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RESEARCH

Impact of climate change and variability on the occurrence and distribution of *Trypanosoma* vectors in The Gambia

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Abstract
Extreme weather events can lead to infectious disease outbreaks, especially those spread by hematophagous flies, and The Gambia is particularly vulnerable to climate change. To the best of our knowledge, no one has ever documented the relationship between climate variability and change and the distribution of the hematophagous flies belonging to the families Glossinidae, Tabanidae, and Stomoxyinae. This paper aims to study the association of temperature and humidity on the distribution of the above species and their families in The Gambia in the recent past and to provide predictions of species abundance and occurrence in the future. A line transect survey was carried out in all the administrative regions of The Gambia to study the prevalence of the flies. Generalized additive models were used to analyze the relationships between the distribution of the insects and their families and the variability in climate conditions in the recent past and in three different future periods. Regarding the recent past, our results show that temperature has significantly impacted the presence of Glossinidae and Tabanidae species, with maximum temperature being the most important factor. Relative humidity was also statistically significantly associated with Tabanidae species. None of the climate variables was found to be associated with the *Tabanus par* and *Tabanus sufis*. Minimum temperature and relative humidity were statistically significantly associated with *Glossina morsitan submorsitan*, while maximum temperature was statistically significantly associated with *Atylotus agrestis* and *Stomoxys calcitrans*. Only relative humidity was statistically significantly associated with the *Glossina palpalis gambiense*. As for the future projections, the results show that rising temperatures impacted the distribution of *Tabanus* species, *Glossina* species, and *Stomoxys calcitrans* in The Gambia. The distribution of *Trypanosoma* vectors in The Gambia is mostly influenced by maximum temperature. The research's conclusions gave climate and public health policymakers crucial information to take into account.

Keywords GAM · Temperature · Climate change · Vector-borne diseases · *Atylotus agrestis* · Glossinidae · The Gambia

Abbreviations

CO_2	Carbon dioxide
AAT	Animal African trypanosomiasis
HAT	Human African trypanosomiasis
GAMs	Generalized additive models
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	5Th Re-Analysis
RCM	Regional Climate Simulations
CORDEX	Coordinated Regional Climate Downscaling Experiment
BJL	Banjul
KMC	Kanifing Municipal Council
WCR	West Coast Region
LRR	Lower River Region
NBR	North Bank Region
CRR-N	Central River Region North
CRRS	Central River Region South
URR	Upper River Region
CDS	Climate Data Store
C3S	Copernicus Climate Change Service
RCP	Representative Concentration Pathway
GCV	Generalized cross-validation

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Introduction

Climate change projections show a rising trend in temperature throughout the twenty-first century unless carbon emissions are fundamentally reduced from today's level (Nnko et al. 2021). Global warming of 1.5 °C and 2 °C will be surpassed during the twenty-first century except for profound reductions in CO_2 and other greenhouse gas emissions in the coming decades (IPCC 2021). The Gambia is one of the countries that are highly vulnerable to the impacts of climate change and variability (Hadida et al. 2022). Given how ectotherm vectors, such as mosquitoes and other flies, have thrived and adapted to certain environments through evolution, these changes can potentially cause species habitat modifications and alterations in vector abundance (Nnko et al. 2021). Climate change could affect the occurrence and transmission of vector-borne diseases of veterinary and public health concern (Black and Mansfield 2016; Hadida et al. 2022; IPCC 2021). Historical and recent impacts of climate change on species distributions and suitability can be supported by evidence across human vector or non-human vector insect species (Rocklöv and Dubrow 2020; Nnko et al. 2021).

Hematophagous flies belonging to the families Glossinidae, Tabanidae, and Stomoxyinae transmit parasites including *Trypanosoma*, *Leishmania*, *Setaria digitate*, *Anaplasma marginale*, equine infectious anemia virus, influenza virus, *Bacillus anthracis*, and *Brucella* species (Baldacchino et al. 2017; Keita et al. 2020).

Stomoxys calcitrans is a significant economic pest of cattle. They are blood-sucking flies that attack domestic and wild animals and sometimes humans (Wall and Shearer 1997). These insects are capable of transmitting trypanosomiasis, equine infectious anemia, African swine fever, West Nile, and Rift Valley fever, among others (Baldacchino et al. 2017).

Atylotus agrestis, as well as *Tabanus par*, *Tabanus sufis*, and *Tabanus taeniatus*, is a member of the Tabanidae family, which has a global distribution and can be found on every continent except Antarctica. While their family's diversity is greatest in the tropics, they are seasonally present in a wide range of landscapes, latitudes, and altitudes (Foil and Hogsette 1994).

The Glossinidae species, including *Glossina morsitans submorsitans* and *Glossina palpalis gambiensis*, are only found in Africa, in a distribution that stretches between 14° North and 29° South of the Equator (Krafsur 2009). Approximately 10 million km^2, limited to sub-Saharan Africa, *Glossina morsitans submorsitans* and *Glossina palpalis gambiensis* are the main vectors of animal African trypanosomiasis (AAT) and human African trypanosomiasis (HAT) in The Gambia, and they were mainly found in the dry, canopied savannah woodland and riverine vegetation, respectively (Rawling et al. 1993; Kargbo and Kuye 2020). Despite the fact that *Glossina* species are capable of transmitting trypanosomes, *Stomoxys calcitrans* and *Atylotus agrestis* are known to transmit trypanosomiasis mechanically and a variety of other diseases. Kargbo et al. (2021) showed the incidence of trypanosome infection to be higher in The Gambia between October and December.

Generalized additive models (GAMs) are an often-used technique to assess statistical association and make predictions, in which non-linearity can be easily incorporated using penalized splines (Aljoumani et al. 2022). Many studies have been carried out to comprehend the relationship and connections between environmental variables and the presence of different species in different locations to predict habitat distributions or study the role of environmental drivers (Antunez et al. 2017; Nguyen et al. 2019; Adams et al. 2020; Song et al. 2023). To the best of our knowledge, no one has ever documented the relationship between climate variability and change and the distribution of Glossinidae species, *Stomoxys calcitrans*, and *Atylotus agrestis* in The Gambia. The primary goal of this study is to investigate (i) how climate variables influence the occurrence of Glossinidae, *Stomoxys calcitrans*, and *Atylotus agrestis* and the occurrence of their families in The Gambia and (ii) to evaluate the impact of changes in temperature on the distribution of *Glossina* specie, *Atylotus agrestis*, and *Stomoxys calcitrans* specie in The Gambia using (a) the interpolated European Centre for Medium-Range Weather Forecasts (ECMWF) 5th Re-Analysis (ERA5) dataset for the recent past from 2012 to 2021 and (b) two Regional Climate Simulations (RCM) performed in the context of the Coordinated Regional Climate Downscaling Experiment (CORDEX) Africa for the future periods of 2021–2040, 2041–2060, and 2061–2080.

Materials and method

Study area

The Gambia is surrounded by Senegal on the east, north, and south and the Atlantic Ocean on the west coast. It is the smallest sub-Saharan country located on the west coast of Africa (Fig. 1). It has a tropical savannah vegetation with a short, rainy season that begins in July and ends in September and a long dry season that extends from October to June (Pinchbeck et al. 2008). Its annual rainfall ranges from 850 to 1200 mm, and average temperatures range from 18 to 33 °C. Relative humidity is about 68% along the coast and 41% inland during the dry season and generally over 70% throughout the country during the wet season (MOA 2003). The mean temperature nationwide is usually 25 °C (Kargbo and Kuye 2020). The meteorological data was obtained from

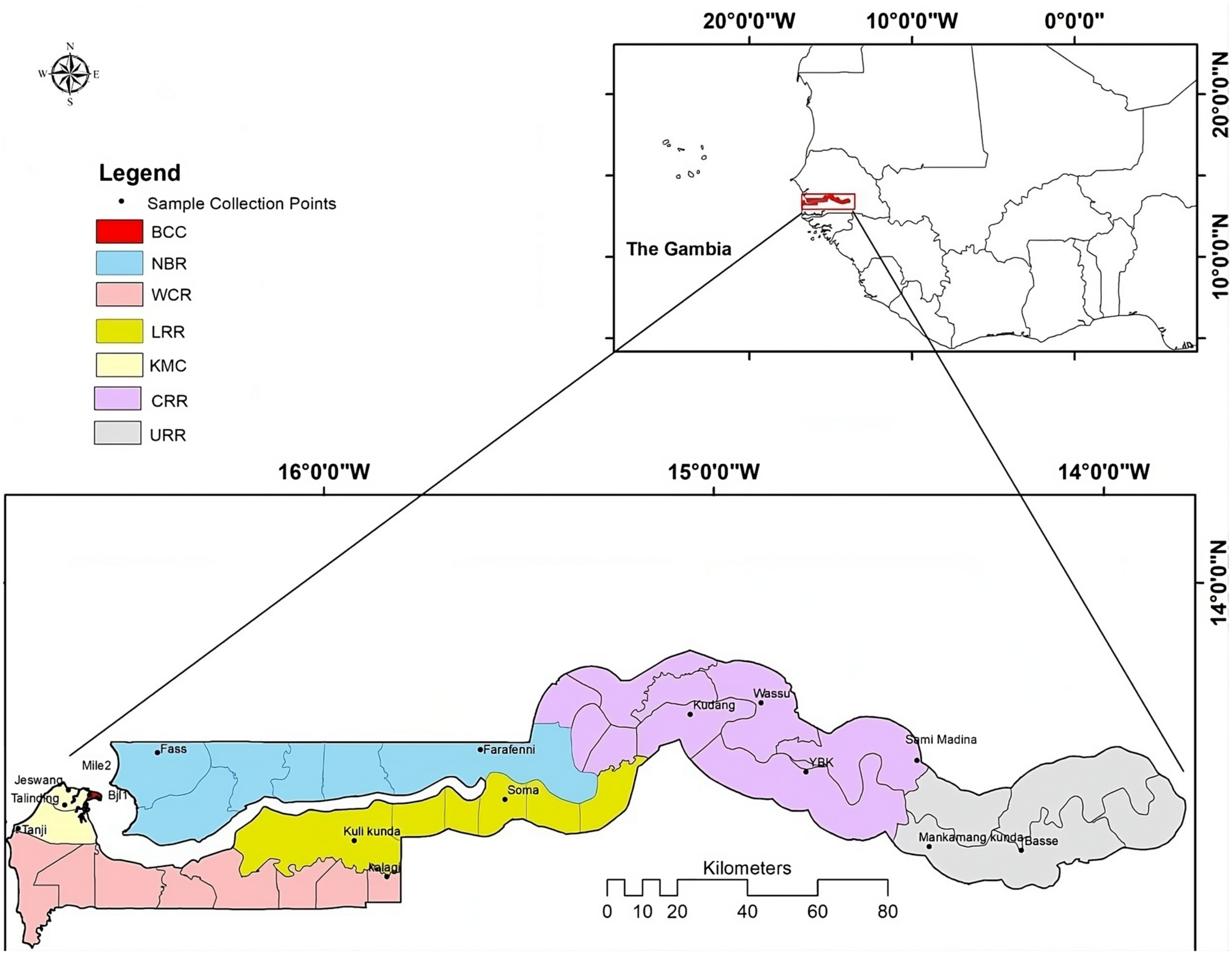

Fig. 1 Location of The Gambia in West Africa showing the points where traps were set for the entomology data collection

the ground weather stations closest to the points where traps have been set for the entomology data collection: in Banjul City Council (Mile two and Banjul), Kanifing Municipal Council (Jeswang and Abuko), West Coast Region (Tanji and Kalagi), Lower River Region (Kulikunda and Soma), North Bank Region (Fass and Farfenni), Central River Region North (Wassu and Sami mandina), Central River Region South (YBK and Kudang), and Upper River Region (Mankamarang kunda and Basse) (Fig. 1).

Entomology survey

Three different types of traps, namely the biconical, Vavoua, and NGU, were baited with four-month-old cattle urine and then set from 6:00 a.m. to 6:00 p.m. in each of the sample collection points indicated in Fig. 1. Seasonal abundance and trap efficiency in catching the flies in The Gambia have already been shown (Kargbo et al. 2021). The traps were deployed for four seasons, specifically from the 1st to the 15th of each month during the Late Rainy season (October 2020), Early Dry season (December 2020), Late Dry season (April 2021), and Early Rainy season (July 2021), across all eight administrative regions of The Gambia (Kargbo et al. 2021).

Environmental data

Minimum and maximum temperature, as well as relative humidity data, were collected from all the meteorological stations near the entomological collection site (Table 1) for four seasons, including the late rainy season (October 2020), early dry season (December 2020), late dry season (April 2021), and early rainy season (July 2021). The actual distance between all meteorological stations and the sites where traps were set to catch ranged between 20 and 30 km. The meteorological stations are located in Jenoi (LRR), Janjanbureh (CRRS), Kuntaur (CRRN), Sapu (CRRS), Basse (URR), Sibanor (WCR), Kaur

Table 1 Models used in this study

Domain	Global climate model	Regional climate model	Experiment	Horizontal resolution	Temporal resolution	Reference
Africa	MPI-M-MPI-ESM-LR (Germany)	CLMcom-KIT-CCLM5-0–15	RCP8.5	0.22 × 0.22	Daily mean from 2021 to 2040, 2041 to 2060 and 2061–2080	Diatta et al. (2021)
	CCCma-CanESM2 (Canada)	CCCma-CanRCM4	RCP4.5			

(NBR), and KMC (Yundum; appendix 1). Additionally, 2-m hourly data for air temperature and relative humidity for the years 2012 to 2021 were retrieved from the ERA5 dataset (Hersbach et al. 2020), to evaluate the influence of temperature and relative humidity on the distribution of *Glossina* species (tsetse flies), *Stomoxys calcitrans*, *Tabanus par*, *Tabanus sufis*, *Tabanus taeniatus*, and *Atylotus agrestis* in The Gambia in the recent past.

The ERA5 is the latest generation of ECMWF global atmospheric reanalysis, covering the period from 1959 onwards (Hersbach et al. 2020). It combines model data with measurements from satellites and in situ instruments and provides hourly estimates of a large number of atmospheric, land, and oceanic climate variables. The data cover the earth on a 30-km grid and resolve the atmosphere using 137 levels from the surface up to a height of 80 km. ERA5 data are available on the Copernicus Climate Change Service (C3S) Climate Data Store (CDS; https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview) on a regular latitude–longitude grid at 0.25° × 0.25° horizontal resolution. The mean temperature values for each month have been computed based on the hourly estimates. Additionally, RCM simulations performed in the context of CORDEX-Africa, available at 0.22° (~ 25 km) horizontal resolution, have been used. Simulated daily mean maximum temperature for the months October, December, April, and July and for the future periods 2021–2040, 2041–2060, and 2061–2080 under the two Representative Concentration Pathway (RCP), 4.5 (RCP4.5) and 8.5 (RCP8.5), are extracted from the RCM CCCma-CanRCM4 (hereafter intermediate-emission scenario model) and the RCM CLMcom-KIT-CCLM5-0–15 (hereafter high-emission scenario model), respectively, to assess the impact of climate change on the occurrence of *Glossina* sp., *Tabanus* spp., and *Stomoxys calcitrans* specie (Table 1) and the abundance of their families. CORDEX-Africa simulations were retrieved from the Climate Data Store (https://cds.climate.copernicus.eu/cdsapp#!/dataset/projections-cordex-domains-single-levels?tab=overview) and have been accessed on the 20th of August, 2022.

Data analysis

We estimated the probability of detection of species and analyzed their presence-absence data by trap type. We also assessed the abundance of "family" species by trap type at the seasonal, regional, and landscape levels. Generalized additive models (GAMs) were used to model the impact of temperature and relative humidity on the occurrence of *Stomoxys calcitrans*, Glossinidae species, and Tabanidae and the abundance of their families in The Gambia. This model offers a middle ground between simple models, such as the linear regression model, and more complex machine learning models, such as neural networks (Aljoumani et al. 2022). They can be fitted to complex, non-linear relationships and produce good predictions (Aljoumani et al. 2022). GAMs have high elasticity because the functional patterns of the covariates can be either linear or non-linear (Hastie and Tibshirani 1986).

We wrapped the independent variables, such as temperature (maximum and minimum) and relative humidity, while the different fly species and the occurrence of their families served as the dependent variables, using the smooth function. More specifically, species occurrence (presence-absence data) and the abundance of their families were fitted using an over-dispersed Poisson distribution regression model using smoothing splines with 4 degrees of freedom for maximum and minimum temperature and relative humidity. The type of trap was included as a fixed factor. As for the model assessment, the minimized generalized cross-validation (GCV) score is applied. GAMs were performed in R software v.4.0.5 as explained by Hastie and Tibshirani (1986). After careful consideration of the theory and examination of the data using the exploratory regression method, one model with significant covariates presented itself as most suitable for predicting the locations of the flies. The feasibility of the modeled environmental suitability based on remotely sensed data was validated with reference to on-site observations after the model was created. Based on the model, spatial maps of predicted abundance were constructed to assess how temperature affects *Stomoxys calcitrans*, tsetse flies, and *Tabanus* species for the recent past (2012–2021) and for three different future periods (2021–2040, 2041–2060, 2061–2080) in The Gambia.

Results

Analysis of trap types

Figure 2 shows the detection probability of species by trap type. As can be seen, the biconical traps were more efficient in catching *Tabanus taeniatus* and *Tabanus sufis* than Vavoua and NGU traps (Fig. 2). The most abundant species caught was *Atylotus agrestis* (35%), followed by *Glossina morsitan submorsitan* (25%) and *Glossina palpalis gambiensis* and *Stoxomys calcitrans* (15–20%; Fig. 2). All other species accounted for less than 5% of the total catch (Fig. 2). The same catch order of all species was maintained among the three trap types (Fig. 2). Figure 3 shows the abundance sums of different species by season and trap type. *Glossinidae* species show peak abundance in the late dry to early rainy season (April–July) for the biconical and NGU traps, while they show equal abundance in all seasons for the Vavoua traps (Fig. 3). All three trap types show peak abundance of Tabanidae and Stomoxyinae species in the late rainy season (October), except in the NGU trap where Tabanidae peaks in the early dry season (December; Fig. 3). Figure 4 shows the abundance sums of different species by region and trap type. The *Glossinidae* and *Tabanidae* species were most abundant in the Lower and Central River Region (LRR, CRRN, CRRS) in all types of traps, probably reflecting the favorable environmental conditions for these species (Fig. 4). The highest abundance of *Stomoxyinae* species was recorded in Kanifing Municipal Council (KMC) and North Bank Region (NBR) in biconical and NGU traps (Fig. 4). Finally, the landscape does not seem to affect trap efficiency (not shown). Although the biconical trap captured the highest numbers of species, our model showed no significant effect of the trap type on family abundance and species occurrence (absence/presence), indicating that the effect of trap type does not affect their distribution.

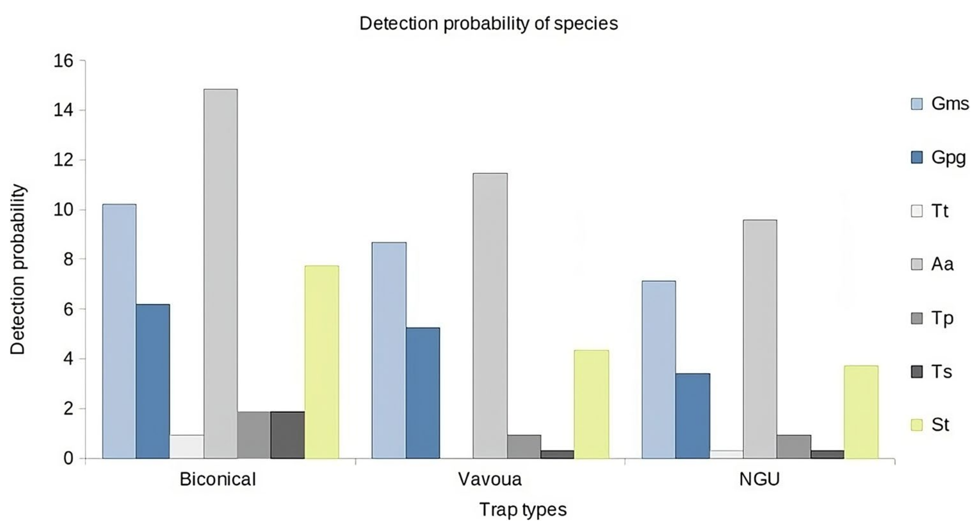

Fig. 2 Detection probability of Glossina (blue shades), Tabanus (gray shades), and Stomoxys (yellow) species by trap type (biconical, Vavoua, and NGU)

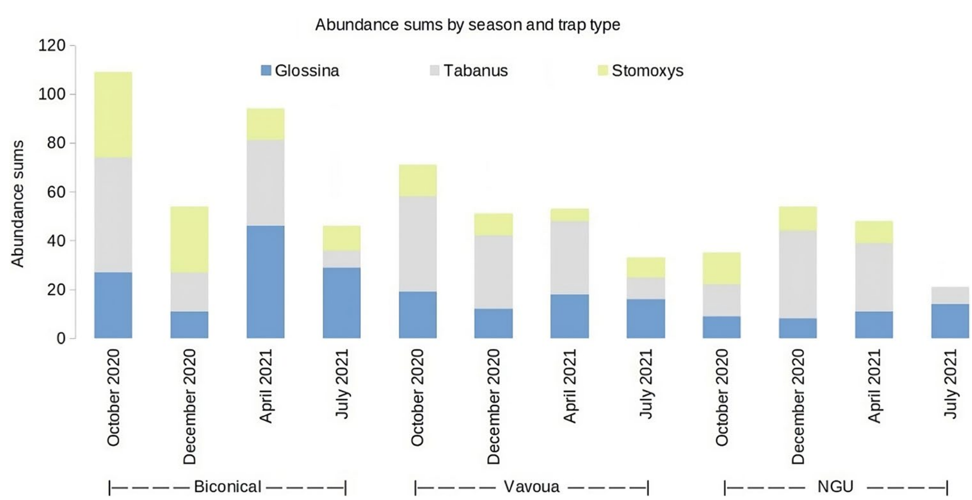

Fig. 3 Abundance sums of species: Glossina (blue), Tabanus (gray), and Stomoxys (yellow) by season: October (late rainy season), December (early dry season), April (late dry season), and July (early rainy season) and trap type (biconical, Vavoua, and NGU)

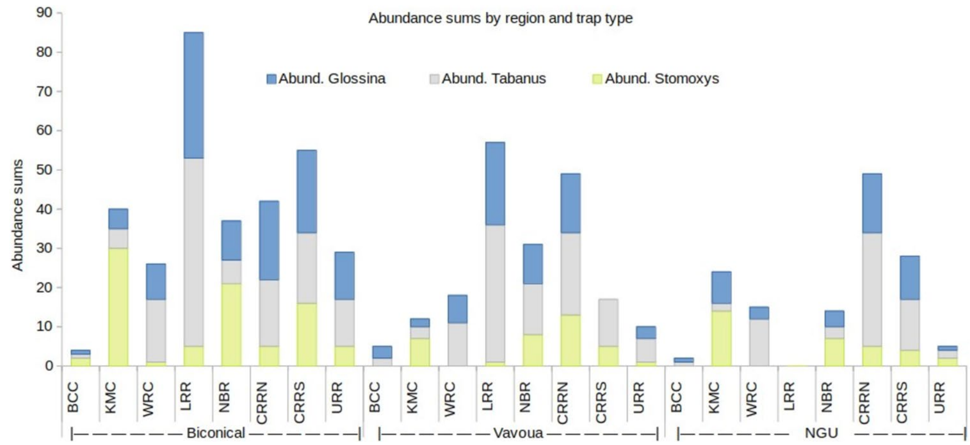

Fig. 4 Abundance sums of species: Glossina (blue shades), Tabanus (gray shades), and Stomoxys (yellow) by region: BCC (Banjul), KMC (Kanifing Municipal Council), WRC (West coast Region), LRR (Lower River Region), NBR (North Bank Region), CRRN (Central River Region North), CRRS (Central River Region South), and URR (Upper River Region) and by trap type (biconical, Vavoua, and NGU)

Impact of climate variability (temperature and relative humidity) and type of trap on Glossina species, Tabanus species, and Stomoxys calcitrans

Table 2 shows the GAM results for the impact of maximum temperature, minimum temperature, and relative humidity on *Glossina* species, *Atylotus agrestis*, *Tabanus par*, *Tabanus sufis*, *Tabanus taeniatus*, and *Stomoxys calcitrans* caught in the country. Our findings show that *Glossina morsitan submorsitan* is affected by both minimum temperature and relative humidity, but *Atylotus agrestis* and *Stomoxys calcitrans* were only significantly impacted by maximum temperature. The investigated climate variables had no discernible impact on *Tabanus par* and *Tabanus sufis*.

Impact of changing temperature on the distribution and abundance of Glossina species, Tabanus species, and Stomoxys calcitrans in The Gambia from 2012 to 2021

We once more examined how temperature has affected the occurrence of *Stomoxys calcitrans*, tsetse flies, and *Tabanus species* in The Gambia during the last 10 years. Figure 5 shows the spatial prediction maps of occurrence probability of *Stomoxys calcitrans* (Fig. 5a), *Glossina morsitans submorsitans* (Fig. 5b), *Glossina palpalis gambiense* (Fig. 5c), *Atylotus agrestis* (Fig. 5d), *Tabanus par* (Fig. 6a), *Tabanus sufis* (Fig. 6b), and *Tabanus taeniatus* (Fig. 6c) based on ERA5 reanalysis for the recent past (2012–2021). The

Table 2 Impact of trap type and climate variability on *Glossina, Tabanus and Stomoxys* species

Vector type	Types of trap			Maximum temperature	Minimum temperature	Relative temperature	Model assessment
	Biconical	**Vavoua**	**NGU**				
Glossina morsitan submorsitan	Es = 0.045 $P \geq 0.001$*	Es = − 0.076 $P = 0.633$	Es = − 0.077 $P = 0.947$	Es = 0.093 $P = 1.856$	Es = 1.000 $P = 0.005$*	Es = 1.00 $P = 0.002$*	GCV = 0.581 DE = 8.67%
Glossina palpalis gambiensis	Es = − 1.119 $P \geq 0.001$	Es = − 0.818 $P \geq 0.062$	Es = − 0.853 $P \geq 0.057$	$X = 2.784$ $P = 0.131$	$X = 1.715$ $P = 0.125$	$X = 1.715$ $P = 0.05$*	GCV = 0.741 DE = 12.3%
Abundance of ***Glossina*** spp.	Es = 0.503 $P \geq 0.001$*	Es = − 0.330 $P = 0.177$	Es = − 0.39 $P = 0.174$	$X = 2.584$ $P = 0.001$	$X = 1.000$ $P = 0.001$*	$X = 1.000$ $P = 0.095$	GCV = 2.675 DE = 22%
Atylotus agrestis	Es = − 0.095 $P = 0.068$	Es = 0.126 $P = 0.108$	Es = 0.988 $P = 0.001$*	Es = 2.108 $P = 0.011$*	Es = 1.033 $P = 0.16$	$X = 1.000$ $P = 0.149$	GCV = 0.231 DE = 7.67%
Tabanus tianiatus	Es = 0.266 $P \geq 0.000$*	Es = − 65.228 $P \geq 0.001$	Es = 26.732 $P \geq 0.001$*	$X = 3.172$ $P \geq 0.001$*	$X = 1.15$ $P \geq 0.001$*	$X = 3.55$ $P \geq 0.001$*	GCV = 5.469 DE = 100%
Tabanus par	Es = − 3.345 $P \geq 0.001$*	Es = 0.435 $P = 0.524$	Es = − 0.435 $P = 0.892$	$X = 2.987$ $P = 0.122$	$X = 1.000$ $P = 0.062$	$X = 2.557$ $P = 0.142$	GCV = 0.376 25.2%
Tabanus sufis	Es = − 3.449 $P = 0.001$*	Es = − 1.558 $P = 0.156$	Es = − 1.186 $P = 0.278$	$X = 2.99$ $P = 0.306$	$X = 2.525$ $P = 0.42$	$X = 2.9$ $P = 0.487$	GCV = 0.287 DE = 28.9%
Stomoxys calcitrans	Es = − 0.823 $P \geq 0.001$*	Es = − 0126 $P = 0.108$	Es = 0.988 $P = 0.001$*	$X = 2.108$ $P = 0.011$*	$X = 1.000$ $P = 1.033$	$X = 1.000$ $P = 0.149$	GCV = 0.231 DE = 7.67%
Abundance of ***Tabanus*** spp.	Es = 0.438 $P = 0.027$*	Es = 0.181 $P = 0.462$	Es = 0.18 $P = 0.505$	$X = 2.933$ $P = 0.037$*	$X = 2.947$ $P = 0.039$*	$X = 1.000$ $P \geq 0.001$*	GCV = 3.135 DE = 27.7%

Es estimate value, *X* reference degree of freedom, *GCV* generalized cross-validation, *DE* deviance explained

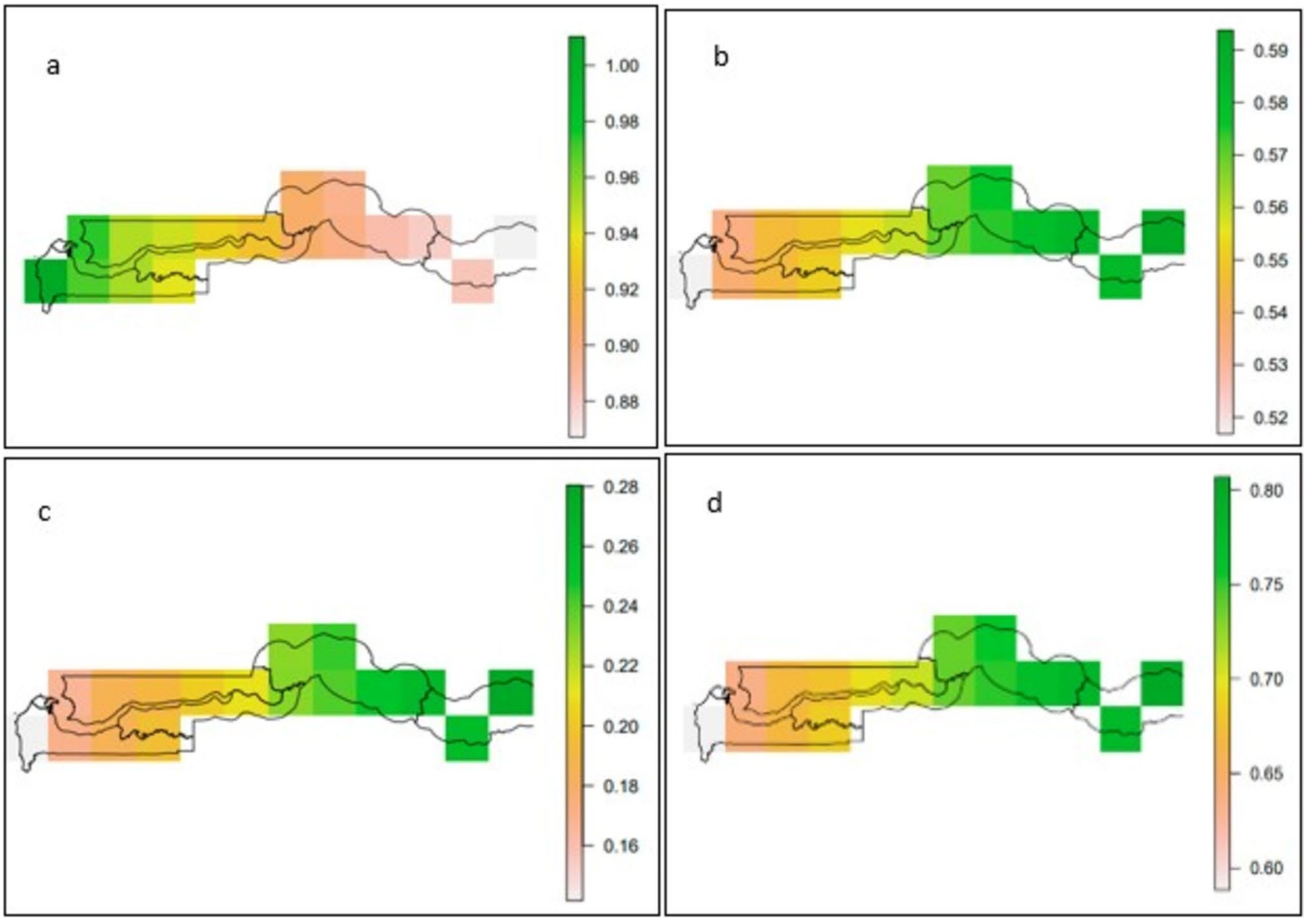

Fig. 5 Potentially suitable area for **a** *Stomoxys calcitrans*, **b** *Glossina morsitans submorsitans*, **c** *Glossina palpalis gambiense*, and **d** *Atylotus agrestis* based on ERA-5 from 2012 to 2021. Dark green coloration shows areas that had the highest probability of finding more flies

western region of The Gambia has the highest predictive chance of finding *Stomoxys calcitrans* (Fig. 5a). *Glossina morsitans submorsitans* and *Glossina palpalis gambiense* infestations are highest in the eastern part of The Gambia (Fig. 5b and c), which includes the CRR and URR, as compared to the western part. The distribution of the *Atylotus agrestis* species follows the same pattern as that of the *Glossina* species (Fig. 5d). The Upper River Region of The Gambia had the highest occurrence in the country.

Impact of changes in temperature on the distribution and abundance of Glossina species, Tabanus species, and Stomoxys calcitrans in The Gambia from 2020 to 2080

Impact on Stomoxys calcitrans

Additionally, the effect of temperature on the future occurrence of *Stomoxys calcitrans* was also investigated. Figure 7 shows the impact of temperature on the distribution and abundance of *Stomoxys calcitrans* in The Gambia under the intermediate- (CCCma-CanRCM; Fig. 7a–c) and high-emission scenario model (CLMcom-KIT-CCLM5-0–15; Fig. 7d–f) for 2021–2040 (Fig. 7a, d), 2041–2060 (Fig. 7b, e), and 2061–2080 (Fig. 7c, f). Results indicate that the distribution of *Stomoxys calcitrans* species will be more concentrated in the western part of The Gambia (urban areas) and some parts of NBR and LRR in all future periods and both RCPs (Fig. 7).

Impact on Glossina morsitans submorsitans

The effect of temperature on the future occurrence of *Glossina morsitans submorsitans* in The Gambia was investigated under the intermediate- (CCCma-CanRCM4; Fig. 8a–c) and the high-emission scenario model (CLMcom-KIT-CCLM5-0–15; Fig. 8d–f) for the future periods 2021–2040 (Fig. 8a, d), 2041–2060 (Fig. 8b, e), and 2061–2080 (Fig. 8c, f). *Glossina morsitans submorsitans* will highly be distributed in CRR and URR, while the regions of WCR, NBR, and LRR will be moderately infected under the RCP4.5 (intermediate-emission scenario model; Fig. 8a, c, and e).

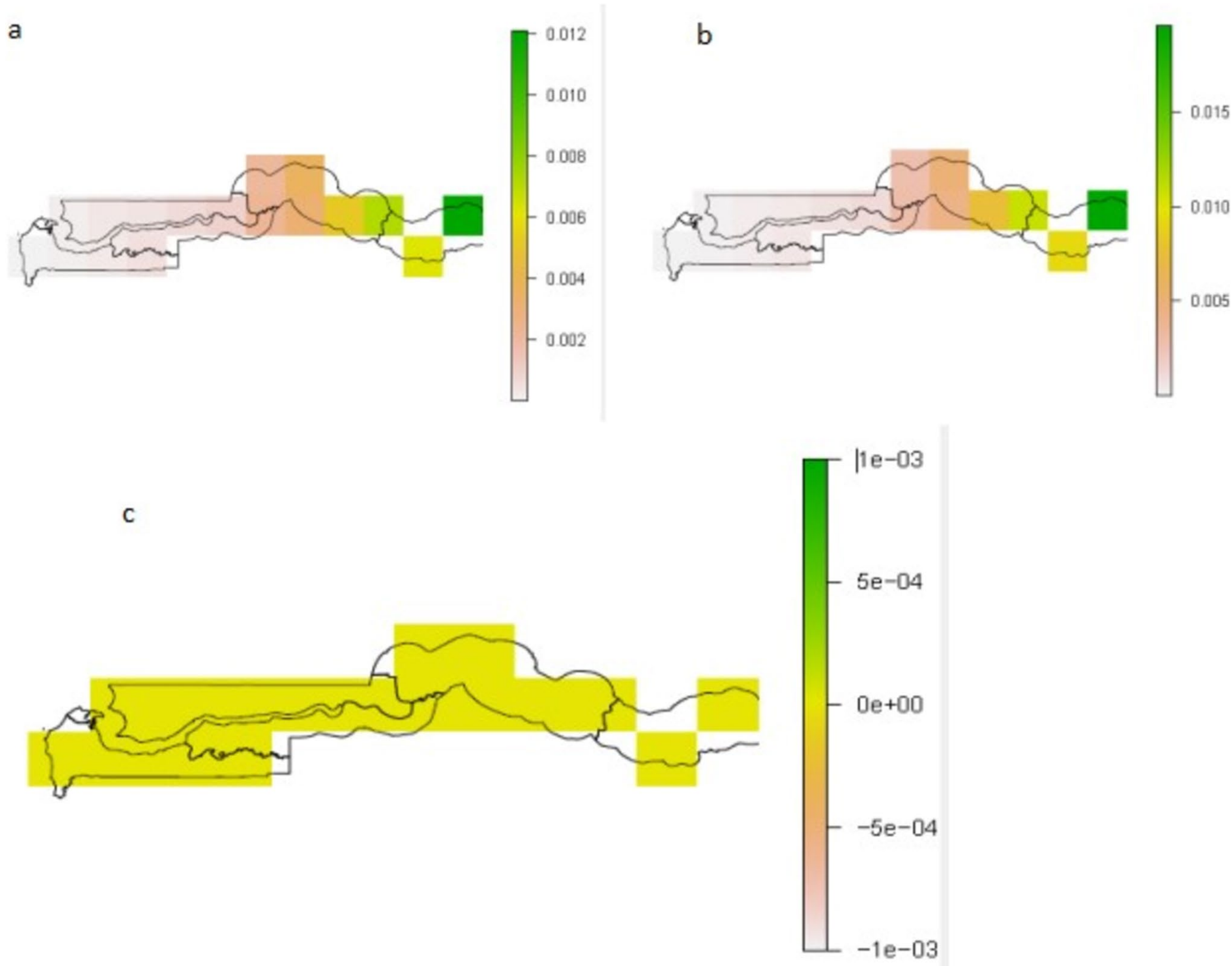

Fig. 6 Potentially suitable area for **a** *Tabanus par*, **b** *Tabanus sufis*, and **c** *Tabanus taeniatus* based on ERA-5 from 2012 to 2021. Dark green coloration shows areas with the highest probability of finding more flies

Additionally, the high-emission scenario model (CLMcom-KIT-CCLM5-0–15) indicates that the abundance of this species will be evenly distributed in The Gambia in all future periods, except for the WCR, KMC, and BJL, which will have a very low abundance of these species (Fig. 8d, e, and f).

Impact on Glossina palpalis gambiensis

Figure 9 shows the impact of temperature on the distribution and abundance of *Glossina palpalis gambiensis* in The Gambia under the intermediate- (CCCma-CanRCM4; Fig. 9a–c) and high-emission scenario model (CLMcom-KIT-CCLM5-0–15; Fig. 9d–f) for the future periods 2021–2040 (Fig. 9a–d), 2041–2060 (Fig. 9b–e), and 2061–2080 (Fig. 9c–f). *Glossina palpalis gambiensis* would be highly distributed in CRR and URR and moderately distributed in the WCR, NBR, and LRR under the intermediate-emission scenario model (CCCma-CanRCM4; Fig. 9a–c). However, Kanifing Municipal Council and Banjul will have the least abundance of these species. As for the high-emission scenario model (CLMcom-KIT-CCLM5-0–15), the distribution of this species will be evenly distributed in The Gambia, except for the WCR, KMC, and Banjul, which will have a very low abundance of these species in all future periods (Fig. 9d–f).

Impact on Atylotus agrestis

Our results also show the impact of temperature on the distribution and occurrence of *Atylotus agrestis* in The Gambia under the intermediate- (CCCma-CanRCM4 Fig. 10a–c) and the high-emission scenario model (CLMcom-KIT-CCLM5-0–15; Fig. 10d–f) for 2021–2040

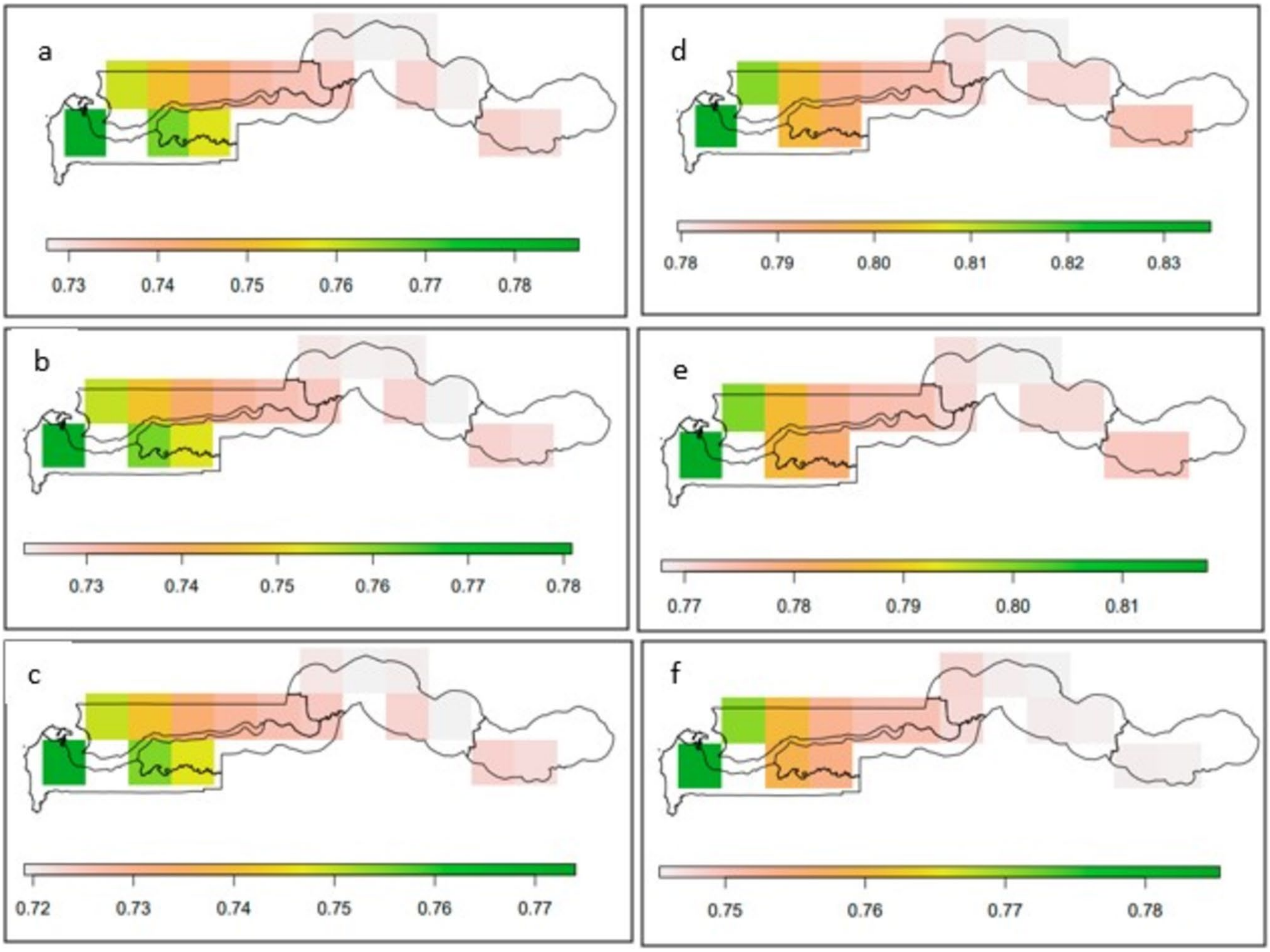

Fig. 7 Spatial prediction maps of projected abundance of *Stomoxys calcitrans* in The Gambia under the intermediate- (CCCma-CanRCM4; **a**–**c**) and the high-emission scenario model (CLMcom-KIT-CCLM5-0–15; **d**–**f**) for the future periods of 2021–2040 (**a**, **d**), 2041–2060 (**b**, **e**), and 2061–2080 (**c**, **f**). Dark green coloration shows areas with the highest probability of finding more *Stomoxys calcitrans* in the future

(Fig. 10a, d), 2041–2060 (Fig. 10b, e), and 2061–2080 (Fig. 10c, f). As predicted, there will be more *Atylotus agrestis* in the CRR and the URR than in the other regions of The Gambia. However, the CCCma-CanRCM4 model under all future periods indicates that *Atylotus agrestis* will be more abundant in all regions of The Gambia except for Banjul and some parts of the West Coast Region of the country (Fig. 10a–c). Some areas of the LRR and WCR will have fewer infestations of these dipterans. The CLMcom-KIT-CCLM5-0–15 model (Fig. 10d–f) showed similar results as that of the CCCma-CanRCM4 model (Fig. 10a–c). The main difference in the predictions of the two models was that the high-emissions scenario model (CLMcom-KIT-CCLM5-0–15) showed a higher prediction of *Atylotus agrestis* in the LRR and a lower abundance of this species in the URR of The Gambia.

Impact on Tabanus par

Figure 11 shows the impact of temperature on the distribution and abundance of *Tabanus par* in The Gambia under the intermediate- (CCCma-CanRCM4; Fig. 11a–c) and high-emission scenario model (CLMcom-KIT-CCLM5-0–15; Fig. 11d–f) for the future periods 2021–2040 (Fig. 11a, d), 2041–2060 (Fig. 11b, e), and 2061–2080 (Fig. 11c, f). *Tabanus par* would be highly distributed throughout the country under the intermediate-emission scenario model (CCCma-CanRCM4; Fig. 11a–c). As for the high-emission scenario model (CLMcom-KIT-CCLM5-0–15), the distribution of this species will be evenly distributed in The Gambia. However, WCR and KMC will be the only regions where the occurrence of the species would be high in all future scenarios (Fig. 11d–f).

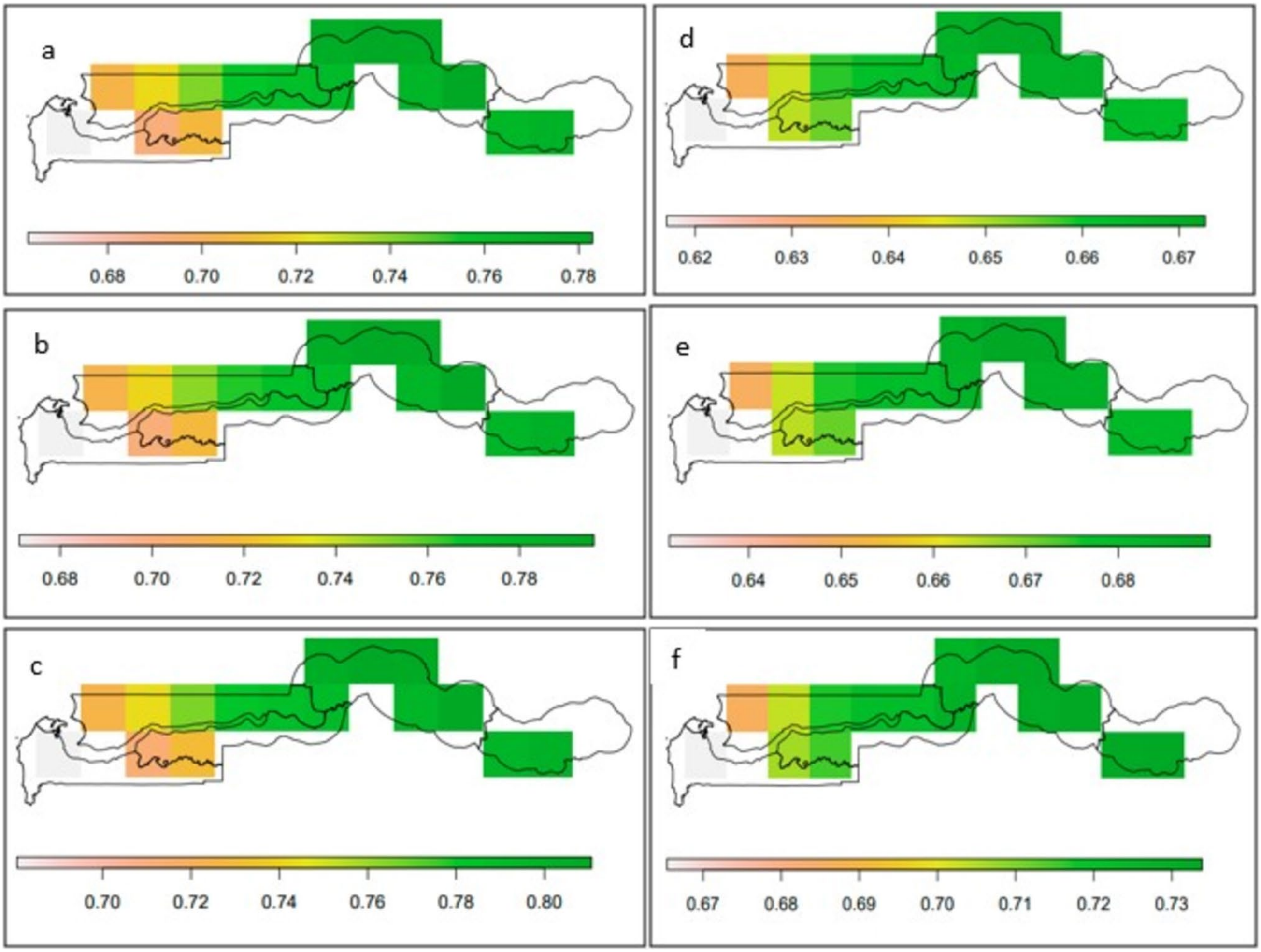

Fig. 8 Spatial prediction maps of projected abundance of *Glossina morsitans submorsitans* in The Gambia under the intermediate- (CCCma-CanRCM4; **a**–**c**) and the high-emission scenario model (CLMcom-KIT-CCLM5-0–15; **d**–**f**) for the future periods of 2021–2040 (**a**, **d**), 2041–2060 (**b**, **e**), and 2061–2080 (**c**, **f**). Dark green coloration shows areas with the highest probability of finding more *Glossina morsitans submorsitans* in the future

Impact on Tabanus sufis

Figure 12 shows the impact of temperature on the distribution and abundance of *Tabanus sufis* in The Gambia under the intermediate- (CCCma-CanRCM4; Fig. 12a–c) and high-emission scenario model (CLMcom-KIT-CCLM5-0–15; Fig. 12d–f) for the future periods 2021–2040 (Fig. 12a, d), 2041–2060 (Fig. 12b, e), and 2061–2080 (Fig. 12c, f). *Tabanus par* would be highly distributed only in the western Gambia, that is, KMC and WCR under the intermediate-emission scenario model (CCCma-CanRCM4; Fig. 12a–c). As for the high-emission scenario model (CLMcom-KIT-CCLM5-0–15), the distribution of this species will be evenly distributed in all the regions of The Gambia (Fig. 12d–f).

Impact on Tabanus taeniatus

Figure 13 shows the impact of temperature on the distribution and abundance of *Tabanus taeniatus* in The Gambia under the intermediate- (CCCma-CanRCM4; Fig. 13a–c) and high-emission scenario model (CLMcom-KIT-CCLM5-0–15; Fig. 13d–f) for the future periods 2021–2040 (Fig. 13a, d), 2041–2060 (Fig. 13b, e), and 2061–2080 (Fig. 13c, f). *Tabanus taeniatus* would be highly distributed only in KMC and some parts of WCR under the intermediate-emission scenario model (CCCma-CanRCM4; Fig. 12a–c). As for the high-emission scenario model (CLMcom-KIT-CCLM5-0–15), the distribution of this species will be only in CRR and some parts of WCR, NBR, and NBR of The Gambia (Fig. 12d–f).

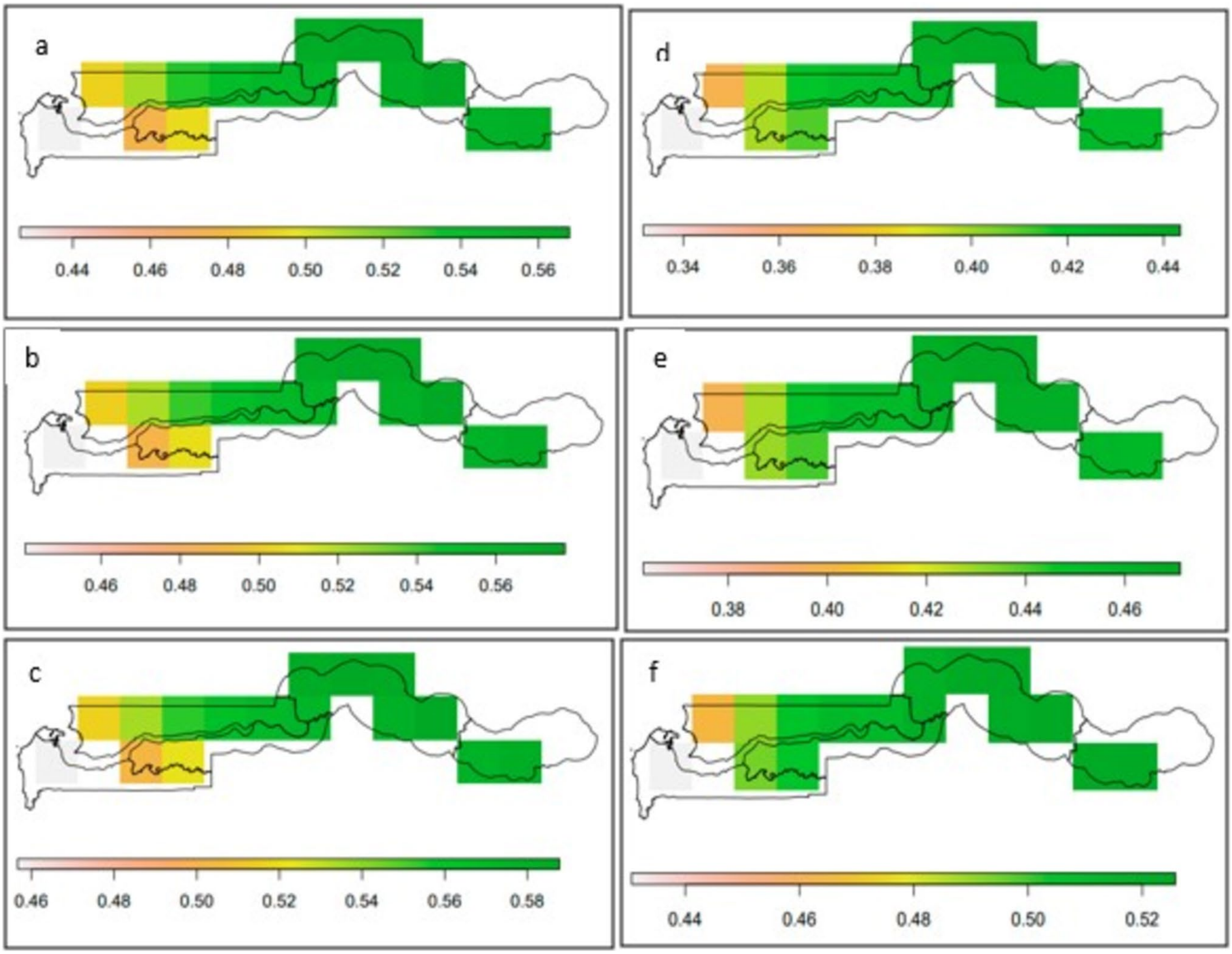

Fig. 9 Spatial prediction maps of projected abundance of *Glossina palpalis gambiense* in The Gambia under the intermediate- (CCCma-CanRCM4; **a**–**c**) and the high-emission scenario model (CLMcom-KIT-CCLM5-0–15; **d**–**f**) for the future periods of 2021–2040 (**a**, **d**), 2041–2060 (**b**, **e**), and 2061–2080 (**c**, **f**). Dark green coloration shows areas with the highest probability of finding more *Glossina palpalis gambiense* in the future

Discussion

Impact of climate variables on vectors

The effects of temperature and relative humidity on the occurrence of *Glossinidae* species, *Tabanus* spp., and *Stomoxys calcitrans* in The Gambia are investigated using a generalized additive model with a smooth spline function. This model enables us to determine temperatures and relative humidity that are optimal for the survival of the *Glossina morsitans submorsitans*, *Glossina palpalis gambiensis*, *Tabanus sufis*, *Tabanus par*, *Tabanus taeniatus*, and *Atylotus agrestis* species in The Gambia. The results of our work point out that temperature is a key factor in determining the spread of *Stomoxys calcitrans* in The Gambia, and this was in agreement with previous studies (Sprygin et al. 2018). Future predictions showed that these flies would be more concentrated in the western part of The Gambia. Issimov et al. (2020) showed that an average temperature of 27–32 °C is required for the development of larva pupated and the emergence of imago. In this investigation, we again demonstrated that a significant contributing factor to the distribution of *Stomoxys calcitrans* in The Gambia was relative humidity.

Our research shows that climate variability has an impact on the abundance and dynamics of *Glossina* species and the spread of these vectors in The Gambia, as it is in many other countries in sub-Saharan Africa, and that this is already changing the distribution of many vectors and vector-borne diseases, particularly *Trypanosomiasis* and *Glossina* species in Northern Zimbabwe by Longbottom et al. (2020), Western Zimbabwe by Matawa et al. (2013), and in Kenya

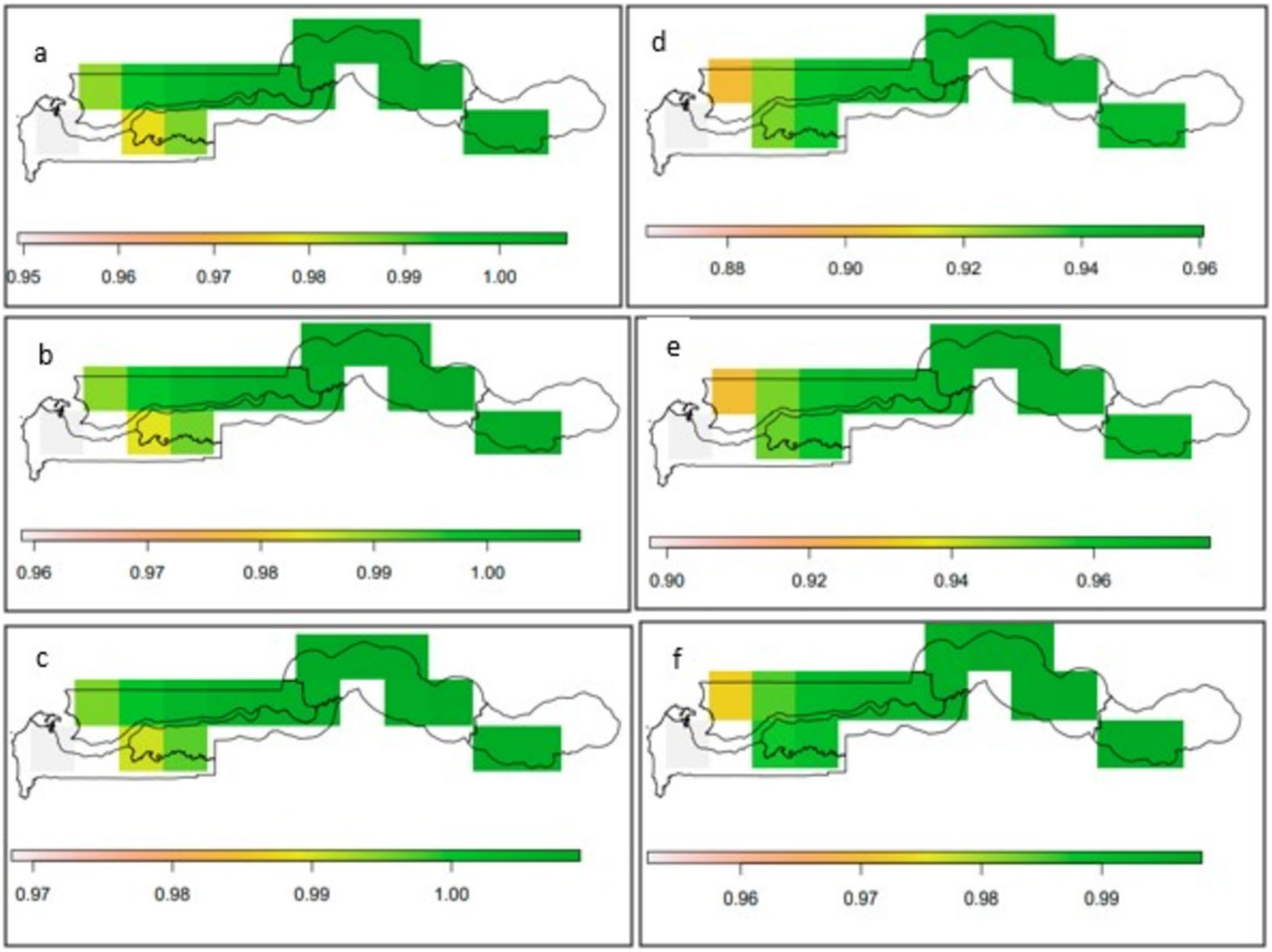

Fig. 10 Spatial prediction maps of projected abundance of *Atylotus agrestis*. in The Gambia under the intermediate- (CCCma-CanRCM4; **a**–**c**) and the high-emission scenario model (CLMcom-KIT-CCLM5-0–15; **d**–**f**) for the future periods of 2021–2040 (**a**, **d**), 2041–2060 (**b**, **e**), and 2061–2080 (**c**, **f**). Dark green coloration shows areas with the highest probability of finding more *Atylotus agrestis* in the future

by Messina et al. (2012). Our study also demonstrated that temperature was the most important climate variable that affected the occurrence and spatio-temporal distribution of *Glossina* species (Are and Hargrove 2020; Cecilia et al. 2021). It has also been determined that the presence of *Stomoxys calcitrans*, *Tabanus species*, and *Glossina* spp. in all of The Gambia's administrative regions costs livestock and crop output in sub-Saharan Africa over 4.5 billion US dollars annually (Oluwafemi et al. 2007; Pagabeleguem et al. 2016; Kargbo et al. 2022).

Our findings revealed a statistical relationship between the abundance of *Glossina* species and maximum temperature. This confirms the findings of earlier studies, which suggest that temperature is a key driver of tsetse population dynamics (Lord et al. 2018; Are and Hargrove 2020; Horváth et al. 2020; Cecilia et al. 2021). Furthermore, we were able to catch *Glossina* species during the late dry season in The Gambia's URR, which recorded a maximum temperature of 42.6 °C and a minimum temperature of 14.1 °C. This contradicted previous findings that temperatures outside of the approximate range of 16–31 °C were lethal for *Glossina morsitans submorsitans* (Are and Hargrove 2020). Lord et al. (2018) reported a significant reduction in *G. pallidipes* populations in Zimbabwe's Zambezi Valley, which they attributed to rising temperatures. Temperatures in The Gambia generally range and fluctuate between 14.1 and 42.6 °C, creating comfortable conditions for residents.

We also report that *Atylotus agrestis* was caught in all regions of The Gambia, and it was the most commonly caught species in this study, particularly in The Gambia's Upper River Region, which recorded temperatures ranging from 14.2 to 40 °C. *Atylotus agrestis* was even more abundant (20 species) in URR than the *Glossina* species in this region, even though URR recorded the highest temperature

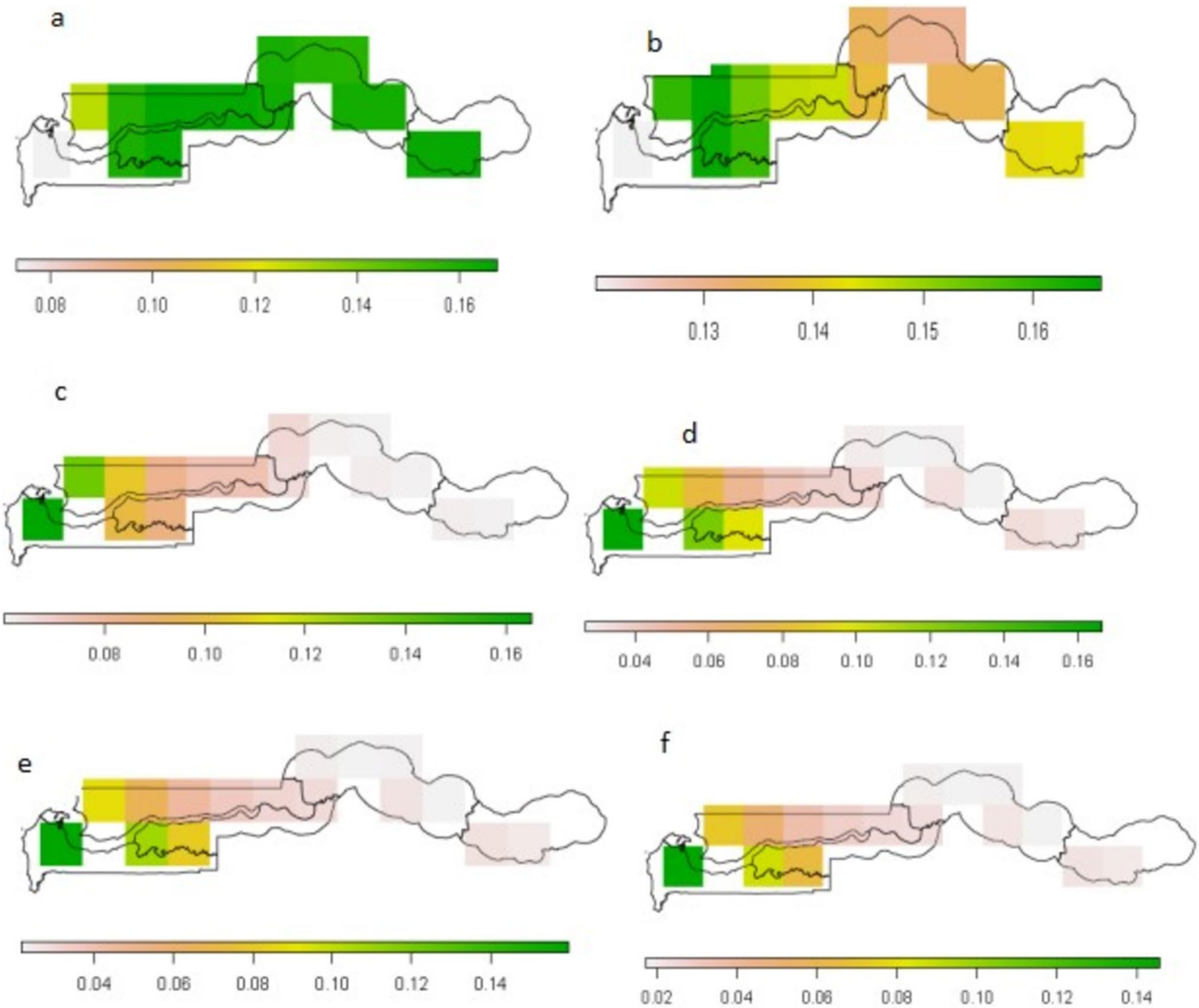

Fig. 11 Spatial prediction maps of projected abundance of *Tabanus par* in The Gambia under the intermediate- (CCCma-CanRCM4; **a**–**c**) and the high-emission scenario model (CLMcom-KIT-CCLM5-0–15; **d**–**f**) for the future periods of 2021–2040 (**a**, **d**), 2041–2060 (**b**, **e**), and 2061–2080 (**c**, **f**). Dark green coloration shows areas with the highest probability of finding more *Tabanus par* in the future

(42.3 °C) and a minimum temperature of 14.2 °C. This result is also similar to that of those who reported that *Tabanidae* species prefer warmer places and can even survive at 17.3 to 41 °C (Baldacchino et al. 2017; Horvath et al. 2020; Lucas et al. 2020). To determine whether relative humidity also affects tsetse flies and *Tabanus* species, we added it as an independent variable to our model. Although our model demonstrated statistical significance, *Glossina* species were captured at different relative humidity levels (34–84%). Our study was also corroborated by other findings. Relative humidity was also shown to be one of the meteorological elements that affected *Tabanus* species survival in Hungary (Herczerg et al. 2015). This report is not in agreement with the findings of Pagabeleguem et al. (2016), who reported that relative humidity had no impact on *Glossina palpalis gambiensis* in an experimental laboratory study. They reported that *Glossina palpalis gambiensis* was able to survive at a relative humidity of 40–76%. As for the effect of relative humidity on *Atylotus agrestis*, our model did not show any statistical significance with this species, even though they were again caught at various levels of relative humidity (34–84%) in The Gambia. Tabanidae *species* such as *Atylotus agrestis* have been reported to dwell better in areas with a relative humidity range of between 76 and 80% (Herczeg et al. 2015; Lucas et al. 2020). However, only *Tabanus tianiatus* was found to have an association with relative humidity out of all the *Tabanus* species in our investigation. The abundance of all the *Tabanus* species was influenced by all the climate

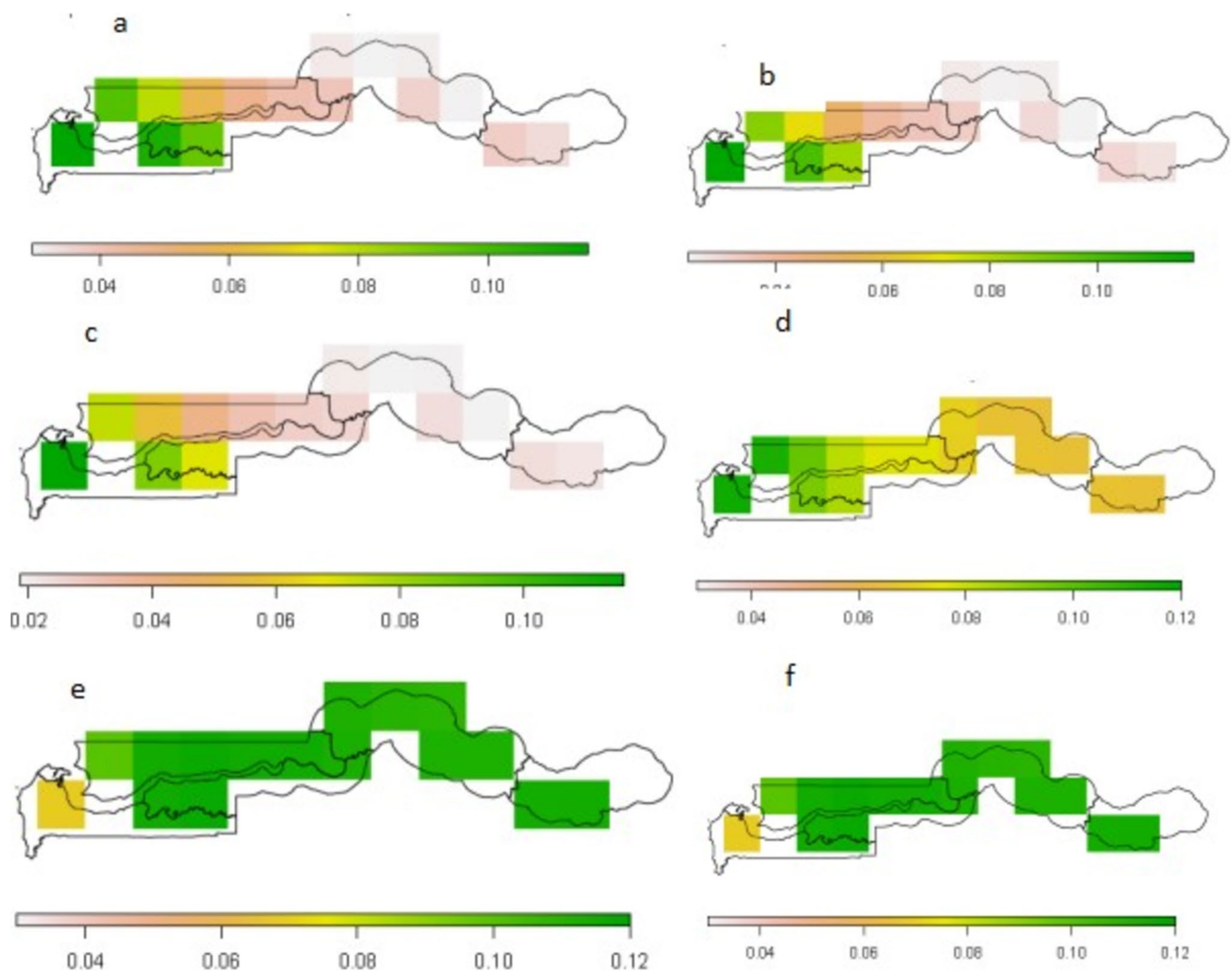

Fig. 12 Spatial prediction maps of projected abundance of *Tabanus sufis* in The Gambia under the intermediate- (CCCma-CanRCM4; **a**–**c**) and the high-emission scenario model (CLMcom-KIT-CCLM5-0–15; **d**–**f**) for the future periods of 2021–2040 (**a**, **d**), 2041–2060 (**b**, **e**), and 2061–2080 (**c**, **f**). Dark green coloration shows areas with the highest probability of finding more *Tabanus sufis* in the future

variables. The *Glossina* species' abundance was exclusively linked with minimum temperature.

Discussion of potential distribution of flies under historical conditions

In this paper, we present the first analysis of the potential distribution of *Trypanosoma* species in The Gambia using the latest climate reanalysis, the ERA5. This approach was similar to the findings of Mistry et al. (2022), who used the ERA5 reanalysis to conduct health impact assessments and evaluations of the comparative performance of ERA5 against traditional station-based data. It has also been used in assessing the relationships between thermal stress and mortality in Europe (Urban et al. 2021). We predicted potentially favorable habitats for *Tabanus* species, *Stomoxys calcitrans*, *Glossina palpalis gambiensis*, and *Glossina morsitans submorsitans* in all regions of the Gambia, including both rural and urban areas, based on historical conditions. Our findings are consistent with the Food and Agriculture Organization of the United Nations (FAO) forecasts from 1999 and 2017 regarding the possible range of *Glossina* species in Africa (Shaw et al. 2014; Welburn et al. 2016). The likelihood of finding these vectors nationwide ranges from being higher in some regions in The Gambia, and this finding is in line with an ecological study done by Zhou et al. (2021), which found that areas with a tropical savanna environment were more susceptible to *Glossina* species. However, the existence of these flies explains why AAT and HAT were identified in The Gambia from 2011 to 2020 (Kargbo et al. 2022).

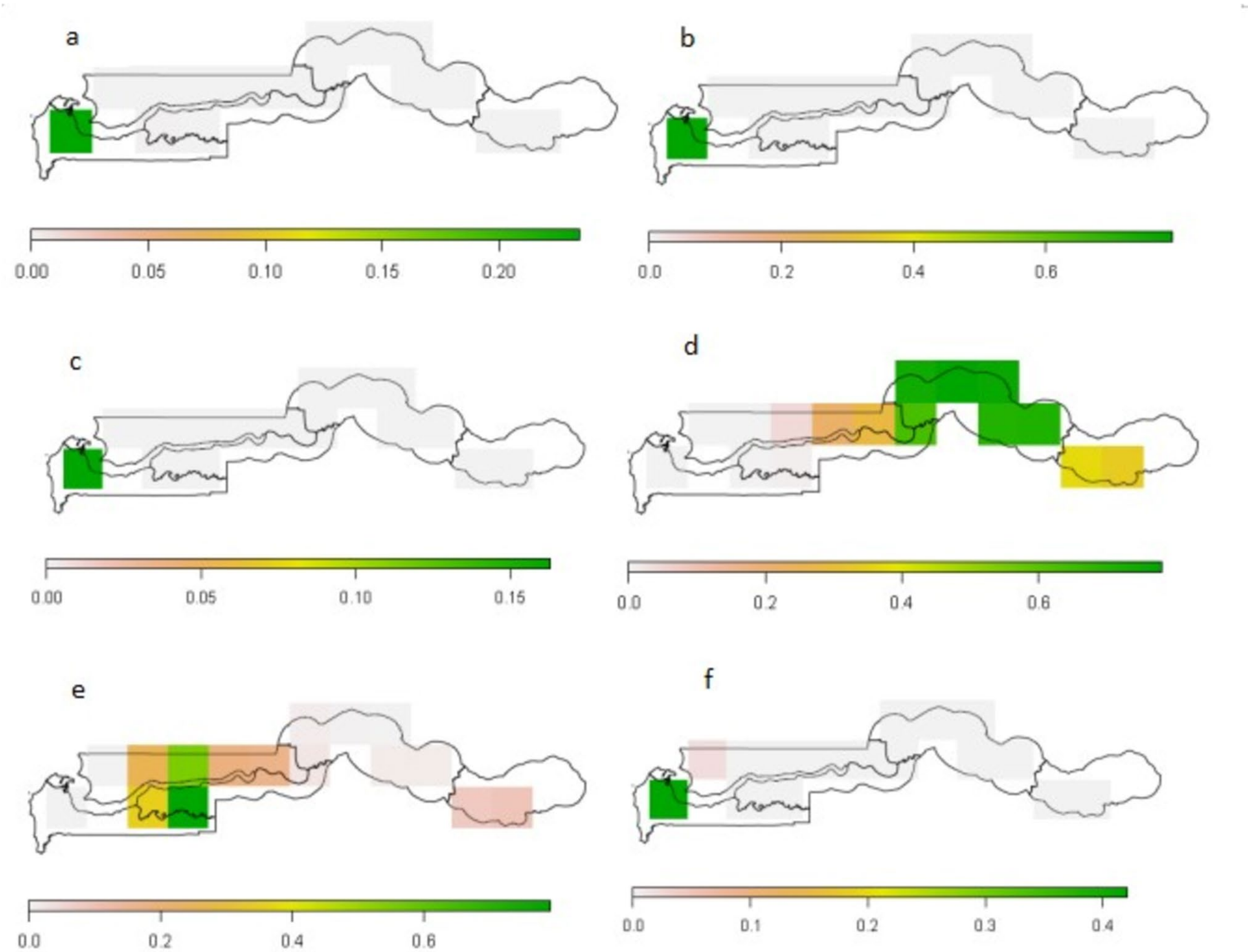

Fig. 13 Spatial prediction maps of projected abundance of *Tabanus taeniatus* in The Gambia under the intermediate- (CCCma-CanRCM4; **a**–**c**) and the high-emission scenario model (CLMcom-KIT-CCLM5-0–15; **d**–**f**) for the future periods of 2021–2040 (**a**, **d**), 2041–2060 (**b**, **e**), and 2061–2080 (**c**, **f**). Dark green coloration shows areas with the highest probability of finding more *Tabanus taeniatus* in the future

Discussion of potential distribution of the flies under future conditions

Both models used showed that *Stomoxys calcitrans* will be more concentrated in the urban areas (KMC, BJL, and some parts of NBR and WCR) of The Gambia in all future periods, even though the rural area will be moderate to poorly suitable for survival. Chaiphongpachara et al. (2022) also identified *Stomoxys calcitrans* as a metropolitan species. Our result also shows that *Glossina palpalis gambiensis,* which was thought to be found only on the south bank of The Gambia (Kargbo and Kuye 2020), will be distributed in all the regions of The Gambia. CRR, URR, and some parts of LRR and NBR will be highly suitable for the survival of these flies, and the lower parts of NBR and LRR will be moderately suitable (Rawlings et al. 1993). *Glossina morsitans submorsitan*, which was also only found in LRR and CRR, will be found in all regions of The Gambia in all future periods. In contrast to *Stomoxys calcitrans*, a lower predicted prevalence was observed in the urban areas, and a higher prevalence was observed in the rural areas for *Atylotus agrestis*. This species is predicted to be evenly distributed in all the rural regions of The Gambia. According to previous research by Kargbo et al. (2021), this species was trapped in all regions of The Gambia. The predicted locations of tsetse flies and other *Trypanosoma* vectors are fundamental to determining the niche, which can be used to improve control efforts, and thereby, local authorities will be more able to eliminate or reduce the populations of these vectors (Messina et al. 2012; Matawa et al. 2013; Ciss et al. 2019). Under climate change scenarios, *Trypanosoma* vectors and African trypanosomiasis are anticipated to (re)-emerge as significant diseases (Messina et al. 2012; Matawa et al. 2013).

Advantages and disadvantages of the study

This study provided scientific information for the prediction of *Stomoxys calcitrans*, *Glossina* species, and *Tabanus* species in The Gambia, which could be used for vector control programs. However, the GAM model estimation is limited due to the short study period, which allowed minimal climate variability and mainly seasonal effects. The few sampling points where these flies were caught could also be a major hindrance. We used an exploratory approach during the modeling process to determine the relationship between vectors and many variables, including seasonality and climate variables, among others. However, it was only the climate variables that showed a significant relationship among the other variables tested. The strength of the paper is that we collected primary data from the field, conducted analyses of association with climate, and also made projections of potential future changes for vectors/species that have never been studied before. The limitation includes a smaller dataset and fewer sampling points and places.

Conclusion

Glossinidae, Tabanidae, and *Stomoxys calcitrans* risk exposing animal and human populations to a variety of diseases such as trypanosomiasis, equine infectious disease, anaplasmosis, listeriosis, anthrax, and loaloa. In this study, we demonstrated the applicability of a generalized additive modeling approach to the species distribution of Glossinidae, *Atylotus agrestis*, and *Stomoxys calcitrans* in The Gambia. We find that the distribution of *Trypanosoma* vectors is mostly influenced by maximum temperature. It is important to understand how climate change may potentially change the distribution of Glossinidae*, Atylotus agrestis*, and *Stomoxys calcitrans* in The Gambia; therefore, we made model projections. While the findings are novel, we suggest further field data collection and analytic studies of these relationships in Africa.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00436-025-08475-3.

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Author contribution AK collected the data; AK, SD, AMO, RFCV, and JR performed data analysis and wrote the manuscript; HKK and JR supervised the study. All authors read and approved the final manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethical approval This study was permitted by the Ethics Committee of the Ministry of Higher Education Science Research and Technology, The Gambia (reference number AFG 85/272/01).

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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