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Impacts of Climate Change Scenarios on *Fasciola gigantica* Risk in Semi-arid West Africa: A Case Study of Sokoto State, Nigeria

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Authors' contributions

This work was carried out in collaboration amongst all authors. Author IH collected the data, analyzed and wrote the manuscript. Authors IH, HB and JK took part in the design, interpreted of the results and corrected the manuscript. All authors read and approved the final version of the manuscript.

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ABSTRACT

Aims: *Fascioliasis* is a parasitic and zoonotic liver disease that reduces the health and productivity of infected cattle and sheep. In recent years, an observed increase in the prevalence of the disease in Western Africa has been attributed to the changes in regional climatic conditions. This study aims to employ climate predictions to predict future seasonal infection risk in Sokoto State, Nigeria and provide a basis for targeted active disease monitoring to inform the need for control measures.
Place and Duration of Study: Department of Geography, School of Science and Engineering, University of Leicester, between November 2014 and October 2018.
Methodology: This study employs the Ollerenshaw index which is commonly used and was modified by Yilma and Malone (1999) to be more suitable for forecasting annual disease risk for *Fasciola hepatica* and *Fasciola gigantica*. Relationships of the annual *F. gigantica* infection risk between historic climate data from WorldClim for 1970-2000 and future climate scenarios from

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HADGEM2-ES based on the IPCC greenhouse gas emission scenarios RCP2.6 and RCP8.5 from 2050 to 2070 are analysed based on the observed relationships between disease prevalence and climatic conditions in the region.

Results: This study reports on the first analysis of the future seasonal infection risk and shows that seasonal infection risk is expected to spread across Sokoto State from a small patch of outbreaks observed in recent years to larger regions under future climate scenarios. Furthermore, the southern part of the study region exhibits the greatest risk of outbreaks due to its higher rainfall compared to other provinces of Nigeria. This pattern is consistent with the prevalence record obtained during field work in the region in 2016.

Conclusion: This study provides a basis upon which active disease monitoring can be targeted on highlighted areas where control measures need to be put in place.

Keywords: Fascioliasis; Western Africa; Ollerenshaw index; HADGEM2-ES; IPCC; RCP.

1. INTRODUCTION

Fascioliasis is plaguing various parts of the world and is regarded as one of the most widespread animal diseases globally [1]. It is a fatal disease that reduces the health and productivity of infected cattle and sheep [2,3]. Besides, public health effects due to fascioliasis constitute substantial economic losses that run into millions of dollars in different parts of the world [4-6].

In Nigeria, the prevalence of fascioliasis has been reported from all ecological zones: North-west; [7,8], North-east [9], South-east [10], South-west; [11] and North-central [12]. The disease was first detected in 1939 in Northern Nigeria impacting the mortality of goats as reported by Burke [7]. Despite the period of over seventy years since the first incidence report and the economic aspect of the losses due to fascioliasis in Nigeria, only a few species-specific distribution models have been developed to guide the control efforts against *F. gigantica* infections.

The essential climate variables that affect the populations of both the fascioliasis parasite and its intermediate host, a snail species, at each stage of development are air temperature, rainfall and potential evapotranspiration [13]. Hence, it is important to understand the role of these climate variables in the transmission of *F. gigantica* in order to understand how changes in climate are likely to affect fascioliasis risk [6]. According to Dinnik and Dinnik [14], temperature within the range of of 24°C-26°C supports efficient growth of miracidia, which develops from *F. gigantica* eggs in faeces, while temperatures exceeding 43°C can lead to mortality of the eggs. Temperatures above 16°C accelerate the growth of *F. gigantica* larvae in the intermediate host. If the infection of the snail with *F. gigantica* lasts for 46-50 days, then the shedding of cercariae commences within a temperature range of 25°C-27°C. In the free-living stage of the parasite after ejection from the snail [15], metacercariae emerge, a new form of encysted cercariae that remain viable under an optimum temperature of 26°C and suitably wet soil moisture conditions. Rainfall and evapotranspiration play an important role in influencing the suitability of habitats for snails as the intermediate host of *F. gigantica* [13].

Given the understanding of the influence of climate on the lifecycle of *F. gigantica*, short-term climate models have been developed to forecast the incidence of fascioliasis in different parts of the world. According to [16] and [17], the forecasts are very valuable in simulating and predicting the disease outbreaks and seasonal patterns of fascioliasis transmission for the design of effective control methods. In England and Wales, the fascioliasis forecasting system was initiated by Ollerenshaw and Rowlands [18] using the climate data obtained from weather stations across the island of Anglesey as well as fascioliasis prevalence data for ten years (1948-1957). The values of potential evapotranspiration were computed using the Penman equation. The equation to compute the risk index is $Mt = n (R-PE+5)$, where n indicates the days with rain, R indicates rainfall and PE is potential evapotranspiration. The limitations of this fascioliasis forecasting index include the demand for various datasets in the calculation of potential evapotranspiration and lack of distinguishing the specific requirements of the two species of fascioliasis [19]. In addition, the index did not use growing degree days (GDD), which indicates the number of days with tolerable limits of temperature for the parasite's survival. However, the application of the climate-based forecast continued in different parts of the world with some modifications to accommodate other relevant variables that contribute to the outbreaks of fascioliasis including growing degree days (GDD) and the Thornthwaite water budget [19,20]. This index created by Ollerenshaw is currently the basis for the prediction of fasciolosis in the short-term for farmers and other stakeholders in the UK by the National Animal Disease Information Service [21].

Fasciola gigantica is a tropical species that is endemic in different parts of Africa including Kenya, Malawi, Tanzania, Zambia, Zimbabwe, Mali, East Africa, Egypt, Botswana, Nigeria and some parts of Asia including Indonesia, Cambodia, Philippines, Iran, India, Pakistan, Burma, Nepal [22,23]. In Africa, the application of the fascioliasis forecasting system was first modified and adapted recently by Malone et al. [5] in East Africa where both species of fascioliasis thrived. Although the incidence shows that fascioliasis occurs in other regions especially West Africa, [24], no known study has applied climate-based forecasting models to predict future *F. gigantica* risk under scenarios of climate change.

All current disease forecasting systems including short-term and long-term predictions of fascioliasis risk have been developed for temperate biomes [6,18]. However, predictions could be useful in determining spatio-temporal variability in seasonal risk due to fascioliasis in many more countries of the world especially in West Africa where such studies are rare. Also, these models can assist farming communities in formulating effective disease control strategies. The availability of HADGEM2-ES simulations of fine-scale climate parameters provides the means for making long-term future projections under different scenarios of climate change.

This study reports on the first analysis of relationships between historic climate data from WorldClim for 1970-2000 (referred to as ‘current’) [25,26] and HADGEM2-ES future climate model simulations with the fasciolasis disease prevalence, in combination with the modified Yilma and Malone index that evolved from Ollerenshaw and Rowlands [18]. The aim is to simulate how changes in climate are likely to alter the *F. gigantica* risk in the future up to 2070 under conditions of two extreme ends of the IPCC representative concentration pathways (i.e. RCP2.6 and RCP8.5). Risk maps based on current climate (1970-2000) and future climate under RCP2.6 (2050 and 2070) and RCP8.5 (2050 and 2070) were created to analyse the likely influence that changing climatic conditions exert on the risk of *F. gigantica* in Sokoto State, Nigeria.

2. MATERIALS AND METHODS

World climate (WorldClim) database version 2 (http://www.worldclim.org) was used as the source of the current climate data that include monthly averages of temperature (maximum, minimum and mean) and precipitation. It contains monthly climate data from weather stations from all parts of the world between 1970 and 2000 [25,26]. The database provides climate surfaces for the entire land surface of the world except for Antarctica based on thin-plate smoothing spline interpolation [27]. According to Hijmanns et al. [26], interpolation was used to reduce the original coarse resolution of approximately 111 km to a finer resolution of 1 km. The climate surfaces of the WorldClim database were later validated using the records of the global weather stations targeted at minimising the uncertainty and errors related to interpolation.

2.1 Future Climate

For simulating future *F. gigantica* risk, this study utilised future climate model simulations from the Hadley Centre Global Environmental Model version 2- Earth System (HADGEM2-ES). The model consists of atmospheric and oceanic components [28]. HADGEM2-ES2 considers the climate change feedbacks with the global biogeochemical systems which can lead to both negative and positive feedbacks [29-32].

HADGEM2-ES model simulations of future climate were used in the fifth Coupled Model Intercomparison Project (CMIP5) and in the Intergovernmental Panel on Climate Change (IPCC) fifth Assessment Report (AR5). The performance of the model regarding the prediction of annual cycles of temperature and precipitation was significantly correlated to ground-based weather station data over different parts of Africa and particularly Nigeria [33].

This study utilised monthly average climate data for two 20-year time periods: 2041-2060 and 2061-2080, centred on the years 2050 and 2070 respectively from the Representative Concentration Pathways (RCPs) RCP8.5 (similar to IPCC A1F1 and B1 SRES) and RCP2.6 (below IPCC SRES B1) [33]. The climate parameters used include monthly mean temperature (°C), maximum, minimum and mean temperature (°C) and total monthly precipitation (mm/month). The climate data were downscaled to 1 km spatial resolution

2.2 Forecast Parameterisation

This study adapted a fascioliasis forecast risk index system modified from Ollerenshaw and Rowlands [18] and applied in East Africa by Malone et al. [5]. The index referred to as a water-based system [34] was based on thermal and soil moisture requirements of *F. gigantica*. It was calculated using an empirical equation that incorporated the use of GDD, rainfall and evapotranspiration in determining the level of risk for fascioliasis transmission:

$$Index\ 1 = (GDD \times Z) \times \frac{Rain - PET}{25}, If Rain - PET > 0, \quad (1)$$

Where, Z indicates the number of days with excess rain and 25 is a correction factor to reduce the surplus water to 2.5 cm.

$$Index\ 2 = GDD \times Daysinmonth, if (R - PET \times 0.8) > 0 \quad (2)$$

Where, GDD = Growing degree days, R= Rainfall (mm/month), PET= Potential evapotranspiration (mm/month).

In equation 1, subtracting the value of potential evapotranspiration multiplied by 0.8 (PET$\times$ 0.8) from rainfall if greater than zero indicates availability of soil moisture storage in the top 2.5 cm of soil based on a water budget model [35,36,37].

GDD assumed that the developmental stages of a living organism occur within some favourable limits of temperature. At the extremes of these limits, the survival of the organism would be threatened [38]. GDD was computed as the monthly mean temperature minus the base development temperature [35] for the *F. gigantica* which is 16°C [14]. The mean monthly temperature was calculated by obtaining the average of the maximum and minimum temperature as follows [35]:

$$\mathrm{MnT} = \frac{\mathrm{Tmax} + \mathrm{Tmin}}{2} \quad (3)$$

$$\mathrm{GDD} = (\mathrm{MnT} - 16^{O}\mathrm{C}) \times \text{ days in month} \quad (4)$$

For the computation of potential evapotranspiration, the study used the Hargreaves equation (equation 5) where Ra is extra-terrestrial radiation (MJ m^{-2} day^{-1}) [39], T_{max} indicates the mean monthly values of the maximum daily air temperature (°C) while T_{min} is the minimum mean monthly values of daily air temperature (°C), λ is the latent heat of vaporisation and T_a is the average monthly air temperature [40].

$$PE = 0.0023(T_{max} - T_{min})^{0.5}(T_a + 17.8)^{\frac{Ra}{\lambda}} \quad (5)$$

Here, we calculated the fascioliasis forecast index using equation 2 for each grid box and imported the results into a Geographic Information System (GIS). The interpretation of the index indicates that up to 600=no risk, 601-1,500=low risk; 1500-3000=moderate and >3000 high risk.

2.3 Study Design

For each of the 23 provinces in Sokoto State, a monthly *F. gigantica* climate-based forecast risk index was computed using the constructed monthly climate forecast model based on the knowledge of the environmental influences on the life cycle of fascioliasis. These provinces constitute the four agricultural zones in Sokoto State as shown in Fig. 1.

2.3.1 *Fasciola gigantica* prevalence data

F. gigantica prevalence data were collected in a field survey from samples of slaughtered cattle carried out from July to August 2016 in 10 provinces of Sokoto State in north-western Nigeria (Fig. 1). In each of these provinces, a total of 30 cattle slaughtered at their respective abattoirs were randomly selected for post-mortem examination. A sedimentation technique was applied by this study as adopted by MAFF [41], Bunza et al. [8], and Magaji et al. [42] at Usmanu Danfodio Veterinary Teaching Hospital Parasitology Laboratory to count *F. gigantica* eggs per gram (EPG) of faeces of each sampled cattle slaughtered.

2.3.2 Spatial analysis

ArcMap 10.3 was used for the generation of fine-scale risk maps of the current and future fascioliasis forecast risk index. This was made at the scale of the 23 provinces (Table 1) that constitute the study area.

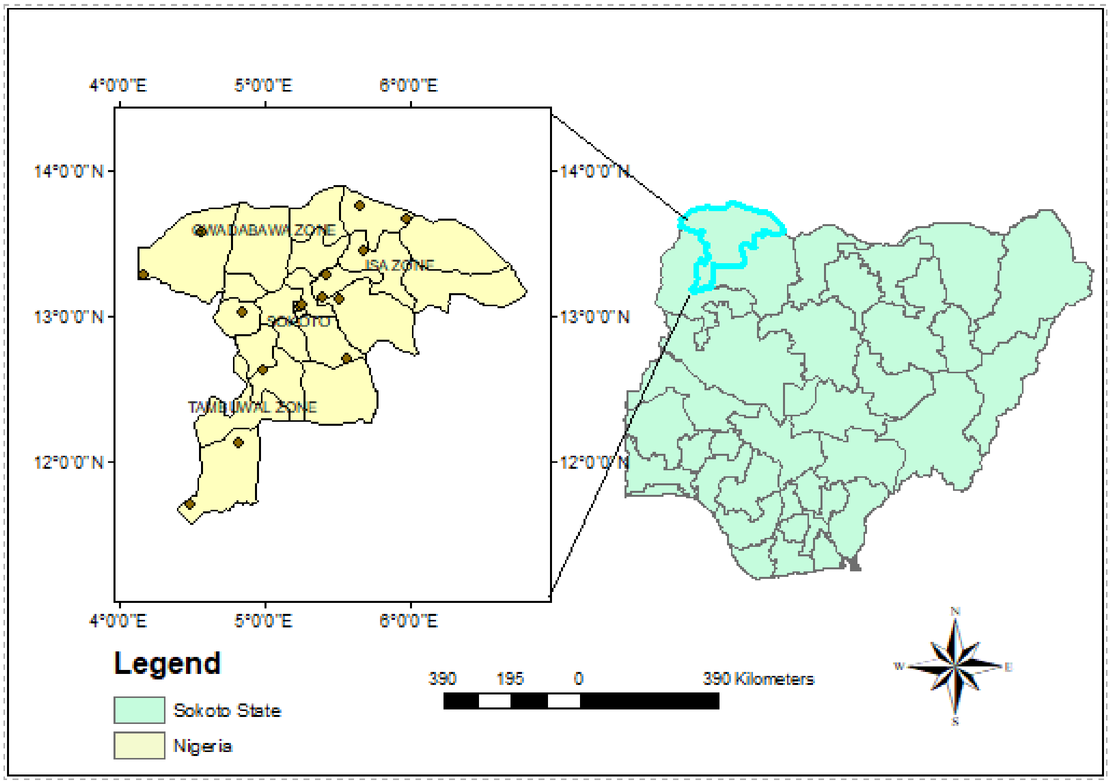

Fig. 1. Location map of Sokoto State in Nigeria showing the four agricultural zones

Table 1. Area, average temperature and mean altitude of the 23 provinces that constitute the four agricultural zones of Sokoto State, Nigeria

Agricultural zone	Province	Area (km^2)	Mean temperature (°C)	Altitude (m)
Gwadabawa	Binji	557	33	238
	Gada	1314	32	300
	Gudu	3463	31	279
	Gwadabawa	989	28	278
	Illela	1244	31	277
	Silame	787	32	248
	Tangaza	2470	30	268
Isa	Goronyo	1703	31	300
	Isa	2161	30	322
	Rabah	2431	32	279
	Sabon Birni	2357	31	334
	Wurno	683	30	300
Sokoto	Bodinga	562	30	289
	DangeShuni	1208	31	311
	Kware	553	32	268
	Sokoto N	51	31	289
	Tureta	2381	30	300
	Wamakko	695	31	268
Tambuwal zone	Kebbe	2609	30	300
	Shagari	1329	30	300
	Tambuwal	1712	30	289
	Yabo	787	31	279

3. RESULTS AND DISCUSSION

3.1 Comparing Current and Future Risk

Forecast indices based on current climate conditions indicate that the highest risk areas were located in the Sokoto and Tambuwal zones (Fig. 2). Similarly, in the year 2050, the forecast indices indicate similar areas of high risk areas under RCP2.6 (Fig. 2A) and RCP8.5 (Fig. 2B). The main difference is that in RCP2.6 the risk areas are spread across more provinces in the Isa zone than in the Gwadabawa zone. Under RCP8.5, both the Isa and Gwadabawa zones show similar extents of high-risk areas. The Tambuwal and Sokoto zones maintain their status as higher risk zones in the year 2070, based on RCP2.6 (Fig. 2C) and RCP8.5 (Fig. 2D). These two RCPs show almost similar risk pattern with Isa having more risk areas than the Gwadabawa zone.

3.2 Monthly Forecast Indices across All the Provinces

The seasonal pattern of transmission of *F. gigantica* in the study area is shown using long-term current climate data (Table 1), future RCP2.6 for 2050 (Table 2), RCP8.5 for 2050 (Table 3), RCP2.6 for 2070 (Table 4) and RCP8.5 for 2070 (Table 5). The shedding period of cercariae from June to September is evident in most of the provinces in Sokoto State with a clear distinction between dry and wet seasons. Similarly, average current climate data show a shedding period of only two to three months (July to September). The future projections of cercariae shedding show differences between RCP2.6 (Table 3) and RCP8.5 (Table 4) for 2050, which were three to four months (June to September) and two to three months (July to September) respectively. The trend in the cercariae shedding is similar for RCP2.6 (Table 5) and RCP8.5 (Table 6) for 2070, when the shedding commences in June to September for only the Sokoto and Tambuwal zones while in the Gwadabawa and Isa zones, the prediction of risk was only from July to September.

3.3 Discussion

The first report of fascioliasis dates back to 1939 in northern Nigeria according to Danbirni et al. [7] and since then only a few studies have been carried out to investigate its spatio-temporal variability across the country as a function of climatic variables. Even in northern Nigeria from where the fascioliasis originated and spread to other parts of the country due to an abundant population of animals [43] no species-specific distribution modelling study has been established to assess the dynamics of *F. gigantica* transmission. However, in the UK the fascioliasis forecast index created by Ollerenshaw and Rowlands [18] is still in use today as a basis for predicting the outbreak of fascioliasis to farmers with a reasonable level of reliability [6].

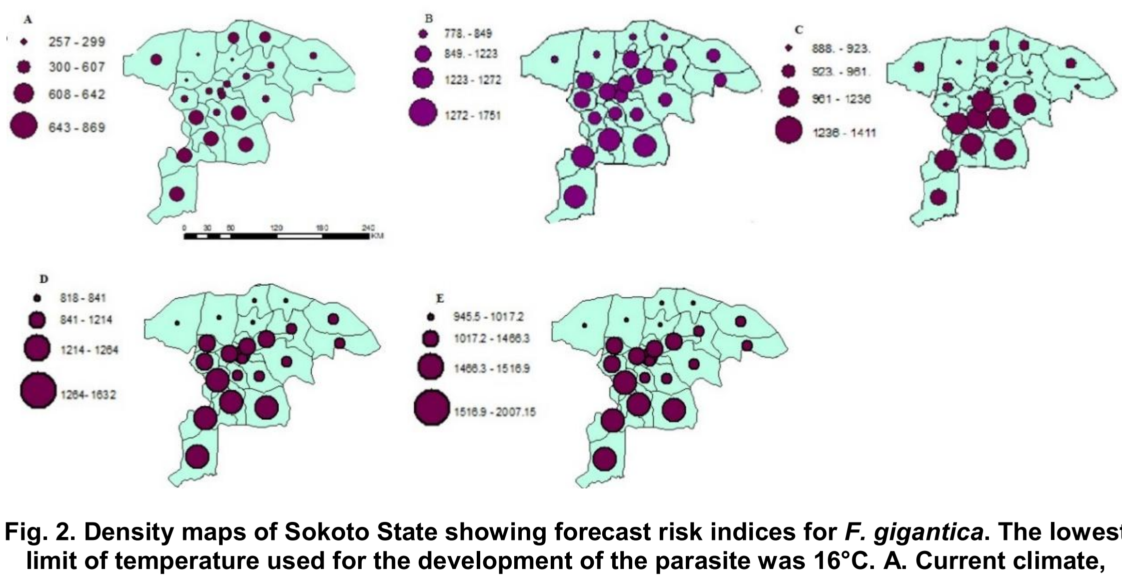

Fig. 2. Density maps of Sokoto State showing forecast risk indices for *F. gigantica*. The lowest limit of temperature used for the development of the parasite was 16°C. A. Current climate, B. RCP2.6 2050, C. RCP8.5 2050, D. RCP2.6 2070, E. RCP8.5 2070

Table 2. Monthly forecast and the patterns of cercariae shedding for *F. gigantica* in the four agricultural zones of Sokoto State based on the monthly average of past climate (1970-2000). The risk index values were more concentrated in August across the provinces in the state. In September only Dange Shuni and Tureta had higher rainfall average than potential evapotranspiration. Also, the period of cercariael shedding was 2 to 3 months. The cumulative risk was also at the medium stage

AG Zone	Province	J	F	M	A	M	J	J	A	S	O	N	D	Annual forecast
GWD	Binji	0	0	0	0	0	0	0	276	0	0	0	0	276
	Gada	0	0	0	0	0	0	333	290	0	0	0	0	623
	Gudu	0	0	0	0	0	0	335	284	0	0	0	0	619
	Gwadabawa	0	0	0	0	0	0	0	288	0	0	0	0	288
	Illela	0	0	0	0	0	0	344	298	0	0	0	0	642
	Silame	0	0	0	0	0	0	319	276	0	0	0	0	595
	Tangaza	0	0	0	0	0	0	0	299	0	0	0	0	299
ISA	Goronyo	0	0	0	0	0	0	319	281	0	0	0	0	600
	Isa	0	0	0	0	0	0	0	257	0	0	0	0	257
	Rabah	0	0	0	0	0	0	328	273	0	0	0	0	602
	Sabon B	0	0	0	0	0	0	312	270	0	0	0	0	582
	Wurno	0	0	0	0	0	0	319	278	0	0	0	0	597
SOK	Bodinga	0	0	0	0	0	0	303	260	0	0	0	0	563
	Dange S	0	0	0	0	0	0	299	257	287	0	0	0	843
	Kware	0	0	0	0	0	0	325	278	0	0	0	0	603
	Sokoto N	0	0	0	0	0	0	321	284	0	0	0	0	605
	Sokoto S	0	0	0	0	0	0	331	276	0	0	0	0	607
	Tureta	0	0	0	0	0	0	282	242	273	0	0	0	697
	Wamakko	0	0	0	0	0	0	329	274	0	0	0	0	604
TAMB	Kebbe	0	0	0	0	0	0	264	231	252	0	0	0	746
	Shagari	0	0	0	0	0	0	289	246	277	0	0	0	814
	Tambuwal	0	0	0	0	0	0	287	243	275	0	0	0	805
	Yabo	0	0	0	0	0	0	308	265	295	0	0	0	869

In Africa, the only known application of the index was in East Africa where it was modified to suit both species of fascioliasis by Malone et al. [5]. To date, as noted by Fox [44] no method of modelling fascioliasis risk ‘supersedes’ that of the Ollerenshaw index due to the paucity of accurate and reliable prevalence records. Ollerenshaw [45] admitted that insufficient data on fascioliasis prevalence was the most significant impediment in the formulation of climate-sensitive forecasting systems. This study presents the first application of the modification of the index by Ollerenshaw and Rowlands [18] for *F. gigantica* prevalence risk as a monthly forecast risk index for Sokoto State in the semi-arid ecological zone of West Africa.

Over the period from 1970-2000 to 2070, the *Fasciola gigantica* risk is expected to disperse across Sokoto State from a small distribution in the former years to the present levels where larger portions of the study area are witnessing outbreaks. The southern part of the study area presents the riskiest area due to more abundant rainfall than in other provinces. This pattern is consistent with the results of field studies where the southern provinces (Tambuwal zone) showed a higher *Fasciola gigantica* prevalence (Fig. 3). Moreover, in Nigeria and all parts of West Africa, especially the Sahel, rainfall decreases from the southern coast to the continental interior [46,47] which reflects the pattern of rainfall in Sokoto State. Rainfall in sufficient quantity always aids the transmission of fascioliasis in all the localities in Sokoto State since the temperature is always above the 16°C threshold and hence not a restrictive factor. It is clear that a high risk occurs in areas with higher rainfall and soil moisture, which reflects the pattern in any area around the globe where fascioliasis thrives [6,24,34,37]. Conversely, all areas that have higher temperatures coupled with low rainfall, especially around the northern tip of Sokoto State bordering on Niger, are likely to experience a moisture deficit that threatens the survival of *F. gigantica*. The only caution to be exercised when referring to these areas as free of risk is a possibility of the presence of lakes and water bodies, since temperature is never the sole limiting factor.

This study suggests that in Sokoto State, temperature and soil moisture are crucial in influencing the seasonal patterns of *F. gigantica* infections due to their effects on the life cycle of the parasite and activity of the intermediate host, the snail. The risk model presented here uses temperature and rainfall as environmental drivers. The spread of the infection in various parts of the state requires knowledge of the effects of other risk determinants that are related to herd, farmer status and pasture management. Kantzoura et al. [48] reported that such risk factors for fasciola infection in sheep and goats when combined with environmental variables in modelling using GIS could provide 'possibilities for regionally adapted control measures' [49,50]. Similarly, drinking water sources such as ponds, streams and lakes were established in Ethiopia as risk factors, especially during the dry season when animals congregate there, aiding transmission of the infection [51]. Knowledge of risk factors complements the use of climate-based models in designing appropriate methods for controlling the transmission of fascioliasis infection in the study area and other parts of northern Nigeria. This study did not utilise the existence of water bodies in building the model, which is a limitation according to a Yilma and Malone [37] as these are a very significant factors in determining the transmission of fascioliasis infection especially in the Sahel.

The annual forecast risk values for the year 2070 under RCPs 2.6 and 8.5 were higher than in the year 2050 based on the preceding RCPs and the current climate. This finding suggests that the risk of fascioliasis in the study area is increasing. Similar likely future trends have been established in most European countries including the UK [6,52]. These findings are in agreement with the annual differentiation in the intensity of transmission across areas of fascioliasis prevalence in response to climate in the UK by Ollerenshaw and Rowlands [18].

Table 3. Monthly forecast and the patterns of cercariae shedding for *F. gigantica* in the four agricultural zones of Sokoto State based on RCP 2.6 2050. In comparison with the past climate average, the shedding period increased by one month. Binji, Gwadabawa, Tangaza and Isa recorded higher total monthly average ranfall than potential evapotranspiration and hence posed high fascioliasis risk based on this future projection under RCP 2.6. The provinces with four months cercariae shedding period were Tureta, Kebbe, Shagari and Tambuwal

AG Zone	Province	J	F	M	A	M	J	J	A	S	O	N	D	Annual forecast
GWD	Binji	0	0	0	0	0	0	450	383	440	0	0	0	1271
	Gada	0	0	0	0	0	0	0	386	441	0	0	0	826
	Gudu	0	0	0	0	0	0	0	361	417	0	0	0	778
	Gwadabawa	0	0	0	0	0	0	449	381	438	0	0	0	1269
	Illela	0	0	0	0	0	0	0	395	455	0	0	0	850
	Silame	0	0	0	0	0	0	437	375	432	0	0	0	1244
	Tangaza	0	0	0	0	0	0	0	392	451	0	0	0	845
ISA	Goronyo	0	0	0	0	0	0	430	366	420	0	0	0	1217
	Isa	0	0	0	0	0	0	423	361	417	0	0	0	1201
	Rabah	0	0	0	0	0	0	428	361	425	0	0	0	1214
	Sabon B	0	0	0	0	0	0	432	369	422	0	0	0	1223
	Wurno	0	0	0	0	0	0	437	369	429	0	0	0	1235
SOK	Bodinga	0	0	0	0	0	0	426	363	416	0	0	0	1205
	Dange S	0	0	0	0	0	0	420	355	410	0	0	0	1185
	Kware	0	0	0	0	0	0	442	372	437	0	0	0	1250
	Sokoto N	0	0	0	0	0	0	439	369	429	0	0	0	1237
	Sokoto S	0	0	0	0	0	0	434	364	423	0	0	0	1221
	Tureta	0	0	0	0	0	467	403	346	396	0	0	0	1611
	Wamakko	0	0	0	0	0	0	440	367	429	0	0	0	1237
TAMB	Kebbe	0	0	0	0	0	514	440	367	429	0	0	0	1751
	Shagari	0	0	0	0	0	481	409	347	399	0	0	0	1636
	Tambuwal	0	0	0	0	0	469	403	344	392	0	0	0	1608
	Yabo	0	0	0	0	0	0	420	360	413	0	0	0	1192

The present study therefore suggests regional-scale annual forecasts can be made for north-western or the entire northern Nigeria using contemporary or current data from satellite or ground-based stations to run a monthly climate-based fascioliasis forecasts system.

The future risk maps show that Sokoto State and other parts of the north-west ecological zone of Nigeria are expected to experience a more severe fascioliasis prevalence within the next 30 to 50 years, i.e. 2050-2070 (Fig. 4). The predicted rainfall analysed in this study was derived from greenhouse gas emission scenarios used for future climate change by the HadGEM2-ES model based on the RCP2.6 and RCP8.5 scenarios for the years 2050 and 2070. The reference model has a sound predictive ability for rainfall and temperature as they correlated highly with ground-based observations in the north, east and west of Nigeria [33]. The relationship was statistically significant particularly in the northern stations. The prediction of future fascioliasis risk based on the HadGEM2-es model should be treated with some caution as there are uncertainties regarding future emissions of greenhouse gases upon which the model is based. Validation of predictions is needed from time to time to keep pace with a changing climate. As reported by Fox [44], correlative models based on long-term projections need continuous 'validation' and 'refinement' to confirm the status of relationships under new, different conditions of climate. However, this study provides evidence of a real risk of an increase in the prevalence of fascioliasis in Sokoto State.

Diffenbaugh and Giorgi [53] described north-western Nigeria as a 'hotspot' of climate change which is expected to be impacted negatively due to the vulnerable population [54]. Climate change has many impacts, which includes promoting disease prevalence and spread [55], affecting Nigeria's agriculture and public health sector [56]. Also, global change in climate enhances resistance to anthelmintic drugs [57] and affects the physiology of the hosts of infection [58].

Table 4. Monthly forecast and the patterns of cercariae shedding for *F. gigantica* in the four agricultural zones of Sokoto State based on RCP 8.5 2050. The fascioliasis risk index under this future projection was highest in August and September. Also,the shedding period was slightly shorter across all the provinces except for Rabah, Bodinga, Dange Shuni, Sokoto north, Tureta and all the provinces in Tambuwal zone

AG Zone	Province	J	F	M	A	M	J	J	A	S	O	N	D	Annual forecast
GWD	Binji	0	0	0	0	0	0	0	440	497	0	0	0	936
	Gada	0	0	0	0	0	0	0	442	498	0	0	0	938
	Gudu	0	0	0	0	0	0	0	446	506	0	0	0	951
	Gwadabawa	0	0	0	0	0	0	0	437	495	0	0	0	932
	Illela	0	0	0	0	0	0	0	0	451	0	0	0	961
	Silame	0	0	0	0	0	0	0	434	489	0	0	0	923
	Tangaza	0	0	0	0	0	0	0	420	471	0	0	0	891
ISA	Goronyo	0	0	0	0	0	0	0	423	478	0	0	0	901
	Isa	0	0	0	0	0	0	0	415	473	0	0	0	887
	Rabah	0	0	0	0	0	0	485	417	480	0	0	0	1382
	Sabon B	0	0	0	0	0	0	0	442	498	0	0	0	939
	Wurno	0	0	0	0	0	0	0	425	486	0	0	0	910
SOK	Bodinga	0	0	0	0	0	0	483	420	471	0	0	0	1374
	Dange S	0	0	0	0	0	0	476	414	467	0	0	0	1356
	Kware	0	0	0	0	0	0	0	430	492	0	0	0	922
	Sokoto N	0	0	0	0	0	0	0	426	488	0	0	0	913
	Sokoto S	0	0	0	0	0	0	493	422	482	0	0	0	1396
	Tureta	0	0	0	0	0	0	459	405	453	0	0	0	1316
	Wamakko	0	0	0	0	0	0	0	427	488	0	0	0	914
TAMB	Kebbe	0	0	0	0	0	0	434	389	413	0	0	0	1294
	Shagari	0	0	0	0	0	0	467	406	455	0	0	0	1327
	Tambuwal	0	0	0	0	0	0	498	426	488	0	0	0	1411
	Yabo	0	0	0	0	0	0	479	418	468	0	0	0	1365

Table 5. Monthly forecast and the patterns of cercariae shedding for *F. gigantica* in the four agricultural zones of Sokoto State based on RCP 2.6 2070. The future projections based on this long-term average revealed fascioliasis infection risk occurring in three to four months. That shows an increase in total monthly average rainfall than potential evapotranspiration in June, July, August and September. The cumulative index was at the medium stage

AG Zone	Province	J	F	M	A	M	J	J	A	S	O	N	D	Annual forecast
GWD	Binji	0	0	0	0	0	0	449	381	434	0	0	0	1264
	Gada	0	0	0	0	0	0	0	383	435	0	0	0	818
	Gudu	0	0	0	0	0	0	0	487	443	0	0	0	830
	Gwadabawa	0	0	0	0	0	0	450	380	434	0	0	0	1263
	Illela	0	0	0	0	0	0	0	394	447	0	0	0	841
	Silame	0	0	0	0	0	0	437	374	428	0	0	0	1238
	Tangaza	0	0	0	0	0	0	0	391	446	0	0	0	836
ISA	Goronyo	0	0	0	0	0	0	427	364	416	0	0	0	1208
	Isa	0	0	0	0	0	0	423	359	411	0	0	0	1194
	Rabah	0	0	0	0	0	0	426	360	419	0	0	0	1204
	Sabon B	0	0	0	0	0	0	429	367	416	0	0	0	1264
	Wurno	0	0	0	0	0	0	0	436	367	0	0	0	1227
SOK	Bodinga	0	0	0	0	0	0	427	361	411	0	0	0	1197
	Dange S	0	0	0	0	0	0	418	355	405	0	0	0	1178
	Kware	0	0	0	0	0	0	440	372	431	0	0	0	1243
	Sokoto N	0	0	0	0	0	0	437	367	425	0	0	0	1228
	Sokoto S	0	0	0	0	0	0	433	363	419	0	0	0	1214
	Tureta	0	0	0	0	0	471	402	344	392	0	0	0	1608
	Wamakko	0	0	0	0	0	0	440	367	425	0	0	0	1232
TAMB	Kebbe	0	0	0	0	0	435	377	332	356	0	0	0	1498
	Shagari	0	0	0	0	0	485	407	346	395	0	0	0	1632
	Tambuwal	0	0	0	0	0	471	403	344	389	0	0	0	1606
	Yabo	0	0	0	0	0	0	422	358	408	0	0	0	1188

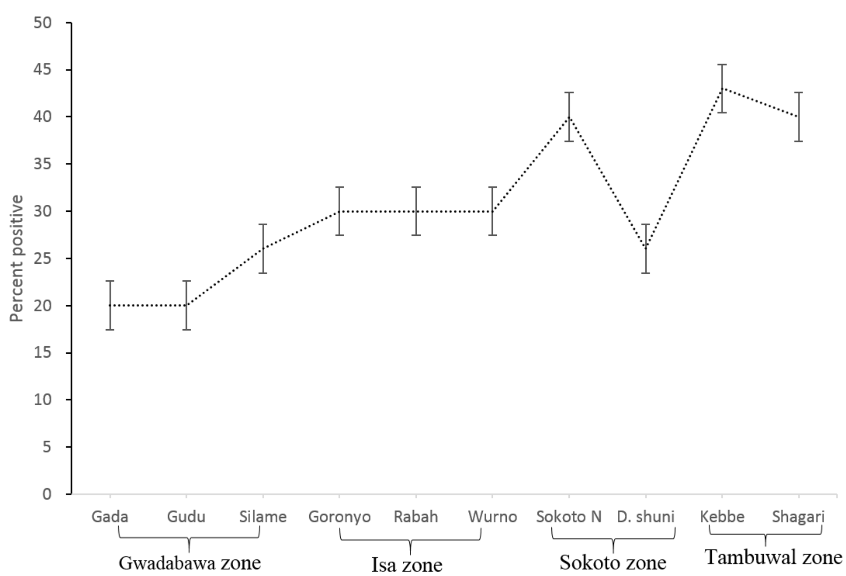

Fig. 3. Percent positive *F. gigantica* infections per zone as established during fieldwork. Infections were highest in the Tambuwal zone followed by the Sokoto zone. This pattern reflects the differences in the amount of rainfall received by each zone which greatly determines infection risk due to the availability of moisture for the survival of fascioliasis and its intermediate host snails

Table 6. Monthly forecast and the patterns of cercariae shedding for *F. gigantica* in the four agricultural zones of Sokoto State based on RCP 8.5 2070. The shedding period under this RCP of climate change was mainly three months across all the provinces except for Tambuwal zone and Tureta. That indicates the spread of fascioliasis risk across all the localities in the future

AG Zone	Province	J	F	M	A	M	J	J	A	S	O	N	D	Annual forecast
GWD	Binji	0	0	0	0	0	0	530	459	528	0	0	0	1516
	Gada	0	0	0	0	0	0	0	460	432	0	0	0	993
	Gudu	0	0	0	0	0	0	0	465	540	0	0	0	1005
	Gwadabawa	0	0	0	0	0	0	0	435	510	0	0	0	946
	Illela	0	0	0	0	0	0	0	471	546	0	0	0	1017
	Silame	0	0	0	0	0	0	518	451	521	0	0	0	1481
	Tangaza	0	0	0	0	0	0	0	468	543	0	0	0	1011
ISA	Goronyo	0	0	0	0	0	0	510	440	512	0	0	0	1462
	Isa	0	0	0	0	0	0	502	434	504	0	0	0	1440
	Rabah	0	0	0	0	0	0	505	436	510	0	0	0	1450
	Sabon B	0	0	0	0	0	0	512	443	511	0	0	0	1466
	Wurno	0	0	0	0	0	0	516	443	518	0	0	0	1476
SOK	Bodinga	0	0	0	0	0	0	504	437	501	0	0	0	1442
	Dange S	0	0	0	0	0	0	496	431	497	0	0	0	1423
	Kware	0	0	0	0	0	0	522	448	525	0	0	0	1495
	Sokoto N	0	0	0	0	0	0	518	443	517	0	0	0	1478
	Sokoto S	0	0	0	0	0	0	513	439	512	0	0	0	1463
	Tureta	0	0	0	0	0	538	479	422	480	0	0	0	1919
	Wamakko	0	0	0	0	0	0	519	443	518	0	0	0	1480
TAMB	Kebbe	0	0	0	0	0	500	452	406	435	0	0	0	1793
	Shagari	0	0	0	0	0	553	485	423	481	0	0	0	1943
	Tambuwal	0	0	0	0	0	538	481	422	474	0	0	0	1914
	Yabo	0	0	0	0	0	576	499	436	497	0	0	0	2007

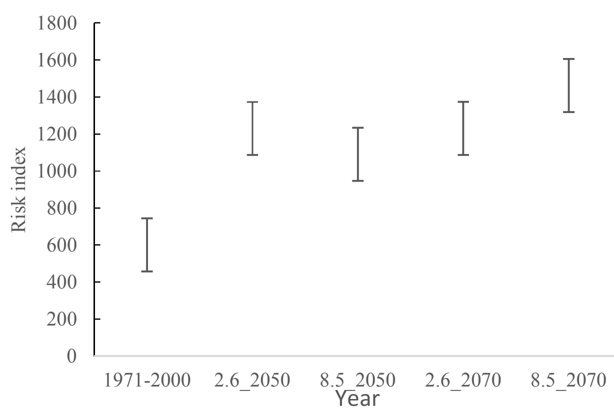

Fig. 4. Comparison of current and future *Fascioliasis gigantica* prevalence risk for different historic (current) and future climate data (RCP2.6 and RCP8.5) for 2050 and 2070. The risk increases from current climate (1970-2000) towards the future, reaching a peak in the high greenhouse gas emission scenario RCP8.5 in 2070. This situation demands that appropriate control measures should be taken against the prevalence of *F. gigantica* in Sokoto state

A gap exists regarding the scales at which the actual changes in the disease transmission occurs and the grid scale of spatio-temporal climate modelling, which limits climate-based forecasts as being rather indicative. However, the risk maps developed here reflect the effects of the variability in changing climate on the spread of fascioliasis infections, thereby indicating the role of climate in influencing the disease occurrence.

This study further suggests that the appropriate timing for prevention of fascioliasis is November to January, the period immediately after the rainy season, and the curative period is February to May before the beginning of the raining season. During the latter period, it is recommended to take drugs that are effective against the young and old liver flukes.

4. CONCLUSION

i. A fascioliasis forecast index based on GDD and the water budget (GDD-WB) using monthly climate data can be applied in Nigeria. Due to the relevance of these models they were adapted and applied in various parts of the world, and the results of such studies are published (UK, Colombia, USA, East Africa in Ethiopia and southern Brazil).
ii. The results suggest that there is spatial variation in *F. gigantica* risk in Sokoto State and northern Nigeria with the risk extending to more locations due to changes in climate under both a high- and a low-emission RCP scenario in 2050 and 2070.
iii. The results further suggest that temporal variation occurs in terms of transmission intensity in Sokoto State and northern Nigeria that provides justification for the establishment of annual *F. gigantica* forecast to inform the livestock farmers of climatic years that would result in high risk due to the possibility of wet grazing areas that would require year-round treatment during the rainy season.
iv. The appropriate time for the treatment of herds by adulticidal fluke drugs that this study suggests is February to May in northern Nigeria when the transmission is not high due to soil moisture deficit. This is the period during which drugs are more effective in stopping the development of flukes to bile duct stages.
v. The spatio-temporal variability in expected disease prevalence found in this study indicates areas where human and capital resources should be targeted for effective monitoring. The data obtained from such monitoring can enhance our understanding of the likely impacts of changes in climate on *F. gigantica* prevalence and information can be derived that can assist in designing appropriate adaptive measures.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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