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Linking spatial distribution of *Rhipicephalus appendiculatus* to climatic variables important for the successful biocontrol by *Metarhizium anisopliae* in Eastern Africa

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ABSTRACT

Cattle production is constantly threatened by diseases like East Coast fever, also known as theileriosis, caused by the protozoan parasite *Theileria parva* which is transmitted by ticks such as the brown ear tick, *Rhipicephalus appendiculatus*. To reduce the extensive use of chemical acaricides, fungal-based microbial control agents such as *Metarhizium anisopliae* have been tested and show promising results against *R. appendiculatus* both in field and in semi-field experiments in Africa. However, no known endeavors to link the spatial distribution of *R. appendiculatus* to climatic variables important for the successful application of *M. anisopliae* in selected East African countries exists. This work therefore aims to improve the successful application of *M. anisopliae* against *R. appendiculatus* by designing a temperature-dependent model for the efficacy of *M. anisopliae* against three developmental stages (larvae, nymphs, adults) of *R. appendiculatus*. Afterward a spatial prediction of potential areas where this entomopathogenic fungus might cause a significant epizootic in *R. appendiculatus* population in three selected countries (Kenya, Tanzania, Uganda) in Eastern Africa were generated. This can help to determine whether the temperature and rainfall at a local or regional scale might give good conditions for application of *M. anisopliae* and successful microbial control of *R. appendiculatus*.

1. Introduction

Livestock and livestock-derived products have proven to play a crucial role for agricultural intensification, food production and sustainable consumption. Cattle are the most widespread ruminant livestock worldwide (Gilbert et al., 2018), raised for their meat, milk leather and, are also used in agriculture as draught animal for pulling carts and transporting crops. In Sub-Saharan Africa, cattle farming highly contributes to reduce poverty and starvation, as main source of income for many rural households and by increasing food supply. Unfortunately, the activity is subject to the attacks from various vector borne pathogens causing death and diseases such as African horse sickness, rift valley fever, and east coast fever. These diseases are usually transmitted by vectors such as ticks and mosquitoes.

Ticks are the main vector of animals diseases (Tongue and Ngapagna, 2019), with around nine species including the brown ear tick, *Rhipicephalus appendiculatus*, known as the principal vector transmitting the *Theileria parva* parasite that cause East Coast fever also known as theileriosis in cattle (Cunningham, 1981; Kimaro et al., 2017). The disease is lethal in cattle and has been reported in 11 countries in Eastern, Central and Southern Africa (CABI, 2019a; Kalume et al., 2011). Assessed direct economic loss associated with theileriosis is huge with more than 1.1 million cattle deaths due to the disease yearly (Kivaria et al., 2007; Mukhebi et al., 1992).

The *Rhipicephalus appendiculatus* life cycle consists of four developmental stages: egg, larvae, nymph, and adult. The peak activity for adults occurs in the rainy season and the peak for larval and nymphal stages occur during the dry season (Short and Norval, 1981). Up to three generations of ticks over a single year can occur in area with enough rainfall (Kasaija et al., 2021; Spickler, 2022). Only nymphs and adults can transmit infections such as the East Coast fever, and only larvae and nymphs can become infected. *Rhipicephalus appendiculatus* feeds on three different hosts (a so-called three-host-tick). Even though it changes the host, it generally does not change the host species (Mwabi et al., 2000).

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Still, *Rhipicephalus appendiculatus* may feed on various group of ruminants including sheep and goat but its preferred hosts are cattle, buffalo and large antelope. Their predilection sites of feeding are ears and anal region (Kasaija et al., 2021). Their occurrences are mainly reported in woodlands or woody savannas, in area where the annual rainfall is at least 24 inches (610 mm) (Spickler, 2022). In Africa, these ticks are commonly found in the eastern, central, and southeastern part of the continent from the sea level to about 2300 meter above the sea.

The expansion of animal husbandry combined with the huge density of livestock available in warm African countries provide a good reservoir for ticks and a suitable environment for the spread of the pathogens they vector. The commonly used approach for the management of ticks include synthetic acaricides and repellents (Cafarchia et al., 2022; Nicholson et al., 2019). Often, these are reported to have negative side effects to humans, animals and the environment and acaricide residues are reported both in meat and milk (Basu and Charles, 2017). Synthetic acaricides are strategically applied at the beginning of the rainy season, to halt the reproduction of adult ticks, and at the end of the rainy season to suppress emerging larvae or adult ticks that withstood the initial treatment (Basu and Charles, 2017). Due to an extensive acaricide application, acaricide resistance have developed in *R. appendiculatus* and many others tick species and reduced efficacy is seen (Sparagano and Giangaspero, 2011; Walker et al., 2014). Due to the situation described above, alternative strategies are developed to control *R. appendiculatus* and its vectored diseases (Nana et al., 2015; Benelli et al., 2016) in a strategy called integrated vector management (IVM) (WHO, 2012). These include vaccination against the vectored viruses; the use of pheromone traps and lure to monitor *R. appendiculatus* and finally the use of biocontrol methods (Benelli et al., 2016).

In Africa, the use of biological control methods as a part of IVM of *R. appendiculatus* has evolved significantly over the years (Hassan et al., 1991; Kaaya et al., 2006; Kaaya and Hedimbi, 2012; Staffa et al., 2020; Zekeya et al., 2020). A study by Hassan et al. (1991) in Kenya demonstrated that chickens were natural predators of ticks and could be used against *R. appendiculatus* (Hassan et al., 1991). Further, five entomopathogenic nematode strains were tested for their pathogenicity on five African ticks species including the brown ear ticks (Kaaya et al., 2006). A few years later Kaaya and Hedimbi (2012) and Nana et al. (2015) reported semi-field experiments showing the success in using two isolates of *Metarhizium anisopliae Sensu stricto* and *Beauveria bassiana* for the control of *R. appendiculatus* at different tick developmental stages. They revealed that up to 100% mortality of larval and nymphal stages was possible. Microbial control can be viewed as applied epizootiology with the goal of inducing an epizootic (defined as an outbreak of a disease in which there is an unusually large number of cases in the targeted insect population) through manipulation Shapiro-Ilan et al, (2012). Models have been used to mimic and predict the success of a biological process as described by Kamga et al (2022). Epizootiological development of an entomopathogenic fungus in an insect population resides on four factors that are known to influence epizootiology: (i) the pathogen population, (ii) the host population, (iii) transmission of the pathogen and (iv) the environment (biotic and abiotic) (Fuxa and Tanada, (1987); Hesketh et al., (2010). These needs to be considered when modelling an epizootic. Despite the successful field evaluation of the efficacy of *M. anisopliae* against *R. appendiculatus* subject to different temperatures, this has not been investigated at a large spatial scale. Temperature has a great influence not only on the epidemic development of *M. anisopliae* in a *R. appendiculatus* population but also on the development and abundance of the parasite *Theileria parva* that is vectored *R. appendiculatus* (Young and Leitch, 1981). Also, relative humidity is known to be an important abiotic factor affecting the epizootiological development of a fungal entomopathogen in a host population (Fuxa and Tanada, 1987). In our study, we therefore included two abiotic factors namely temperature and rainfall in our modelling framework to explore the success of a specific introduction and predict the optimum release and the management strategies subject to these two abiotic factors.

Mathematical modelling has always been a reliable tool for understanding and predict complex interactions in biological system driven by climate variability (Sumner et al., 2017; Guimapi et al., 2020b; Chiuya et al., 2021). In the context of ticks and the tick-borne disease system, analytical models using differential equations have been developed to study the vector-host interaction between cattle and *R. appendiculatus* (Mwambi et al., 2000; Gilioli et al., 2009). Further, a mechanistic model was recently developed by Tardy et al. (2021) to highlight the importance of hosts movement and tick population dynamics as keys drivers of the tick-borne pathogen spread in heterogeneous landscapes (Tardy et al., 2021). Climate-driven models have been used to explore how temperature influence the performance of entomopathogenic fungi against arthropod plant pests (Guimapi et al., 2020a; Omuse et al., 2021). One important aspect is, however, often missing and that is how to link these models' prediction with climate data and generate maps which will display the spatial variability of the climatic variables in question and hence the potential efficacy of the entomopathogenic fungus. By using these maps, it will hopefully be easier to select areas for successful application fungal based microbial control of the pest.

Maps are powerful tools for visualizing the spatial variability of the interaction between component described by models. The mechanism of ticks' interaction with their host in East Africa is continuously changing due to the effect of climate change and the constant expansion of land-use for cattle production (Chiuya et al., 2021). It has been demonstrated that the movement of livestock might contribute to up to 90% in the transmission of the vector-borne disease within livestock (Sumner et al., 2017). Considering livestock dynamic and climate variability, the ability to circumscribe spatially the area of potential efficacy of *M. anisopliae* against *R. appendiculatus* could add great value for eco-friendly management of livestock in Africa.

The objectives of this paper are: (i) To design a temperature-dependent model for the potential efficacy of *M. anisopliae* isolate ICIPE7 *Sensu stricto* as a biocontrol agent of three *R. appendiculatus* developmental stages (larvae, nymphs, adults); and (ii) To generate a temperature and rainfall based spatial prediction of potential areas where *M. anisopliae* isolate ICIPE7 *Sensu stricto* might be able to infect and kill *R. appendiculatus* in selected countries in East Africa.

2. Materials and methods

2.1. Study area

Countries in East-African where *R. appendiculatus* is commonly reported and where large cattle populations are found were the focus of the study. These are Tanzania, Kenya, Uganda and Ethiopia (Lars, 2020). Within these countries, *R. appendiculatus* distribution consists of various discontinued patches restricted by suitable hosts and climatic factors (CABI, 2019b).

2.2. Input dataset

2.2.1. Laboratory virulence data

The *M. anisopliae Sensu stricto* isolate ICIPE7 used in this study was obtained from icipe's Arthropod Germplasm Centre. The strain was isolated from an engorged *Amblyomma variegatum* female collected from Rusinga Island, Kenya, in 1996 and was previously reported to be virulent against *R. appendiculatus* (Nana et al. 2015). The *M. anisopliae* isolate was grown for 2 weeks on SDA plates. Conidia were then harvested from the SDA plates and suspended in sterile distilled water with 0.05% Triton X-100. A spore suspension of 1.0×10^6 conidia ml^{-1} was prepared and was then assessed for viability of the fungus (Nana et al. 2015). Conidial germination > 90 % after 18–20 h on Sabouraud dextrose agar was considered adequate for use in this laboratory experiments.

The 1.0×10^6 conidia ml^{-1} solutions were then used to test the efficacy of *M. anisopliae* isolate ICIPE7 towards *R. appendiculatus* in laboratory experiments at five temperatures (15, 20, 25, 30, 35 °C) in three tick developmental stages (larvae, nymphs, and adults). Sixty individuals of each *R. appendiculatus* developmental stage were inoculated with *M. anisopliae* isolate ICIPE7 at a consternation of 1.0×10^6 conidia ml^{-1} and a control treated with 0.05% Triton 100-X in sterile distilled water. The application of the fungus was done by using a 1-L garden sprayer to spray onto batches of 60 larvae, 60 nymphs and 60 adults *R. appendiculatus* displayed on a large filter paper (25×25 cm) on a laboratory bench. Batches of 10 treated ticks were placed in a single petri dish with moist filter paper. The Petri dishes were sealed with parafilm and incubated at (15, 20, 25, 30 or 35°C), 85 ± 5% RH and a 12:12h L:D photoperiod for 2 weeks. They were then recorded daily for mortality. Dead ticks were placed in a moist chamber and observed for fungal outgrowth to confirm mortality due to fungal inoculation. Every experiment was done for 10 days and replicated three times. Mean percentage mortality at each of these temperatures was estimated and the entire data recorded and structured per replicate and temperature to serve as input for the temperature-dependent modeling process.

2.2.2. Climatic data

Climate data were used to perform the spatial projection of the zone of efficacy of the entomopathogenic isolate ICIPE7 against *R. appendiculatus* toward the targeted countries. Temperature is considered as the main climatic factor in the context of this work and were obtained from the WorldClim database (http://www.worldclim.org/current) (Fick and Hijmans, 2017). Rainfall data were also considered important and was obtained from the same database. These dataset are made of layers containing monthly mean, maximum and minimum records in raster files in "Flat" format (*.flt* and *.hdr* file), with a spatial resolution varying from 10 arc-minutes (~20 km) to 30 arc-seconds (~1 km). The to 30 arc-seconds (~1 km) was used in the context of this study.

2.3. Modelling approach

2.3.1. Estimation of the model parameters

The estimation of the model parameters was done following the complete model fitting process. The process consists of pre-regression, regression, and post-regression steps, which were all performed by the entomopathogenic fungi application (EPFA) software version 1.0 (Guimapi et al., 2020a). The EPFA is an open-source decision support system designed with a component-based software architecture and built by combining R and Java programming language. The software provides the user through the user interface a set of 82 mathematical equations that can be selected to fit the data. The regression was performed on each of the 82 equations by estimating the parameters of each of these equations; afterward the goodness of fit was done based on a various criterion to evaluate these models. Detailed on the procedures and steps to estimate the best model parameters as per the define input data can be found in (Guimapi et al., 2020a).

2.3.2. Models' selection criteria and goodness of fit

There are currently many available techniques to assess the goodness of fit of a model to data which are also useful for selecting of the best fitted model when several mathematical expressions are fitted to the same dataset. The best selected model depends on many factors that consider visual assessment, the biological knowledge of the studied process and the good interaction between the biologist and the modelers. Several selections criteria were used which include R-squared (R^2), R-squared adjusted (R^2_Adj), Akaike's Information Criterion (AIC), Root mean squared error (RMSE) and sum of squared residuals (SSR) given by the following expression (Guimapi et al., 2020a).

$$R_z^2 = 1 - \sum_{k=1}^{n} \left(y_k - \widehat{y}_{kz}\right)^2 - \sum_{k=1}^{n} \left(y_k - \overline{y}\right)^2 \tag{1}$$

Where, $\overline{y}$ is the observed median, y the observed mean and $\widehat{y}_{kz}$ is the k^{th} predicted value from the i^{th} function.

$$R^2_{\_Adj} = 1 - \left(1 - R_z^2\right)\left(\frac{n-1}{n-k-1}\right) \tag{2}$$

where, *n* is the number of observations, *k* is the number of parameters of the z^{th} sub-model while and R_z^2 the R–squared (R^2)

$$AIC = nln - \left(\sum_{k=1}^{n} w_k \left(Y_{O_k} - Y_{E_k}\right)^2\right) + 2p \tag{3}$$

Where, *n* represents the number of observations, *p* is the number of parameters, w_k is the weight required for each observation, Y_{O_k} the observed values and Y_{E_k} the estimated values for the *k*th observation.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{k=1}^{N} y_k - \widehat{y}_k^2}{N}} \tag{4}$$

Where, y_k is the kth measurement, and $\widehat{y}_k$ is its corresponding prediction

$$\mathrm{SSR} = \sum_{k=1}^{n} \left(\widehat{y}_k - \overline{y}\right)^2 \tag{5}$$

Where $\widehat{y}_k$ is the *k*th value of the variable to be predicted, $\overline{y}$ predicted value of y_i

2.3.3. Temperature-dependent mortality model

For each of the tick developmental stages, the selected best fitting equation was used as a temperature-dependent model to describe the efficacy of the *M. anisopliae* isolate ICIPE7 in controlling *R. appendiculatus*. These models are the Allahyari (2005) model for the Larval stage, the Wang and Engel (1998) model for the Nymphal stage and the Log normal 3-parameter (Archontoulis and Miguez, 2015) for the Adult stage. The mathematical expression for each model is given below:

The Allahyari model for Larvae

$$m(T) = p\delta^n(1-\delta^n)\text{where } \delta = \frac{T - T_{\min}}{T_{\max} - T_{\min}} \ldots n \in Z \rightarrow n \in R; m \in Z \rightarrow T \in R \tag{6}$$

Where P, n and m are constants values, $T_{mim}$and $T_{\max}$respectively minimum and maximum temperature.

The Wang et Engel model for Nymphs

$$m(T) = \frac{2\left((\mathrm{T} - \mathrm{Tmin})^{\left(\frac{\log(2)}{\log\left(\frac{\mathrm{Tmax}-\mathrm{Tmin}}{\mathrm{Topt}-\mathrm{Tmin}}\right)}\right)}\right)\left((\mathrm{Topt} - \mathrm{Tmin})^{\left(\frac{\log(2)}{\log\left(\frac{\mathrm{Tmax}-\mathrm{Tmin}}{\mathrm{Topt}-\mathrm{Tmin}}\right)}\right)}\right) - \left((\mathrm{T} - \mathrm{Tmin})^{\left(\frac{2*\log(2)}{\log\left(\frac{\mathrm{Tmax}-\mathrm{Tmin}}{\mathrm{Topt}-\mathrm{Tmin}}\right)}\right)}\right)}{\left((\mathrm{Topt} - \mathrm{Tmin})^{\left(\frac{2*\log(2)}{\log\left(\frac{\mathrm{Tmax}-\mathrm{Tmin}}{\mathrm{Topt}-\mathrm{Tmin}}\right)}\right)}\right)} \tag{7}$$

Where T_{mim},$T_{\max}$and T_{opt} are respectively the minimum, maximum, and optimum temperature for the mortality caused by the fungus.

The Log normal 3-parameter for Adults

$$m(T) = a.\exp\left(-0.5*\left(\frac{\log\left(\frac{T}{T_{opt}}\right)}{b}\right)^{2}\right) \tag{8}$$

Where a is a constant and and T_{opt} is the optimum temperature for the mortality caused by the fungus.

2.3.4. Spatial projection of the efficacy model in the studied area

The spatial projection of the zone of efficacy is initiated by uploading the temperature datasets layers into the EPFA software. For the region of interest, a spatial grid object is created and in each cell location of the grid, the average temperature value is extracted. Afterward, the temperature-dependent model is used to estimate the probability of the successful application within the cell location. The process is repeated for all the point coordinated of the grid (Guimapi et al., 2020). The resulting spatial grid data frame is then converted and saved into ASCII file format (.asc); which was uploaded into the geographic information system (GIS) software ArcMap for editing and visualization. The process was repeated for each country and for each of the three different tick developmental stages.

2.4. Model assessment

To assess the ability of the output map to provide guidelines for the deployment of EFP at large scales in the selected countries (Kenya, Uganda and Tanzania), the spatial projection of the predicted zone of *M. anisopliae* isolate ICIPE7 efficacy was primary compared to the reported potential geographical distribution of *R. appendiculatus* (Leta et al., 2013; Kasaija et al., 2021). Moreover, as it has been reported that by previous studies, ticks are able to maintain their activity continuously over the year in large area with warmer weather and annual rainfall greater than 610 mm per year (Spickler, 2022) . We overlaid the annual rainfall of the respective countries on the generated maps of potential zone of efficacy to compare it and check if there is certain spatial correlation. Indeed, this was done to ensure that the areas predicted with high potential of *M. anisopliae* isolate ICIPE7 efficacy fit with the location where the temperature and rainfall patterns are highly favorable for the establishment and survival of *R. appendiculatus*.

3. Results

The graphical representation of the temperature driven models for *R. appendiculatus* larva, nymph and adult developmental stages are presented in Fig. 1. The model corresponding parameters and shown in Table 1. Parameters estimated from the models using the laboratory data allowed an estimation of the mortality prediction for the corresponding stage.

3.1. Temperature-dependent model

The efficacy of *M. anisopliae* was influenced by temperature. The extreme temperatures (15 and 35 °C) had significant negative effects resulting in low mortalities. Mortality rates increased significantly with increasing temperatures from 20 to 30 °C, and was highest at 30 °C (91.4%) (Fig. 1) (Table 1).

3.2. Spatial projection of the efficacy

The spatial variability of the potential zone of *M. anisopliae* isolate ICIPE7 efficacy against the larva, nymph, and adult developmental stage of *R. appendiculatus* is presented in Figs. 2, 3 and 4 respectively.

The spatial projection of the potential efficacy of *M. anisopliae* isolate ICIPE7 against *R. appendiculatus* suggest that temperature and rainfall patterns generally appears to be important for a successful application of the fungal biopesticide at large scale, especially while targeting the immature developmental stage of *R. appendiculatus*. Indeed, based on the expected level of efficacy from the different developmental stage, the projected mortality is expected to be higher at the larva and the nymph

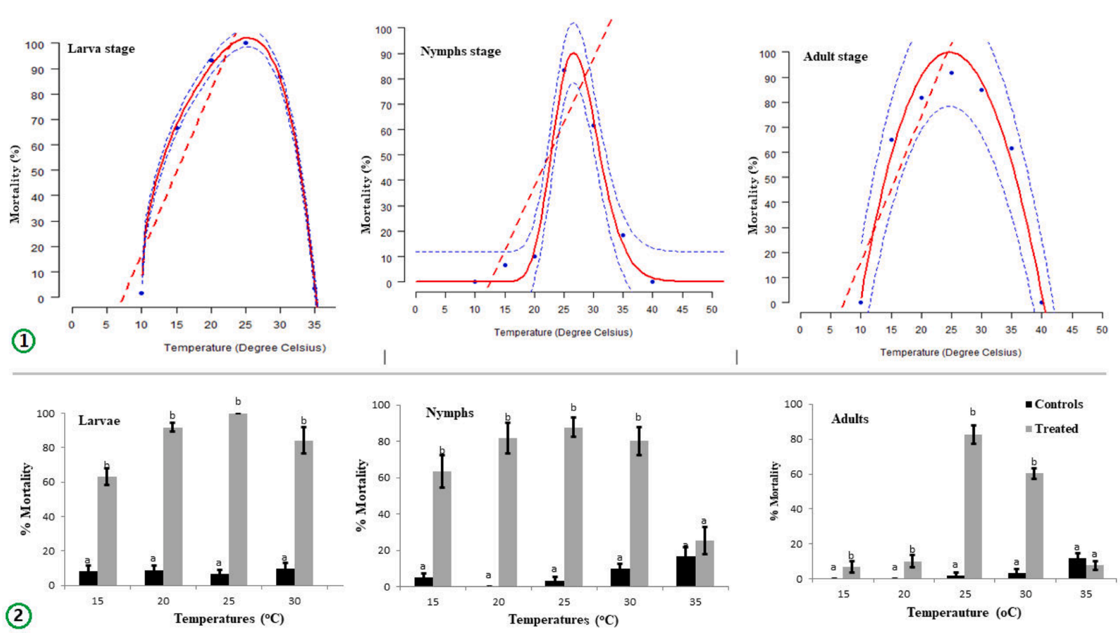

Fig. 1. Temperature-dependent *R. appendiculatus* mortality (Observed and predicted) caused by *M. anisopliae* isolate ICIPE7 using (1) both non-linear and linear modelling approach and (2) the histogram for different temperatures. The blue dot represents the proportion of *R. appendiculatus* killed by *M. anisopliae* isolate ICIPE7 at the corresponding temperatures in the experiments for the specific developmental stage. The red curve represents the (a) Allahyary model for the larval stage; (b) Wang er Engel model for the nymphal stage; (c) Log normal 3-paramete model for the adult stage. The dashed blue curve shows the boundary (lower and upper) of the 95% confidence interval. The control represents the expected mortality rates for uninfected ticks (larvae, nymphs and adults).

Table 1
Parameters of the various models characterizing the effect of temperature on *M. anisopliae* isolate ICIPE7 efficacy against different developmental stages of *R. appendiculatus*.

Developmental Stage	Model Name	Model parameter	Model Statistic						
			DF	*P*	*R2*	*R2_Adj*	*AIC*	*RMSE*	
Larvae	Allahyari	P	1.384	4	<0.001	0.9989	0.9986	-16.1	0.0134
		Tmax	35.124						
		Tmin	9.998						
		n	0.444						
		m	5.089						
Nymphs	Wang & Engel	Tmin	9.921	2	0.0007	0.9735	0.9602	-11.78	0.0589
		Tmax	40.222						
		Topt	24.701						
Adults	Log normal 3-parameter	a	0.902	2	0.0001	0.9891	0.9836	-20.27	-0.824
		b	-0.143						
		Topt	26.617						

Df: degree of freedom, R2: Coefficient of determination, AIC: Akaike's Information Criterion, RMSE: Root Mean Squared Error

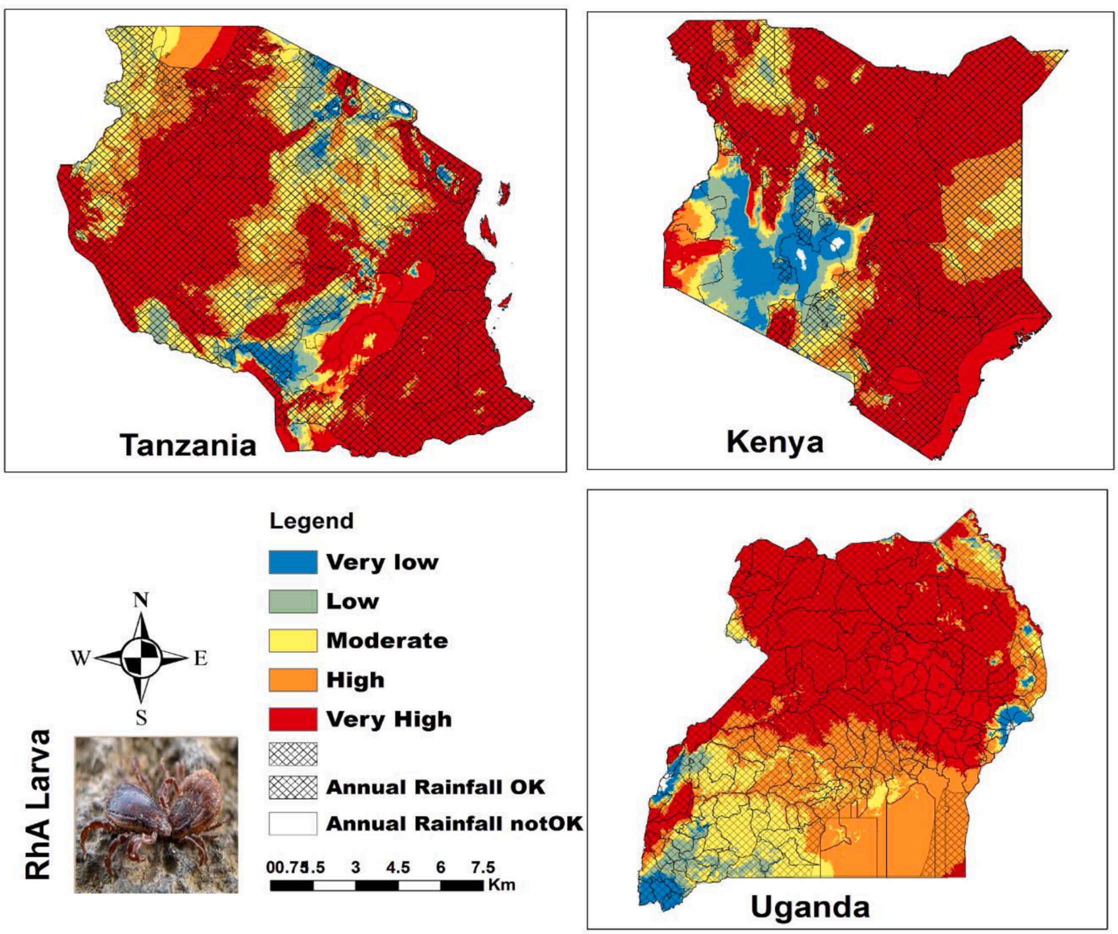

Fig. 2. Spatial projection of the potential efficacy of *M. anisopliae* isolate ICIPE7 as a biocontrol agent of the larval stage of *R. appendiculatus* in (a) Tanzania, (b) Kenya and (c) Uganda based on temperature and rainfall as the main factors.

stage than at the adult stage. The areas with moderate, high, and very high level of *M. anisopliae* isolate ICIPE7 efficiency against *R. appendiculatus* corelate well with the location with adequate amounts of rainfall (>610 mm/ year)

4. Discussion

To improve the chances for a successful application of *M. anisopliae* isolate ICIPE7 as a biocontrol agent of three developmental stages of *R. appendiculatus* (larvae, nymphs, adults), this work proposes a temperature-dependent model. Afterwards we generated a spatial prediction of potential suitable areas where *M. anisopliae* isolate ICIPE7 might potentially result in good *R. appendiculatus* control in three selected countries (Kenya, Tanzania, Uganda) in Eastern Africa.

It is already well established that modelling and computer simulation are key tools to improve the field implementation of the biological control strategy in IPM (Agboka et al., 2022; Guimapi et al., 2020b; Kamga et al., 2022). Indeed many models have been developed in the past decades to help understand the distribution, abundance and dynamic of *R. appendiculatus* in Central and East Africa (King et al., 1988; Okely et al., 2020; Olwoch et al., 2008; Perry et al., 1991; Vajana et al., 2018; Zannou et al., 2021; Zeman and Lynen, 2006). In Zeman and

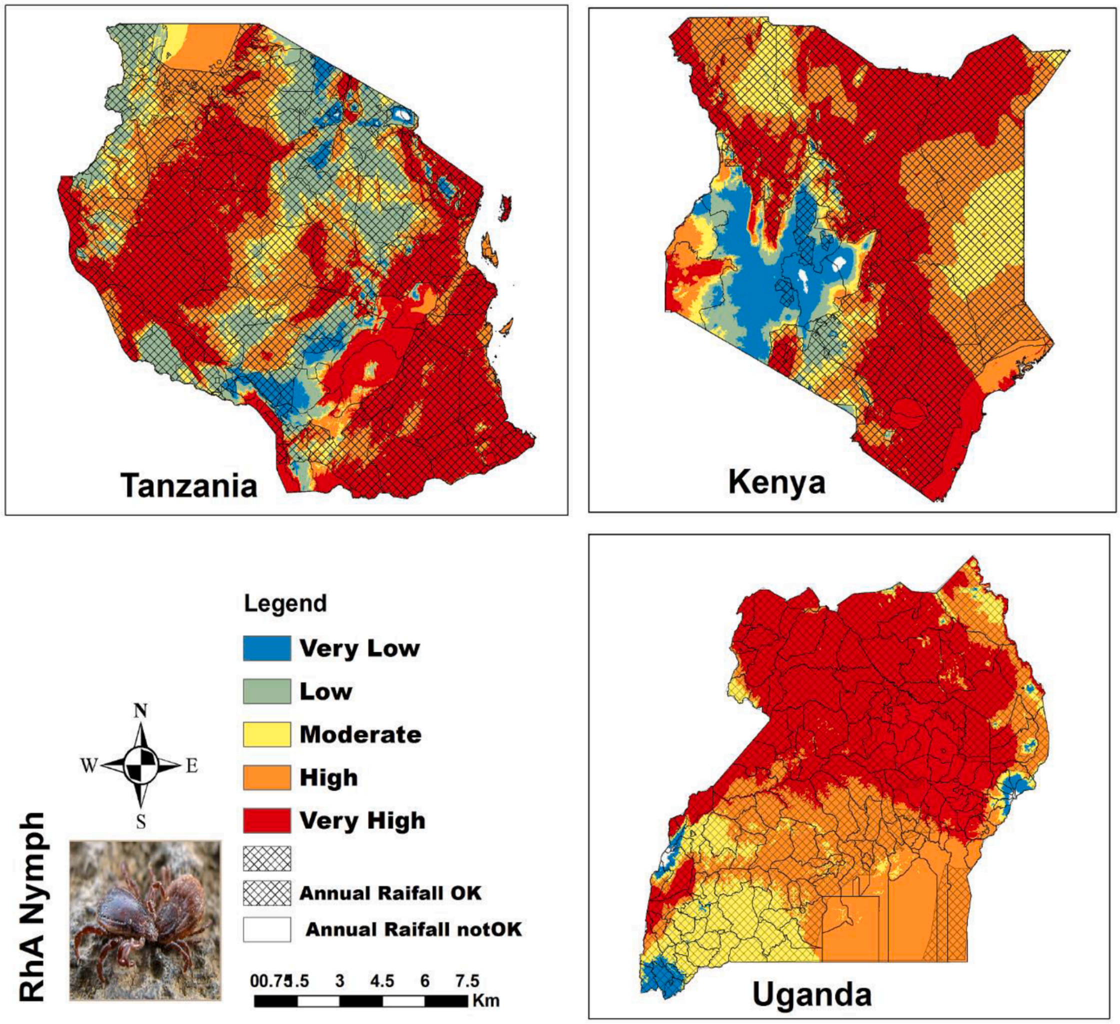

Fig. 3. Spatial projection of the potential efficacy of *M. anisopliae* isolate ICIPE7 as a biocontrol agent of the nymphal stage of *R. appendiculatus* in (a) Tanzania, (b) Kenya and (c) Uganda based on temperature and rainfall as the main factors.

Lynen (2006), they used cattle infestation data with four modelling techniques to evaluate and compare the spatial prediction of the potential distribution of *R. appendiculatus* in Tanzania under varying environmental conditions (Zeman and Lynen, 2006). The study by Vajana et al. (2018) investigated the adaptation of local Ugandan cattle to the east cost fever by combining ecological modelling and landscape genomics appraoches (Vajana et al., 2018). Futhermore, ecological niche modelling approach was used by Olwoch et al. (2008) to produce East Coast Fever risk maps in sub-Saharan Africa based on current and future modeled distribution of *R. appendiculatus* (Olwoch et al., 2008). More recently Okely et al. (2020) maped the environmental suitability of the Crimean-Congo hemorrhagic fever virus against the suitability of various tick vectors inclucing *R. appendiculatus*. All these models have in common that they focus on spatially predicting the potential areas for the establishment of *R. appendiculatus* in relation to climatic factors affecting cattle dynamics. Even the complex epidemiological model designed by Gilioli et al. (2009) that study the dynamic of the East Coast Fever in East Africa between cattle and tick using various scenario did not explore the effect of releasing fungal-based biocontrol agents on the dynamic of *R. appendiculatus* (Gilioli et al., 2009). Our work therefore extent these previous studies by mapping the areas of potential successful release of one of the fungal-based biocontrol agent *M. anisopliae* isolate ICIPE7, with the expectation to improve the field implementation strategy and control of *R. appendiculatus* in East Africa.

Adaptative management require the ability to accommodate the field implementation of integrated management strategy to the environmental changes. This is feasible with environmental modeling through models that embed key climates factors that help to capture and track how changes of climate variables influence the success of the control strategy (Tonnang et al., 2017). There is a risk that changes in land use and vegetation might extend the distribution of *R. appendiculatus* and hence increase the outbreaks of the vectored diseases in cattle (Smith and Parker, 2010). Direct effect involves milk and wool production which at a certain extent are temperature dependent, while indirect effect is the increase of vectored diseases which are also dependent on the climate. Further, global warming is affecting vegetation pattern distribution, and this will have immediate effect on cattle farming in Africa, requiring them to migrate toward suitable area with available pasture (Sumner et al., 2017).

Whitin the IPM/ IVM framework, the relationship between the biological control agent and the targeted pest is always a complex and dynamic process that involve the interaction of many biotic and abiotic factors. Previous laboratories and field studies have proven temperature to be the key abiotic factor that drive the successful release of and control by fungal entomopathogen against a target pest (Kasaija et al., 2021; Spickler, 2022). However, other abiotic factors such as rainfall, relative humidity and production practice used by famers are also known to have a great influence too. Therefore, the limitation of the current work is that the maps produced here are only temperature dependent and do not consider the effect of others important abiotic or

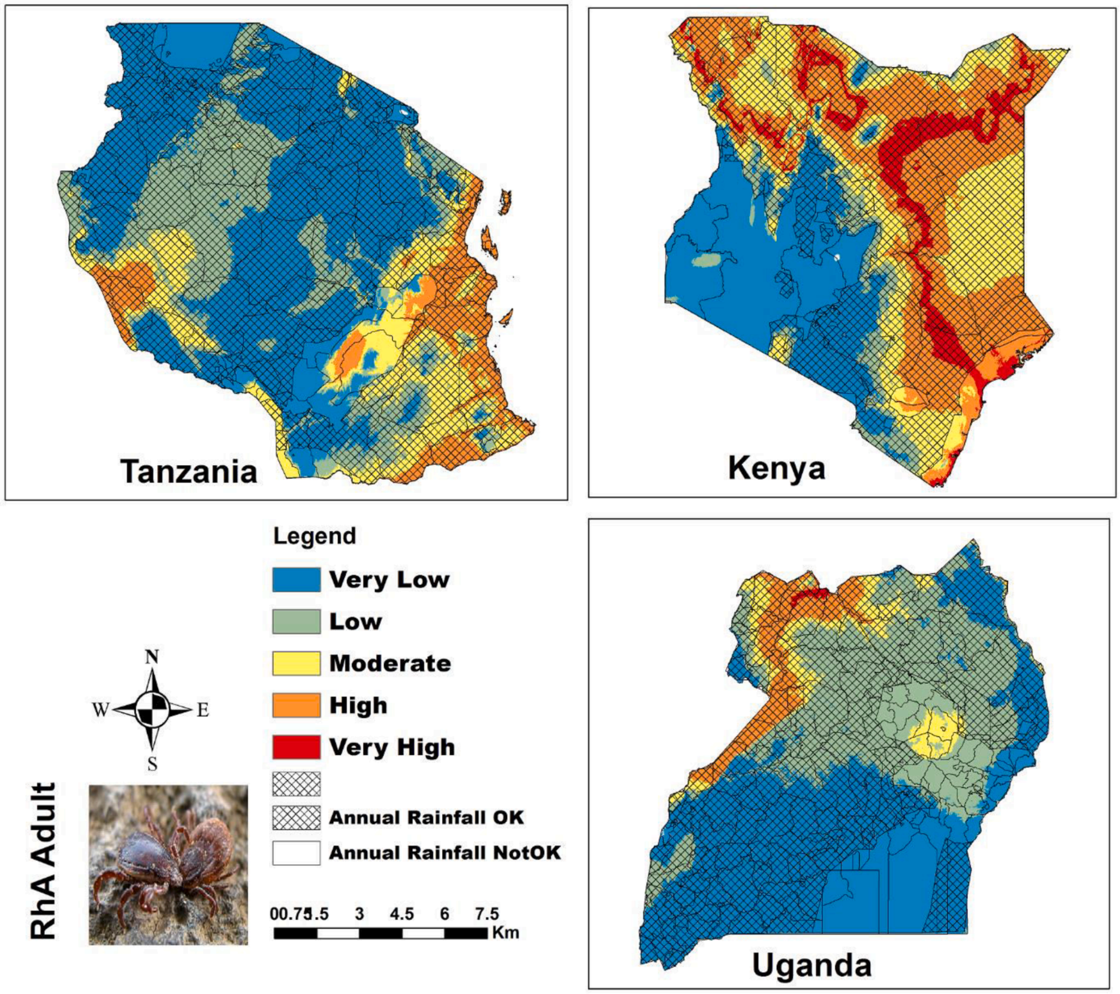

Fig. 4. Spatial projection of the potential efficacy of *M. anisopliae* isolate ICIPE7 as a biocontrol agent of the adult stage of *R. appendiculatus* in (a) Tanzania, (b) Kenya and (c) Uganda based on temperature and rainfall as the main factors.

biotic factors. Future modeling work with a systemic integrated and dynamic approach needs to include several other factors. It is important, however, to find out which of these factors are most important to include. This will rely on a good knowledge of the cattle-disease-vector-entomopathogen epizootiological system and a very close collaboration between the epizootiologist and the modeler as described by Mwambi et al. (2000) . Based on earlier studies, we suggest however, that the following factors might be relevant to include: (i) the host population, (ii) the transmission and (iii) the pathogen population (Hesketh et al., 2010; Mwambi et al., 2000).

Both worldwide and in Africa some fungal-based biocontrol agents are available as alternatives to chemical acaricides for controlling ticks on cattle (Alonso-Díaz and Fernández-Salas, 2021; Kaaya and Hedimbi, 2012; Klingen and van Duijvendijk, 2016; Nana et al., 2015; Samish et al., 2008). The field deployment of these products varies based on the available formulation, spray material and the scale of the area of interest. Previous studies reported a decline of up to 61% of ticks *Boophilus microplus* (Acari: Ixodidae) larva population following aerial dissemination of *M. anisopliae* in pasture (Ángel-Sahagún et al., 2010). Such result could be further improved by targeting the dissemination mainly to areas where the efficacy of the fungal based control agent is expected to be high due to favorable climatic condition. This will constitute an improvement that the current work is addressing through modelling and spatial analysis base on the right temperature range and precipitation (mm/year) (Alonso-Díaz and Fernández-Salas, 2021). The spot-spray application strategy of *M. anisopliae* explored by Nana et al. (2015) has proven to be effective against *R. appendiculatus* resulting in up to 80% mortality in a semi-field experiment. Based on the results it would be interesting to take this one step further and explore whether linking our spatial application map to drones for rapid and precise deployment of *M. anisopliae* in the field. The spatial projection of the potential zone of efficacy of the fungal isolate coupled with the proper identification of the right developmental stage of *R. appendiculatus* within cattle population by extension officer would help identify the zone to prioritize during application for optimal control. Some efforts should be put into place by these country to promote the adoption of fungal-based technology, especially in context where the cost of the application against the pest might turn cheaper in comparison to the budget used to import acaricides (Kaaya and Hedimbi, 2012)

In conclusion, we used laboratory data of the *R. appendiculatus* mortality caused by *M. anisopliae* isolate ICIPE7 at different temperatures on specific developmental stages of the tick to model and map the biocontrol potential of this isolate in three selected East African country with high prevalence of East Coast fever in cattle. The entomopathogenic fungi application (EPFA) software version 1.0 (Guimapi et al., 2020a) was used to build a temperature-dependent model and to generate maps that could serve as guide toward suitable locations where the fungal based biocontrol agent might be applied for a successful control. This model tool may improve IVM of this cattle disease in East Africa. Future work will consider modelling more factors important for the epidemiological development of this fungal based biocontrol agent in *R. appendiculatus* populations. Moreover, the use of ticks' population models should also be considered in the future to explore and understand the overall effect of the fungus on ticks' development stage in relation to landscape characteristic, weather, and other environmental factors affect the spatiotemporal abundance and diversity of ticks. Specific field data and information are needed prior performing that task as it would help estimate and calibrate the model parameters to fit tick dynamic of our area of interest. Generating maps that include these improved models will hopefully result in a more accurate spatial and temporal projection of where and when the control agent may result in successful control of *R. appendiculatus* (the brown ear tick). Moreover, successful control strategies for tick-borne diseases such East Coast Fever must be assisted by a surveillance system that inform about the population dynamic of *R. appendiculatus*, the risk of the transmission of the disease, or the effectiveness of a successful implementation of a suitable control strategy.

CRediT authorship contribution statement

Ritter A. Guimapi: Conceptualization, Data curation, Formal analysis, Methodology, Resources, Writing – original draft, Writing – review & editing. **Ingeborg Klingen:** Funding acquisition, Methodology, Resources, Writing – original draft, Writing – review & editing. **Henri E.Z. Tonnang:** Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing. **Paulin Nana:** Conceptualization, Funding acquisition, Methodology, Resources, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The author(s) declare no competing interests.

Data availability

Data will be made available on request.

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