Modeling the Spatial Distribution of Culicoides Species (Diptera: Ceratopogonidae) as Vectors of Animal Diseases in Ethiopia

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Abstract

Culicoides biting midges (Diptera: Ceratopogonidae) are the major vectors of bluetongue, Schmallenberg, and African horse sickness viruses. This study was conducted to survey *Culicoides* species in different parts of Ethiopia and to develop habitat suitability for the major *Culicoides* species in Ethiopia. *Culicoides* traps were set in different parts of the country from December 2018 to April 2021 using UV light Onderstepoort traps and the collected Culicoides were sorted to species level. To develop the species distribution model for the two predominant *Culicoides* species, namely *Culicoides imicola* and *C. kingi*, an ensemble modeling technique was used with the Biomod2 package of R software. KAPPA True skill statistics (TSS) and ROC curve were used to evaluate the accuracy of species distribution models. In the ensemble modeling, models which score TSS values greater than 0.8 were considered. Poisson regression models were used to evaluate the relationship between *C. imicola* and *C. kingi* catch and various environmental and climatic factors. During the study period, a total of 9148 *Culicoides* were collected from 66 trapping sites. Of the total 9148, 8576 of them belongs to seven species and the remaining 572 Culicoides were unidentified. The predominant species was *C. imicola* (52.8%), followed by *C. kingi* (23.6%). The abundance of these two species was highly influenced by the agro-ecological zone of the capture sites and the proximity of the capture sites to livestock farms. Climatic variables such as mean annual minimum and maximum temperature and mean annual rainfall were found to influence the catch of *C. imicola* at the different study sites. The ensemble model performed very well for both species with KAPPA (0.9), TSS (0.98), and ROC (0.999) for *C. imicola* and KAPPA (0.889), TSS (0.999), and ROC (0.999) for *C. kingi*. *C. imicola* has a larger suitability range compared to *C. kingi*. The Great Rift Valley in Ethiopia, the southern and eastern parts of the country, and the areas along the Blue Nile and Lake Tana basins in northern Ethiopia were particularly suitable for *C. imicola*. High suitability for *C. kingi* was found in central Ethiopia and the Southern Nations, Nationalities and Peoples Region (SNNPR). The habitat suitability model developed here could help researchers better understand where the above vector-borne diseases are likely to occur and target surveillance to high-risk areas.

Introduction

African horse sickness (AHS) and bluetongue (BT), as well as Schmallenberg virus (SBV), are among the best-known animal diseases transmitted by adult female Culicoides biting midges [1–3]. AHS is a non-contagious viral disease of equids [1,3] while BT, and SBV affect ruminants [1,4]. AHS disease is endemic in many parts of Africa, especially in the central and eastern parts of the continent, where it periodically makes short excursions beyond these areas [5,6]. BT has also historically been endemic in many countries located between 40° north and 35° south latitude [7]. However, since 1998, an unprecedented spread of BT has been observed in the Mediterranean basin [8]. SBV is a recent arboviral disease known to cause abortions, stillbirths, and congenital malformations in cattle, sheep, and less commonly, goats [9]. SBV was first detected in Germany in 2011 and since then the disease has spread to almost all European countries [4]. The disease has also been reported outside Europe from Ethiopia [10].

Ethiopia experiences serious and repeated outbreaks of AHS every year. From 2007 to 2010, about 737 outbreaks were reported in different parts of the country [11]. However, the status of BT and SBV is not well understood, which may be due to misdiagnosis of the diseases with other common ruminant diseases such as foot and mouth disease (FMD), peste des petits ruminants (PPR), lumpy skin disease, and sheep and goat pox, which cause similar clinical symptoms [12]. However, there are some serological reports of BT [13,14]. For SBV, although there is no molecular evidence or virus isolation, a high apparent seroprevalence of 56.6% has been reported [10].

Culicoides biting midges (Diptera: Ceratopogonidae) is a genus of the smallest blood-sucking flies, which measures up to 3 millimetres in size. The genus has a worldwide distribution, except in Antarctica and New Zealand, and it has more than 1400 known species [15,16]. *Culicoides* are known to transmit a wide range of pathogens. More than 50 arboviruses belonging to the Bunyaviridae, Reoviridae, and Rhabdoviridae families have been isolated from various Culicoides species [17].

Culicoides breed in a variety of habitats and tend to stay near their hosts, including in and around farms, decaying vegetation, manure, pond edges, and moist soils. Female Culicoides often seek blood as a protein source for the development of their eggs. Therefore, they often bite their hosts such as amphibians, birds, and mammals, including humans and domestic animals to feed on their blood [18].

Several studies have investigated the occurrence and species composition of Culicoides species throughout the world [19–23]. Some have predicted the potential current and future geographic distribution of Culicoides midges using different climatic and environmental variables [24–29]. To date, several Culicoides species have been detected in Ethiopia, including *C. milnei*, *C. zuluensis*, *C. imicola*, *C. neavei*, *C. fulvithorax*, and *C. isioloensis* [30] and *C. fuscicaudae* [31].

For effective risk management, it is essential to know the species composition and abundance of Culicoides populations in an area [32]. This study is, therefore, aimed to survey *Culicoides* species in different parts of Ethiopia and to develop habitat suitability for the prevalent species.

Materials And Methods

Culicoides collection sites

The current study was conducted in different parts of Ethiopia belonging to two regions. Hawassa town, Gamo Gofa, Konso and Wolayita in the South Nation Nationalities and People Region (SNNPR) and Jimma, Oromia Special Zone, East Shewa and Borena in the Oromia Region (Fig. 1). The areas were selected based on previous reports of Culicoides-borne diseases, namely AHS, bluetongue and SBV. The study is in accordance with relevant guidelines and regulations.

Culicoides Collection and Identification

Culicoides trapping was conducted from December 2018 to April 2021, consisting of two rounds. Sampling of the first round was conducted from December 2018 to April 2019 in Hawassa town, Gamo Gofa, Konso, Wolayita, East Shewa and Borena zones, while the second round was conducted from November 2020 to April 2021 in East Shewa, Jimma and Oromia Special zones. *Culicoides* were collected using UV light/suction traps developed by Onderstepoort Veterinary Institute (OVI, South Africa) and powered by a 12V car battery. Trap locations were selected to ensure that they were locations conducive to the reproduction of *Culicoides* species. These include areas near water bodies, wetlands, livestock farms, and/or equine stables (Table 1). The location of each trap site was obtained with Global Positioning System (GPS). Traps were set from dusk (6:00 pm) to dawn (6:00 am) and were placed both outdoors and indoors. Traps were hung from tree branches or building eaves at a height of 1.5-2 m above the ground. Insects were collected overnight in the cups of the traps and retrieved the next morning. All catches were transported to a local laboratory and placed in a -4°C refrigerator for 15 min to tranquillize insects. *Culicoides* species were first separated from other insects under a stereomicroscope, then transferred to an insect collection tube containing 70% ethanol, and finally transported to the entomology laboratory at the National Animal Health Diagnostic and Investigation Centre (NAHDIC) for species identification.

Table 1
Total number of traps in each zone

Zones	Total number of traps	Total number of traps near animal farm		Total number of traps near water bodies
		Indoor (inside farms)	Outdoor (outside farms)	
First round sampling				
East Shewa	13	-	6	7
Hawassa town	10	-	10	-
Gamo Gofa	8	1	5	
Wolayita	8	6	2	-
Borena	6	-	4	2
Konso	1	-	-	1
Second round sampling				
East Shewa	4	-	4	-
Oromia Special Zone	10	-	10	-
Jimma	6	-	6	-
Total	66	7	44	15

Species identification and enumeration were performed by observation of morphological features of Culicoides under a stereomicroscope. Most Culicoides midges have a wing pigmentation pattern and a distribution of wing macrotrichia consisting of grey and white spots; these patterns are unique to each species and can be easily observed under a dissecting microscope. The specimens were mounted on a slide and under the light microscope, morphological features such as shape, size, the number of female spermathecae, and the distance between eyes were observed [33]. Then we observed the ratio of antennae XI /X (length of segment XI divided by the length of segment X) and the shape and size of the 3rd palpal segment. Finally, we compared all the observed features with the images in the IIKC database (Interactive Identification Key for Culicoides) [33].

Spatial Distribution Modeling (SDM)

The geographic distribution of the two most common Culicoides spp was predicted using an ensemble modeling technique. Species distribution models consists of three main aspects: species occurrence data (dependent variable), layers of environmental variables (independent variables), and a modeling algorithm.

Climate and environmental variables that characterize favorable habitats for Culicoides were selected based on a literature review of presence and abundance models [25,34–36]. Minimum, mean, and maximum temperature, precipitation, solar radiation (kJ m^{-2} day^{-1}), wind speed (ms^{-1}), water vapor pressure (kPa) and altitude were downloaded from the WorldClim database version 2 (http://worldclim.org/).

Land cover data was downloaded from the European Space Agency's GlobCover Portal (http://due.esrin.esa.int/page_globcover.php). Livestock distribution data was downloaded from the website of FAO livestock systems (http://www.fao.org/livestock-systems/). Soil type was downloaded from (https://www.iiasa.ac.at/web/home/research/researchprograms/water/HWSD>html). All data layers were projected in the same projection system with a spatial resolution of 2.5 arc minutes using QGIS 3.4.1.

Data analysis

Ensemble modeling technique using biomod2 package of R software (http://cran.rproject.org/web/packages/biomod2/index.html) was used to develop the SDM. The package uses ten different methods: general linear models (GLM), general boosted models (GBM, also called boosted regression trees), general additive models (GAM), classification tree analysis (CTA), artificial neural networks (ANN), surface range envelope (SRE), flexible discriminant analysis (FDA), multiple adaptive regression splines (MARS), random forests (RF), and maximum entropy (MAXENT) [37]. Because the above ten modeling techniques require both absence and presence data to determine the suitability range of species, pseudo-absence data were generated using Surface Range Envelope (SRE). The data was split into two parts, 80% was used to train the model and 20% was used to test model performance. Models were evaluated using the results of 3-fold cross-validation in 30 models (10 techniques × 3 replicates).

The performance of models were evaluated using the true-skill statistic (TSS), the area under the receiver-operating characteristic curve (ROC) curve, and the Cohen's kappa statistic (Kappa). TSS is a threshold-dependent evaluation (sensitivity + 1, specificity − 1), with values closer to one indicating model accuracy [38]. For ensemble modeling, only models which score TSS values greater than 0.8 were considered. AUC scores range from 0 to 1, with models with scores above 0.5 providing better predictions than random draws [39].

A univariable Poisson regression model was used to evaluate the relationship between *C. imicola* and *C. kingi* catch and various environmental and climatic factors.

Results

Entomological survey

During the study period, a total of 9148 *Culicoides* were collected from 66 trapping sites. Of the total 9148, 8576 of them belongs to seven species and the remaining 572 *Culicoides* were unidentified. Of the seven species identified, *C. imicola* was the most abundant species with 4830 (52.8%), followed by *C. kingi* with 2160 (23.6%), *C. milnei*, *C. schultezi* and *C. Zuluensis*, which accounted for 9%, 6.8%, and 1.4% of the catch, respectively (Table 2). Most *Culicoides* were caught in Jimma zone (28.5%), followed by Hawassa town (19.4%) and Oromia special zone (17.4%).

Table 2
Culicoides species collected across the study sites

Culicoides species	Collection sites								Number and %
	Hawassa town	East Shewa	Gamo Gofa	Wolayita	Borena	Segen Valley	Oromia Special Zone	Jimma	
C. imicola	1512	775	228	113	133	196	696	1177	4830 (52.8%)
C. kingi	142	4	23	2	419	316	328	926	2160 (23.6%)
C. milnei	-	-	-	-	-	-	289	533	822 (9%)
C. schultzei	28	20	-	-	80	488	-	-	616 (6.8%)
C. zuluensis	89	41	-	-	-	-	-	-	130 (1.4%)
C. pycnostictus	2				16				18 (0.2%)
Others	5	16	98	17	161	-	275	-	572 (6.2%)
Total (%)	1778 (19.4%)	856 (9.3%)	349 (4%)	132 (1.4%)	809 (9%)	1000 (11%)	1588 (17.4%)	2636 (28.5%)	9148 (100%)

Most Culicoides were collected in the vicinity of the animal pen 6926 (75.7%), 1000 Culicoides were collected near rivers, which constitute 11% of the catch (Table 3).

Table 3
Culicoides species collected from different habitats

Culicoides species	Indoor	Lake shore	Animal pen	Near pond	Outdoor on field	River	Total count
C. imicola	59	203	4251	49	72	196	4830
C. kingi	1	64	1409	171	199	316	2160
C. milnei	-	-	822	-	-	-	822
C. schultzei	-	7	121	-	-	488	616
C. zuluensis	-	20	110	-	-	-	130
C. pycnostictus	-	-	18	-	-	-	18
Unidentified	8	100	195	-	143	-	572
Total (%)	68 (0.74%)	394 (4.3%)	6926 (75.7%)	220 (2.4%)	414 (4.5%)	1000 (11%)	9148 100%

Factors associated with Culicoides imicola **and** Culicoides kingi **occurrence**

The association of region, agro-ecological zonation and habitat with the abundance of *C. imicola* and *C. kingi* was evaluated using univariable Poisson regression, and all factors were found to have a significant effect on the number of catches of *C. imicola* and *C. kingi* (Tables 4 and 5). As shown in Tables 4 and 5, significantly more *Culicoides* were caught in the Oromia region compared to the SNNPR region. Higher catches were made in a subhumid agro-ecological zone. Greater numbers of *C. imicola* and *C. kingi* were caught within or near animal pens than in other habitats.

Table 4
Factors associated with *C. imicola* occurrence using univariable Poisson regression analysis

Factors	**Number of traps**	**Total number of *C. imicola* collected**	**Mean number of *C. imicola* collected (Mean ± SD)**	**Poisson regression coefficient**	**p-value**
Region					
Oromia	24	2781	115.9 ± 156.7	Ref	
SNNPR	26	2049	78.8 ± 107.3	-0.3855	0.000
Agro-ecological zonation					
Arid	23	2053	89.3 ± 109.9	Ref	
Semi-Arid	15	521	34.7 ± 47.1	-0.94386	
Sub-humid	12	2256	188.0 ± 190.6	0.744488	0.000
Habitat					
Animal pen	28	4251	150.2 ± 156.8	Ref	
Indoor	6	59	9.8 ± 12.5	-2.726	0.000
Outdoor	2	72	36.0 ± 3.0	-1.428	0.000
Water shore*	14	448	35.3 ± 47.2	-1.448	0.000

*Water shore includes river side, near pond, and lake shore

Table 5
Factors associated with *C. kingi* occurrence using univariable Poisson regression analysis

Factors	Number of traps	Total number of *C. kingi* collected	Mean number of *C. Kingi* collected (Mean ± SD)	Poisson regression coefficient	p-value
Region					
Oromia	10	1677	167.7 ± 231.3	Ref	
SNNPR	15	483	32.2 ± 78.5	-1.650	0.000
Agro-ecological zonation					
Arid	16	721	45.1 ± 77.9	Ref	
Semi-Arid	4	184	46.0 ± 72.2	0.021	0.803
Sub-humid	5	1255	251.0 ± 300.1	1.717	0.000
Habitat					
Animal pen	14	1409	100.6 ± 212.4	Ref	
Indoor	1	1	1.0 ± 0	-4.612	0.000
Outdoor	2	199	99.5 ± 9.5	-0.0114	0.880
Water shore*	8	551	68.9 ± 107.8	-0.379	0.000
*Water shore includes river side, near pond, and lake shore					

Climatic variables and altitude/elevation are significantly related to the occurrence of *C. imicola* and *C. kingi*, as shown in Tables 6 and 7. When the mean annual minimum temperature, mean annual maximum temperature, and elevation increase, the number of catches of *C. imicola* and *C. kingi* decreases. However, an increase in mean annual precipitation was found to increase the catches of *C. imicola* and *C. kingi*.

Table 6
Climatic factors associated with *C. imicola* occurrence using univariable Poisson regression analysis

Factors	Mean ± SD	Minimum	Maximum	Poisson regression coefficient	p-value
Altitude/elevation (masl)	1572 ± 311	843	2390	-0.0052855	0.000
Mean annual minimum temperature (^{o}C)	13.72 ± 2.37	9.122	18.28	-0.4173723	0.000
Mean annual maximum temperature (^{o}C)	27.63 ± 1.63	23.05	30.98	-0.7725938	0.000
Mean annual precipitation (mm)	82.79 ± 23.29	35.58	129.33	0.0130550	0.000

Table 7
Climatic factors associated with *C. kingi* occurrence using univariable Poisson regression analysis

Factors	Mean ± SD	Minimum	Maximum	Poisson regression coefficient	p-value
Altitude/elevation (masl)	1572 ± 311	843	2391	-0.0100289	0.000
Mean annual minimum temperature (ºC)	13.72 ± 2.37	9.122	18.28	-1.2033084	0.000
Mean annual maximum temperature (ºC)	27.63 ± 1.63	23.05	30.98	-0.4614878	0.000
Mean annual precipitation (mm)	82.79 ± 23.29	35.58	129.33	0.0079859	0.000

Species distribution modeling

We chose to model the distribution of the two most common *Culicoides* species, *C. imicola* and *C. kingi*. The ensemble model performed very well for both species with (KAPPA (0.9), TSS (0.98), and ROC (0.999) for *C. imicola* and (KAPPA (0.889), TSS (0.999), and ROC (0.999) for *C. kingi*.

C. imicola has a wider suitability range compared to *C. kingi*. The Great Rift Valley in Ethiopia and southern and eastern Ethiopia have a high suitability range for *C. imicola*. Suitability of *C. imicola* is also high in northern Ethiopia, particularly along the Blue Nile and Lake Tana catchments. Central Ethiopia has a patchy suitability range. The model predicts Gambela, Benshangul Gumuz, western parts of Oromia, Tigray, Afar, and Somali region as moderately suitable (Fig. 2).

A high suitability range for *C. kingi* was observed in central Ethiopia and in SNNPR. The ensemble model predicted the other parts of the country as moderately suitable, with the exception of the Afar and Somali regions, for which the model predicted lower suitability (Fig. 3).

According to the results of this ensemble modeling, the distribution of *C. imicola* depends mainly on soil type (15.7%), altitude (12.5%), livestock distribution (12.5%), solar radiation (12.1%), and mean annual minimum temperature (11.8%). For *C. kingi*, they are wind speed (43.4%), soil type (10.8%), altitude/elevation (10.6%), and vapor pressure (8.8%) (Table 8).

Table 8
Variables contribution in the predicted distribution of *C. imicola* and *C. kingi*

Variables	Contribution (%)	
	C. imicola	*C. kingi*
Soil type	15.8	10.8
Altitude	12.5	10.6
Livestock distribution	12.5	7.4
Solar radiation	12.1	6.4
Mean annual minimum temperature (^oC)	11.8	1.3
Annual precipitation (mm)	9.7	3.3
Land Cover	8.9	3.3
Vapor pressure	7.0	8.8
Wind speed	5.0	43.4
Mean annual maximum temperature (^oC)	4.8	4.7

Discussion

AHS, BT bluetongue and SBV are economically important Culicoides-borne viral diseases affecting equids and ruminants. The importance of these arboviral diseases derives from their very wide geographic distribution, potential for rapid spread, and large economic impact [1,2]. A considerable number of studies reported widespread occurrence of these diseases in Ethiopia. Demissie [40] reported AHS from Gamo Gofa, Wolaita and Hadiya zones of SNNPR. Zeleke et al [41] reported the occurrence of AHS in southern (Awassa, Hossana, Wondogenet, and Hagereselam), western (Jimma, Bedelle, Nekemte, Horroguduru, and Chaliya), and central (Bishoftu, Meki, Zeway, Filtimo, and Bekejo) Ethiopia using virus neutralization tests. Ayelet et al [42] reported AHS from Ada'a, Bahir Dar, Mecha, Dangla, Jimma and Sodo and Aklilu et al [11] reported AHS from central Ethiopia using reverse transcription polymerase chain reaction (RT-PCR) and virus isolation. Gizaw et al [13] reported the presence of group-specific antibodies against bluetongue virus using competitive enzyme-linked immunosorbent assay (c-ELISA) from Adami Tulu, Amibara, Areka, Arsi Negelle, Bene Tsemay, Doyo Gena, G/Mekeda, Fafan, and Jinka. Abera et al [14] reported the presence of bluetongue antibodies from Jimma, Bonga and Bedelle using c-ELISA and Gulima [43] reported the presence of bluetongue antibodies from Amhara regional state in northern Ethiopia. There is only one study on the sero-prevalence of SBV in Ethiopia. The author reported a very high apparent seroprevalence of 56.6% [10].

These diseases are transmitted by females of several species of midges belonging to the large genus Culicoides (Diptera: Ceratopogonidae) (which includes more than 1,300 described species worldwide [44,45]. In this study, morphological identification confirmed the presence of seven species in Ethiopia. In the current study, various Culicoides species were collected, of which C. imicola was the largest number 4830 (52.8%). Similar to these results, entomological surveys carried out in many sub-Saharan African countries show that C. imicola is the dominant species [22,23, 46–48]. A previous study by Mulatu and Hailu [30], reported the presence of *C. imicola, C.*

milnei, *C. neavei*, *C. zuluensis*, *C. fulvithorax* and *C. isioloensis* in western parts of Ethiopia and Khamala and Kettle [31] reported the presence of *C. fuscicaudae*.

Poisson regression models were used to model the relationship between various environmental and climatic factors and the distribution of C. imicola and C. kingi catch. For both species, significantly higher catch was obtained in the subhumid agro-ecological zone. This finding suggests that Culicoides species require breeding habitat with high relative humidity and high temperatures [49]. In the current study, higher numbers of Culicoides were caught in traps placed near animal pens. This result is consistent with Riddin et al [50] that reported high Culicoides catches near horse barns. The abundance of Culicoides near animal pens is mainly due to the presence of suitable breeding sites represented by moist soil sites, leaking animal watering troughs, and pond edges contaminated with feces [51].

The present study shows that mean annual minimum temperature, mean annual maximum temperature, and elevation are unfavorably related to *C. imicola* and *C. kingi* catches. Increases in mean annual minimum temperature, mean annual maximum temperature, and altitude/elevation significantly decreased the number of catches. However, higher catch numbers were positively associated with an increase in mean annual precipitation. Gusmão et al [21] et al suggests that persistent or heavy rain can create conditions for biting midges to proliferate but it can also be a barrier to the activity of adult (winged) biting midges and prevent them from flying. Rain can prevent adults from leaving their shelters. Culicoides vector activity generally declines or even ceases at low temperatures, and high temperatures (≥ 40˚C) are also lethal [36]. Foxi et al [51] also reported relatively poor tolerance of *Culicoides* to lower temperatures.

Various climatic and environmental factors were used to model the species distribution of *C. imicola* and *C. kingi*. Soil type, altitude/elevation, livestock distribution, solar radiation, and mean minimum annual temperature were the most important variables for the *C. imicola* model. Wind speed, soil type, altitude/elevation, and vapor pressure were the variables that contributed most to the model for *C. kingi*. Although there is no previous information on the climatic requirements of *C. kingi*, numerous studies have examined the role of various climatic and environmental factors on the distribution and abundance of *C. imicola*. Global ensemble modeling of *C. imicola* by Leta et al [29] reported temperature covariates contributing 64% to their model. This is supported by Veronesi et al [52] which showed that temperature can affect fecundity, hatching, and survival of *C. imicola*. When reared at a higher temperature (28°C), *C. imicola* exhibited higher variability in fecundity and lower hatch rates, and the mean emergence rate from pupae was highest at 20°C. The distribution of *C. imicola* is probably directly limited by its relatively low tolerance to lower temperatures [53]. As temperatures rise, adults hatch and populations gradually increase to reach a peak in abundance in spring or summer, depending on the site, which is a function of spring temperatures and summer drought. Because temperature shortens larval development time and the time between two blood meals, thus increasing laying frequency, which has a positive effect on population dynamics (and their growth), we expected that temperature would have a significant effect on abundance [24].

Our study also showed that solar radiation and livestock distribution are influential variables in the spread of *C. imicola.* According to Conte et al [54], intense solar radiation on *C. imicola* larval habitat combined with high nighttime temperatures accelerates larval development, resulting in multiple generations/season. The importance of livestock as a source of blood meals for *C. imicola* is well established [55]. *C. imicola* is a bloodsucking insect that tends to feed on blood and breed near livestock and humans. The frequency of contact between Culicoides and vertebrate hosts is closely related to the multiplication of the pathogen and the risk of transmission [55,56].

In this study, *C. imicola* was found to have a larger suitable range compared to *C. kingi*. Globally, *C. imicola* is widespread in tropical and subtropical regions of Africa, the southern part of Europe, and some parts of Asia [57]. The model describes that all regions have a small to large range of suitable areas, with Oromia and SNNPR regions having a larger range of suitable areas. High suitability for *C. imicola* was also demonstrated in the Amhara region, particularly adjacent to the Blue Nile basin and Lake Tana, in southern Afar, and in areas of the Somali region adjacent to Oromia. The results of the current model overlap in many ways with the previously published model of Leta et al [29]. The current model emphasizes at national level by elaborating the distribution of *C. imicola* and *C. kingi* suitability in different regions of the country.

In conclusion, the entomological study shows the occurrence of C. imicola and C. king in different parts of Ethiopia, with C. imicola predominating. The widespread occurrence of these species indicates a higher risk of SBV, BT and AHS in different parts of Ethiopia. The models could help to understand the risk of introduction and spread of SBV, BT, and AHS.

Declarations

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Availability of data and materials

The datasets generated during and/or analyzed during the current study are available from the corresponding author up on request.

Authors' contributions

EF: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing
GT: Formal analysis, Investigation, Writing – original draft
HD: Data curation, Investigation

DM: Data curation, Investigation

TT: Data curation, Investigation

DT: Data curation, Investigation

HN: Conceptualization, Formal analysis, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing
TM: Data curation, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing
MBJ: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing

SL: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing

Ethics approval and consent to participate

Ethical approval was obtained from ethics committee of the College of Veterinary Medicine and Agriculture of Addis Ababa University. Written informed consents were obtained from all households who participated in the study.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Figures

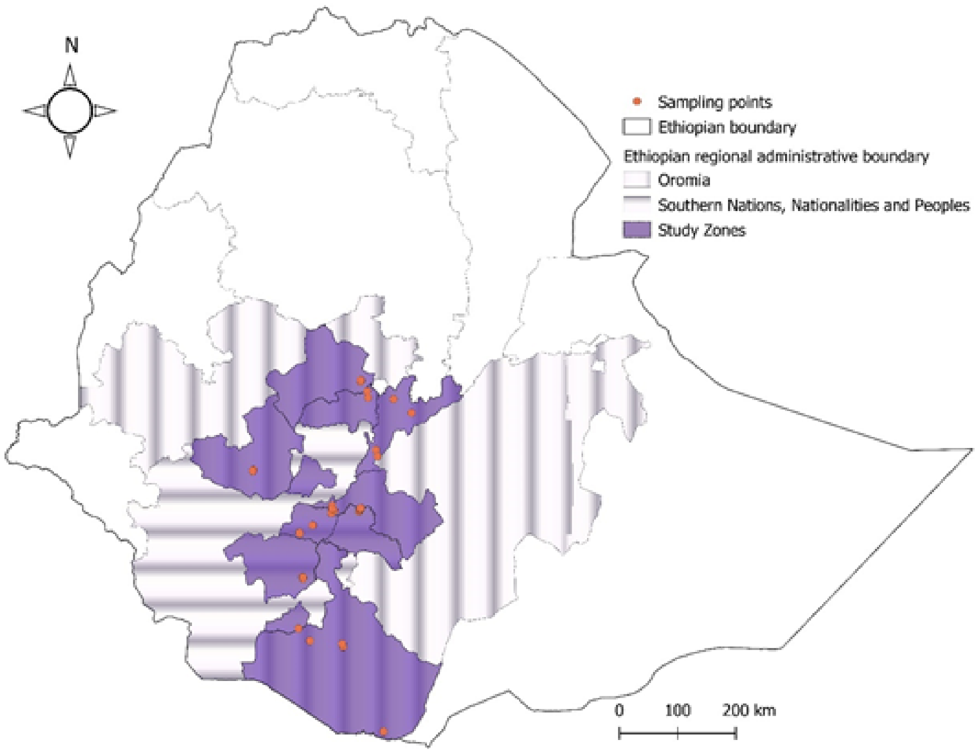

Figure 1

Map of *Culicoides* collection sites

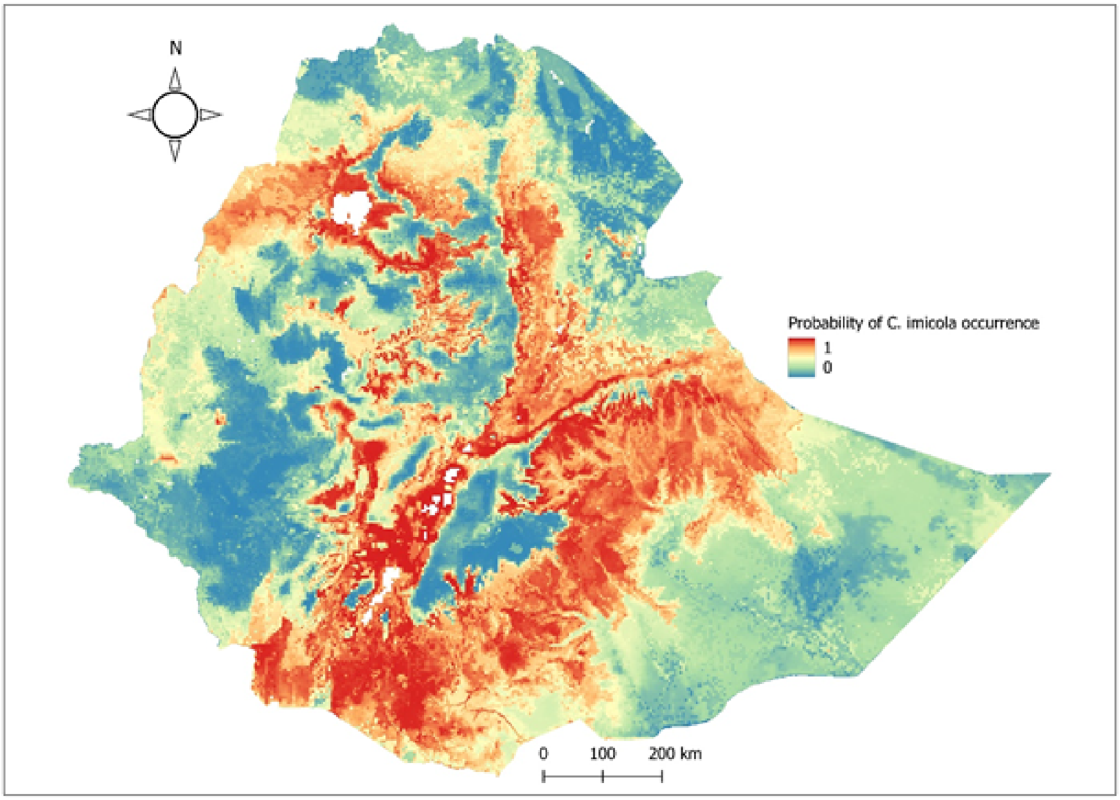

Figure 2

Probability of *C. imicola* occurrence in Ethiopia. Highly suitable areas are represented with red color while unsuitable areas are represented using blue colour.

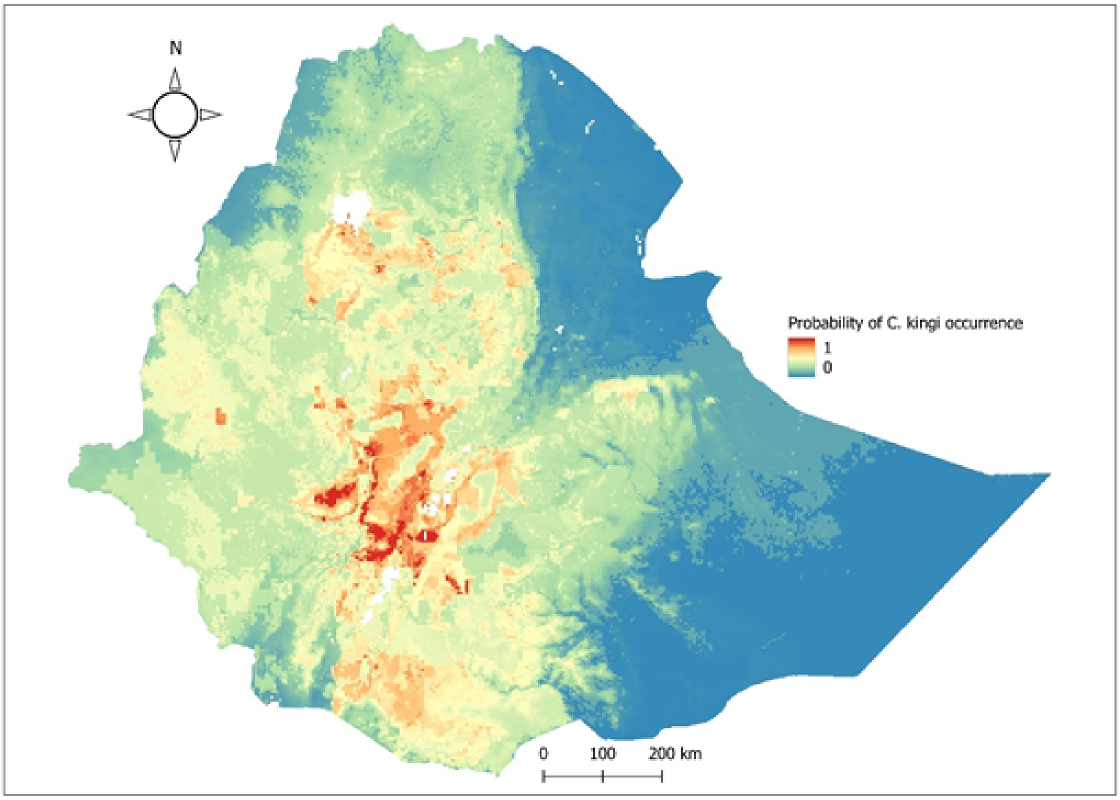

Figure 3

Probability of *C. kingi* occurrence in Ethiopia. Highly suitable areas are represented with red color while unsuitable areas are represented using blue color.