact that schistosomiasis remains a much larger public health problem in Africa. Additionally, Africa is considered one of the most vulnerable continents to climate change and climate variability, which, coupled with a low adaptive capacity to deal with the negative impacts of climate change, further aggravates the situation (Preston et al., 2011; IPCC, 2013).

As such, we found that there is a mismatch between knowledge supply and need, and more emphasis should be directed towards understanding the implications of climate change on schistosomiasis in the most vulnerable regions. We also identified a bias with regards to the schistosome species studied: only few publications pertained to climate change and *S. haematobium* and its intermediate host snails (Fig. 3), and none using predictive modelling, despite the fact that it is precisely this species that currently is emerging in Europe (Boissier et al., 2015). One explanation could be a limited availability of studies on the effect of temperature on the development of various life cycle stages of *S. haematobium*, not least within the broad range of *Bulinus* intermediate host snails. Furthermore, there is little updated and synthesised data on the geographical distribution of *Bulinus* intermediate

host snails in Africa, and close to none in Europe (Kincaid-Smith et al., 2017). This observation represents a considerable gap in our knowledge required to improve predictions of the effect of global warming on future distribution and transmission of urogenital schistosomiasis in particular.

Finally we note that a higher proportion of studies predict a decrease in schistosomiasis risk with climate change in the central and eastern parts of Africa, compared to studies located at higher latitudes, which in part can be explained by *S. mansoni* and *S. haematobium* being near/over their upper thermal threshold for parasite development (Fig. 6). We emphasise that the physiological differences in thermal relationships across snail and schistosome species need to be taken into account in future predictions of their geographical distribution and spread under the effects of global climate change.

An alternative, more holistic approach to the prevailing “single-species” climate change impact modeling approach, would be to fully embrace that all organisms are part of complex social-ecological systems and that the interconnectedness between species need to be accounted for, as recently advocated by the emerging field of ecohealth (Bergquist et al., 2017). The next generation of climate change impact assessment methods should thus ideally take into account the full complexity of schistosomiasis transmission dynamics, including the effects of the broader social-ecological contexts in which transmission occurs.

As a way forward, we suggest a combination and synthesis of statistical-empirical distribution modelling with process-based models of snail lifecycles and parasite development, underpinned by a solid knowledge of snail ecology, be further explored. Yet, a significant challenge to overcome before we can take full advantage of more complex modelling approaches is the scarcity of historical, long-term data-series on schistosomiasis and not least on the geographical distribution of the many species of schistosome intermediate host snails. While the first challenge is currently being dealt with through the construction of open-access databases such as the GNTD database initiative (Hürlimann et al., 2011), the latter is challenged by the cumbersome methods currently available to collect and identify snail species (Kincaid-Smith et al., 2017). Newly developed molecular tools,

such as environmental DNA (eDNA) holds promise to detect both intermediate host snails, parasites and even reservoir hosts at large spatial and temporal scales, which could prove very useful as inputs to climate change-schistosomiasis impact models (Bass et al., 2015).

5.1. Schistosomiasis in a warmer world: risk or opportunity?

The outstanding question then is what the net effect of climate change on schistosomiasis will be. There is little doubt that a changing climate will alter the availability of schistosome parasite-snail niche space, and that this will vary according to the different ecologies of the many different intermediate host snail species of schistosomiasis. While research thus far indicate a mixed picture, with a potentially decreasing availability of climatic niche space, especially for *S. haematobium*, at lower latitudes in Africa, we see that this species has been able to resurface in colder climates, as witnessed by a recent outbreak of urogenital schistosomiasis in southern Europe. The establishment of transmission on Corsica was possible because suitable snail species already existed there, and due to the dispersion of the parasite with the increased movement of people from endemic areas in West Africa (Boissier et al., 2016). In conjunction with an increased window of transmission in which the parasite cercariae may be emitted by the snails as the potential transmission seasons get warmer and longer, this is expected to provide more optimal conditions for the parasite to establish and spread in Europe (Kincaid-Smith et al., 2017).

Opposite to these effects, there could be a “beneficial” role for climate change since suitable areas for snail survival and parasite development, could be lost from large areas in West and Central Africa (Stensgaard et al., 2013). However, this could easily be offset by an increased creation of freshwater sites via dam construction and irrigation schemes, as dependency on irrigated agriculture grow and hydro-power production with the predicted increases in dry spells in many parts of Africa with climate change, which have been known to create environments in which schistosomes and snails flourish and disease prevalence soared (Steinmann et al., 2006; Diakité et al., 2017). Whether or not climate change will work for or against the efforts to control and eventually eliminate schistosomiasis in 2025 thus remains an outstanding, but pressing question (WHO, 2012).

Acknowledgements

ASS and MES are grateful to Knud Højgaard's Fond for supporting the **Research Platform for Disease Ecology, Climate and Health**, and thank the Danish National Research Foundation for its support of the Center for Macroecology, Evolution and Climate (grant no. DNRF96). PV acknowledges financial support from the European Research Council (ERC) for an Advanced ERC grant (no. 323180). We also thank the many collaborators, who continuously contribute with geo-referenced schistosomiasis survey data to the GNTD database.

References

- Appleton, C.C., 1977. Influence of above-optimal constant temperatures on South-African *Biomphalaria pfeifferi* (Krauss) (Mollusca-Planorbidae). *Trans. R. Soc. Trop. Med. Hyg.* 71, 140–143.
- Bass, D., Stentiford, G.D., Littlewood, D.T.J., Hartikainen, H., 2015. Diverse applications of environmental DNA methods in parasitology. *Trends Parasitol.* 31, 499–513.
- Bergquist, R., Brattig, N.W., Chimbari, M.J., Zinsstag, J., Utzinger, J., 2017. Ecohealth research in Africa: where from-where to? *Acta Trop.* 175, 1–8.
- Boissier, J., Mone, H., Mitta, G., Barges, M.D., Molyneux, D., Mas-Coma, S., 2015. Schistosomiasis reaches Europe. *Lancet Infect. Dis.* 15, 757–758.
- Boissier, J., Grech-Angelini, S., Webster, B.L., Allienne, J.F., Huyse, T., Mas-Coma, S., Toulza, E., Barre-Cardi, H., Rollinson, D., Kincaid-Smith, J., Oleaga, A., Galinier, R., Foata, J., Rognon, A., Berry, A., Mouahid, G., Henneron, R., Mone, H., Noel, H., Mitta, G., 2016. Outbreak of urogenital schistosomiasis in Corsica (France): an epidemiological case study. *Lancet Infect. Dis.* 16, 971–979.
- Brown, D.S., 1994. *Freshwater Snails of Africa and Their Medical Importance*, 2nd Edition. Taylor & Francis, London, pp. 609.
- Buckley, L.B., Waaser, S.A., MacLean, H.J., Fox, R., 2011. Does including physiology improve species distribution model predictions of responses to recent climate change? *Ecology* 92, 2214–2221.
- Campbell-Lendrum, D., Manga, L., Bagayoko, M., Sommerfeld, J., 2015. Climate change and vector-borne diseases: what are the implications for public health research and policy? *Philos. Trans. Biol. Sci.* 370.
- Casimiro, E., Calheiros, J., Santos, F.D., Kovats, S., 2006. National assessment of human health effects of climate change in Portugal: approach and key findings. *Environ. Health Perspect.* 114, 1950–1956.
- Chen, M.G., Feng, Z., 1999. Schistosomiasis control in China. *Parasitol. Int.* 48, 11–19.
- Diakité, N.R., Winkler, M.S., Coulibaly, J.T., Guindo-Coulibaly, N., Utzinger, J., N'Goran, E.K., 2017. Dynamics of freshwater snails and *Schistosoma* infection prevalence in schoolchildren during the construction and operation of a multipurpose dam in central Côte d'Ivoire. *Infect. Dis. Poverty* 6, 93.
- Dormann, C.F., Schymanski, S.J., Cabral, J., Chuine, I., Graham, C., Hartig, F., Kearney, M., Morin, X., Romermann, C., Schroder, B., Singer, A., 2012. Correlation and process in species distribution models: bridging a dichotomy. *J. Biogeogr.* 39, 2119–2131.
- El-Emam, M., Madsen, H., 1982. The effect of temperature, darkness, starvation and various food types on growth, survival and reproduction of *Helisoma duryi*, *Biomphalaria alexandrina* and *Bulinus truncatus* (Gastropoda: planorbidae). *Hydrobiologia* 88, 265–275.
- Fordham, D.A., Akcakaya, H.R., Araujo, M.B., Keith, D.A., Brook, B.W., 2013. Tools for integrating range change, extinction risk and climate change information into conservation management. *Ecography* 36, 956–964.
- Foster, R., 1964. Effect of temperature on development of *Schistosoma mansoni* Sambon 1907 in intermediate host. *J. Trop. Med. Hyg.* 67, 289–292.
- Gautret, P., Mockenhaupt, F.P., von Sonnenburg, F., Rothe, C., Libman, M., Van De Winkel, K., Bottieau, E., Grobusch, M.P., Hamer, D.H., Esposito, D.H., Parola, P., Schlagenhauf, P., GeoSentinel Surveillance, 2015. Local and international implications of schistosomiasis acquired in Corsica, France. *Emerg. Infect. Dis.* 21, 1865–1868.
- Gordon, R.M., Davey, T.H., Peaston, H., 1934. The transmission of human bilharziasis in Sierra Leone, with an aclimate changeout of life cycle of the schistosomes concerned, *S. mansoni* and *S. haematobium*. *Ann. Trop. Med. Parasitol.* 28, 323–415.
- Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. *Int. J. Climatol.* 25, 1965–1978.
- Hotez, P.J., Alvarado, M., Basáñez, M.G., Bolliger, I., Bourne, R., Boussinesq, M., Brooker, S.J., Brown, A.S., Buckle, G., Budke, C.M., Carabin, H., Coffeng, L.E., Fevre, E.M., Furst, T., Halasa, Y.A., Jasrasaria, R., Johns, N.E., Keiser, J., King, C.H., Lozano, R., Murdoch, M.E., O'Hanlon, S., Pion, S.D.S., Pullan, R.L., Ramaiah, K.D., Roberts, T., Shepard, D.S., Smith, J.L., Stolk, W.A., Undurraga, E.A., Utzinger, J., Wang, M.R., Murray, C.J.L., Naghavi, M., 2014. The Global Burden of Disease study 2010: interpretation and implications for the neglected tropical diseases. *PLoS Negl. Trop. Dis.* 8, e2865.
- Huey, R.B., Kearney, M.R., Krockenberger, A., Holtum, J.A.M., Jess, M., Williams, S.E., 2012. Predicting organismal vulnerability to climate warming: roles of behaviour, physiology and adaptation. *Philos. Trans. Biol. Sci.* 367, 1665–1679.
- Hürlimann, E., Schur, N., Boutsika, K., Stensgaard, A.S., de Himpsl, M.L., Ziegelbauer, K., Laizer, N., Camenzind, L., Di Pasquale, A., Ekpo, U.F., Simoonga, C., Mushinge, G., Saarnak, C.F.L., Utzinger, J., Kristensen, T.K., Vounatsou, P., 2011. Toward an open-access global database for mapping, control, and surveillance of neglected tropical diseases. *PLoS Negl. Trop. Dis.* 5, e1404.
- IPCC, 2013. *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA.
- John, R., Ezekiel, M., Philbert, C., Andrew, A., 2008. Schistosomiasis transmission at high altitude crater lakes in Western Uganda. *BMC Infect. Dis.* 8, 110.
- Joubert, P.H., Pretorius, S.J., Dekock, K.N., Vaneeden, J.A., 1984. The effect of constant low-temperatures on the survival of *Bulinus africanus* (Krauss), *Bulinus globosus* (Morelet) and *Biomphalaria pfeifferi* (Krauss). *S. Afr. J. Zool.* 19, 314–316.
- Kalinda, C., Chimbari, M., Mukaratirwa, S., 2017. Implications of changing temperatures on the growth, fecundity and survival of intermediate host snails of schistosomiasis: a systematic review. *Int. J. Environ. Res. Public Health* 14 pii: E80.
- Kearney, M., Porter, W., 2009. Mechanistic niche modelling: combining physiological and spatial data to predict species' ranges. *Ecol. Lett.* 12, 334–350.
- Kelly-Hope, L., Thomson, M.C., 2008. Climate and infectious diseases. In: Thomson, M.C., Herrera, R.G., Beniston, M. (Eds.), *Seasonal Forecasts, Climatic Change and Human Health* (Adv Glob Change Res). Springer, Dordrecht.
- Kincaid-Smith, J., Rey, O., Toulza, E., Berry, A., Boissier, J., 2017. Emerging schistosomiasis in Europe: a need to quantify the risks. *Trends Parasitol.* 33, 600–609.
- Lafferty, K.D., 2009. The ecology of climate change and infectious diseases. *Ecology* 90, 888–900.
- Lafferty, K.D., Mordecai, E.A., 2016. The rise and fall of infectious disease in a warmer world. *F1000research* 5https://doi.org/10.12688/f1000research.8766.1. PMID 27610227.
- Malone, J.B., Zukowski, S.H., 1992. Geographic models and control of cattle liver flukes in the Southern USA. *Parasitol. Today* 8, 266–270.
- Malone, J.B., Nieto, P., Tadesse, A., 2006. Biology-based mapping of vector-borne parasites by geographic information systems and remote sensing. *Parassitologia* 48, 77–79.
- Mangal, T.D., Paterson, S., Fenton, A., 2008. Predicting the impact of long-term temperature changes on the epidemiology and control of schistosomiasis: a mechanistic model. *PLoS One* 3, e1438.
- Martens, W.J.M., Jetten, T.H., Rotmans, J., Niessen, L.W., 1995. Climate-change and vector-borne diseases—a global modeling perspective. *Glob. Environ. Change—Hum. Pol. Dimen.* 5, 195–209.
- Martens, W.J.M., Jetten, T.H., Focks, D.A., 1997. Sensitivity of malaria, schistosomiasis

- and dengue to global warming. *Clim. Chang* 35, 145–156.
- Mas-Coma, S., Valero, M.A., Bargues, M.D., 2008. Effects of climate change on animal and zoonotic helminthiasis. *Rev. Sci. Tech. OIE* 27, 443–457.
- Mas-Coma, S., Valero, M.A., Bargues, M.D., 2009. Climate change effects on trematodiasis, with emphasis on zoonotic fascioliasis and schistosomiasis. *Vet. Parasitol.* 163, 264–280.
- McCreesh, N., Booth, M., 2013. Challenges in predicting the effects of climate change on *Schistosoma mansoni* and *Schistosoma haematobium* transmission potential. *Trends Parasitol.* 29, 548–555.
- McCreesh, N., Booth, M., 2014a. The effect of increasing water temperatures on *Schistosoma mansoni* transmission and *Biomphalaria pfeifferi* population dynamics: an agent-based modelling study. *PLoS One* 9 e101462.
- McCreesh, N., Booth, M., 2014b. The effect of simulating different intermediate host snail species on the link between water temperature and schistosomiasis risk. *PLoS One* 9 e87892.
- McCreesh, N., Nikulin, G., Booth, M., 2015. Predicting the effects of climate change on *Schistosoma mansoni* transmission in eastern Africa. *Parasites Vectors* 8, 4.
- McManus, D.P., Dunne, D.W., Sacko, M., Utzinger, J., Vennervald, B.J., Zhou, X.N., 2018. Schistosomiasis. *Nat. Rev. Dis. Primers* 4, 13.
- Pacifici, M., Foden, W.B., Visconti, P., Watson, J.E.M., Butchart, S.H.M., Kovacs, K.M., Scheffers, B.R., Hole, D.G., Martin, T.G., Akcakaya, H.R., Corlett, R.T., Huntley, B., Bickford, D., Carr, J.A., Hoffmann, A.A., Midgley, G.F., Pearce-Kelly, P., Pearson, R.G., Williams, S.E., Willis, S.G., Young, B., Rondinini, C., 2015. Assessing species vulnerability to climate change. *Nat. Clim. Change* 5, 215–225.
- Palasio, R.G.S., Casotti, M.O., Rodrigues, T.C., Menezes, R.M.T., Zanotti-Magalhaes, E.M., Tuan, R., 2015. The current distribution pattern of *Biomphalaria tenagophila* and *Biomphalaria straminea* in the northern and southern regions of the coastal fluvial plain in the state of Sao Paulo. *Biota Neotropica* 15, 3.
- Parmesan, C., 2006. Ecological and evolutionary responses to recent climate change. *Annu. Rev. Ecol. Syst.* 37, 637–669.
- Pedersen, U.B., Midzi, N., Mduluzi, T., Soko, W., Stensgaard, A.S., Vennervald, B.J., Mukaratirwa, S., Kristensen, T.K., 2014a. Modelling spatial distribution of snails transmitting parasitic worms with importance to human and animal health and analysis of distributional changes in relation to climate. *Geospat. Health* 8, 335–343.
- Pedersen, U.B., Stendel, M., Midzi, N., Mduluzi, T., Soko, W., Stensgaard, A.S., Vennervald, B.J., Mukaratirwa, S., Kristensen, T.K., 2014b. Modelling climate change impact on the spatial distribution of fresh water snails hosting trematodes in Zimbabwe. *Parasites Vectors* 7, 536.
- Pedersen, U.B., Karagiannis-Voules, D.A., Midzi, N., Mduluzi, T., Mukaratirwa, S., Fensholt, R., Vennervald, B.J., Kristensen, T.K., Vounatsou, P., Stensgaard, A.S., 2017. Comparison of the spatial patterns of schistosomiasis in Zimbabwe at two points in time, spaced twenty-nine years apart: is climate variability of importance? *Geospat. Health* 12, 59–66.
- Pflüger, W., 1980. Experimental epidemiology of schistosomiasis 1. The prepatent period and cercarial production of *Schistosoma mansoni* in *Biomphalaria* snails at various constant temperatures. *Z. Parasitenkd* 63, 159–169.
- Pflüger, W., 1981. Experimental epidemiology of schistosomiasis 2. Pre-patency of *Schistosoma mansoni* in *Biomphalaria glabrata* at diurnally fluctuating temperatures. *Z. Parasitenkd* 66, 221–229.
- Pflüger, W., Roushdy, M.Z., El Emam, M., 1984. The prepatent period and cercarial production of *Schistosoma haematobium* in *Bulinus truncatus* (Egyptian field strains) at different constant temperatures. *Z. Parasitenkd* 70, 95–103.
- Poulin, R., 2006. Global warming and temperature-mediated increases in cercarial emergence in trematode parasites. *Parasitology* 132, 143–151.
- Preston, B.L., Yuen, E.J., Westaway, R.M., 2011. Putting vulnerability to climate change on the map: a review of approaches, benefits, and risks. *Sustain. Sci.* 6, 177–202.
- Purse, B.V., Golding, N., 2015. Tracking the distribution and impacts of diseases with biological records and distribution modelling. *Biol. J. Linn. Soc.* 115, 664–677.
- Rubaba, O., Chimbari, M.J., Mukaratirwa, S., 2016. The role of snail aestivation in transmission of schistosomiasis in changing climatic conditions. *Afr. J. Aquat. Sci.* 41, 143–150.
- Schur, N., Hürlimann, E., Stensgaard, A.S., Chimfwembe, K., Mushinge, G., Simoonga, C., Kabatereine, N.B., Kristensen, T.K., Utzinger, J., Vounatsou, P., 2013. Spatially explicit *Schistosoma* infection risk in eastern Africa using Bayesian geostatistical modelling. *Acta Trop.* 128, 365–377.
- Sinervo, B., Mendez-de-la-Cruz, F., Miles, D.B., Heulin, B., Bastiaans, E., Villagran-Santa Cruz, M., Lara-Resendiz, R., Martinez-Mendez, N., Calderon-Espinosa, M.L., Meza-Lazaro, R.N., Gadsden, H., Avila, L.J., Morando, M., De la Riva, I.J., Victoriano Sepulveda, P., Rocha, C.F., Ibargüengoytia, N., Aguilar Puntriano, C., Massot, M., Lepetz, V., Oksanen, T.A., Chapple, D.G., Bauer, A.M., Branch, W.R., Clobert, J., Sites Jr., J.W., 2010. Erosion of lizard diversity by climate change and altered thermal niches. *Science* 328, 894–899.
- Stanton, M.C., Adriko, M., Arinaitwe, M., Howell, A., Davies, J., Allison, G., LaCourse, E.J., Muheki, E., Kabatereine, N.B., Stothard, J.R., 2017. Intestinal schistosomiasis in Uganda at high altitude (> 1400 m): malacological and epidemiological surveys on Mount Elgon and in Fort Portal crater lakes reveal extra preventive chemotherapy needs. *Infect. Dis. Poverty* 6, 34.
- Steinmann, P., Keiser, J., Bos, R., Tanner, M., Utzinger, J., 2006. Schistosomiasis and water resources development: systematic review, meta-analysis, and estimates of people at risk. *Lancet Infect. Dis.* 6, 411–425.
- Stensgaard, A.S., Utzinger, J., Vounatsou, P., Hürlimann, E., Schur, N., Saarnak, C.F.L., Simoonga, C., Mubita, P., Kabatereine, N.B., Tchuente, L.A.T., Rahbek, C., Kristensen, T.K., 2013. Large-scale determinants of intestinal schistosomiasis and intermediate host snail distribution across Africa: does climate matter? *Acta Trop.* 128, 378–390.
- Stensgaard, A.S., Booth, M., Nikulin, G., McCreesh, N., 2016. Combining process-based and correlative models improves predictions of climate change effects on *Schistosoma mansoni* transmission in eastern Africa. *Geospat. Health* 11, 406.
- Sturrock, R.F., 1966. The influence of temperature on the biology of *Biomphalaria pfeifferi* (Krauss), an intermediate host of *Schistosoma mansoni*. *Ann. Trop. Med. Parasitol.* 60, 100–105.
- Sunday, J.M., Bates, A.E., Dulvy, N.K., 2012. Thermal tolerance and the global redistribution of animals. *Nat. Clim. Change* 2, 686–690.
- Sunday, J.M., Bates, A.E., Kearney, M.R., Colwell, R.K., Dulvy, N.K., Longino, J.T., Huey, R.B., 2014. Thermal-safety margins and the necessity of thermoregulatory behavior across latitude and elevation. *Proc. Natl. Acad. Sci. U. S. A.* 111, 5610–5615.
- Sutherst, R.W., 2004. Global change and human vulnerability to vector-borne diseases. *Clin. Microbiol. Rev.* 17, 136–173.
- Utzinger, J., N'Goran, E.K., Caffrey, C.R., Keiser, J., 2011. From innovation to application: social-ecological context, diagnostics, drugs and integrated control of schistosomiasis. *Acta Trop.* 120 (Suppl. 1), S121–S137.
- Walther, G.R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J.C., Fromentin, J.M., Hoegh-Guldberg, O., Bairlein, F., 2002. Ecological responses to recent climate change. *Nature* 416, 389–395.
- Wang, Y.J., Rao, Y.H., Wu, X.X., Zhao, H.N., Chen, J., 2015. A method for screening climate change-sensitive infectious diseases. *Int. J. Environ. Res. Public Health* 12, 767–783.
- WHO, 2012. The London Declaration on Neglected Tropical Diseases. (Accessed 05 June 2018). http://www.who.int/neglected_diseases/London_Declaration_NTDs.pdf.
- Yang, G.J., Vounatsou, P., Zhou, X.N., Tanner, M., Utzinger, J., 2005. A potential impact of climate change and water resource development on the transmission of *Schistosoma japonicum* in China. *Parassitologia* 47, 127–134.
- Yang, G.J., Gemperli, A., Vounatsou, P., Tanner, M., Zhou, X.N., Utzinger, J., 2006. A growing degree-days based time-series analysis for prediction of *Schistosoma japonicum* transmission in Jiangsu province, China. *Am. J. Trop. Med. Hyg.* 75, 549–555.
- Zhou, X.N., Guo, J., Wu, X.H., Jiang, Q.W., Zheng, J., Dang, H., Wang, X.H., Xu, J., Zhu, H.Q., Wu, G.L., Li, Y.S., Xu, H.X.J., Chen, G., Wang, T.P., Zhu, Y.C., Qiu, D.C., Dong, X.Q., Zhao, G.M., Zhang, S.J., Zhao, N.Q., Xia, G., Wang, L.Y., Zhang, S.Q., Lin, D.D., Chen, M.G., Hao, Y., 2007. Epidemiology of schistosomiasis in the Peoples' Republic of China, 2004. *Emerg. Infect. Dis.* 13, 1470–1476.
- Zhou, X.N., Yang, G.J., Yang, K., Wang, X.H., Hong, Q.B., Sun, L.P., Malone, J.B., Kristensen, T.K., Bergquist, N.R., Utzinger, J., 2008. Potential impact of climate change on schistosomiasis transmission in China. *Am. J. Trop. Med. Hyg.* 78, 188–194.
- Zhu, G., Fan, J., Peterson, A.T., 2017. *Schistosoma japonicum* transmission risk maps at present and under climate change in mainland China. *PLoS Negl. Trop. Dis.* 11, e0006021.