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High-resolution predictive mapping for *Rhipicephalus appendiculatus* (Acari: Ixodidae) in the Horn of Africa

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Abstract The brown ear tick *Rhipicephalus appendiculatus*, vector of East Coast fever (ECF) and related cattle diseases caused by *Theileria parva* has never been reported from the Horn of Africa. Habitat suitability for this tick species was predicted using Maxent modelling technique based on *R. appendiculatus* records in Sub-Saharan Africa. Two models were developed: the first is based on the tropical *R. appendiculatus* distribution and the one is based on the distribution records in the temperate region of Sub-Saharan Africa. The tropical model shows favourable habitat in much of the Ethiopian highlands. The whole Djibouti, the south eastern Ethiopian lowlands, majority of Somalia and Eritrea were found to be not suitable for the survival and development of this tick species. Highly suitable areas occur in areas which have moderate temperature and high precipitation. Introductions of *R. appendiculatus* into the Horn of Africa probably have been prevented by the natural barrier between the known *R. appendiculatus* distribution range in East Africa and the Horn of Africa. The effect of an introduction of *R. appendiculatus* and thereby ECF into the Horn of Africa could be catastrophic since the cattle in this area have no immunity against ECF, and mortality might be considerable in all age groups of cattle.

Keywords East Coast fever · Habitat suitability · Horn of Africa · Maxent · *R. appendiculatus*

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Introduction

The brown ear tick *Rhipicephalus appendiculatus* is the main vector of the hemo-protozoan parasite *Theileria parva*, the causative agent of East Coast fever (ECF) (Perry et al. 1991). ECF is one of the most economically important cattle diseases because of high mortality, morbidity and other production losses associated with the disease (Mwambi et al. 2000). The disease causes heavy mortality in exotic Bos-taurus cattle of all breeds as well as in cross-bred and susceptible populations of indigenous Bos-indicus breeds. In susceptible cattle population the mortality can be as high as 95 % (Norval et al. 1991).

Rhipicephalus appendiculatus is widely distributed throughout eastern, central and southern Africa from southern Sudan in the north to the east coast of South Africa in the south, but it is absent from the Horn of Africa. ECF is present through the distributional range of *R. appendiculatus*, with the exception of southern Mozambique, Swaziland and South Africa where it was eradicated (Norval et al. 1991).

The geographical distribution of tick species are defined by a range of factors (Tonnesen et al. 2004). Climatic favourability is known to be the main factors that determine the geographical distribution of a tick species (Estrada-Pena 2001, 2006). *R. appendiculatus* mainly found in areas which have high precipitation and moderate temperature. The vegetation requirements for *R. appendiculatus* are known to include both grass and limited tree cover (Norval et al. 1991). Therefore, distribution of this tick is restricted to savannah and woodland savannah areas with a substantial annual rainfall. This tick species is usually absent from extensive and heavily forested zones (Madder et al. 2002; Norval et al. 1991).

Rhipicephalus appendiculatus is not a native tick species in the Horn of Africa. In an extensive survey of the whole country of Ethiopia (Pegram et al. 1981) did not record this tick. No report has been made about the presence of this tick species from Horn of Africa in general and from Ethiopia in particular. The potential of any species to invade regions other than their native ranges can be predicted by considering the conditions that describes the environmental preference of that species in those regions (Estrada-Pena et al. 2006b). A variety of species distributions modelling methods are available to predict potential suitable habitat for a species (Elith et al. 2006; Guisan and Thuiller 2005; Guisan and Zimmermann 2000). A couple of decades ago Norval et al. (1991) predicted the suitability of the Ethiopian highlands for *R. appendiculatus* using the climate-matching model CLIMEX at 25 km^2 spatial resolution. However, they used a coarse-resolution of 25 km^2 which could prevent their climate-matching model to capture a fine-scale suitable habitat. Furthermore, this modelling technique is not able to simulate locality-specific population dynamics (Perry et al. 1991).

The absence of *R. appendiculatus* and hence ECF from the Horn of Africa is unexpected as both occur in the neighbouring countries, Kenya and South Sudan. The environmental conditions of the highland areas in south western, central and northern Ethiopia are similar to those of other highland areas in eastern Africa where this tick is recorded. The aim of this study is to refine and re-evaluate the results reported by Norval et al. (1991) and to highlight the possible environmental preference differences between the *R. appendiculatus* populations in tropical and temperate region. We used Maxent modelling at spatial resolution of 30 arc-second. This modelling technique was designed to work on presence-only data and was reported to have a better prediction performance than logistic regression (Sumarga 2011), GARP (Elith et al. 2006; Phillips et al. 2006) and generalised additive models and BIOCLIM (Elith et al. 2006).

Materials and methods

Study area

The focus of this paper is on the Horn of Africa, comprising Djibouti, Eritrea, Ethiopia and Somalia. The area covers approximately 2,000,000 km^2 and is inhabited by roughly 100 million people. The region is one of the most food insecure regions worldwide and is characterized by recurrent droughts and other natural disasters which hamper livestock and crop production. About 80 % of the area is classified as arid and semi-arid lands and sub-humid lowlands which receive on average <400–880 mm of rainfall per year. This area is sparsely populated and greater than 40 % of the total area is unproductive because of severe environmental degradation resulting from both natural conditions and human actions. The highland areas where the majority of people live has average temperature rarely exceeds 20 °C and receives an annual rainfall of not less than 2,000 mm. These highland areas play an important role since majority of the crop production is done in this area (Fig. 1).

Tick data

The study is based on occurrence records of *R. appendiculatus* in Sub-Saharan Africa (Fig. 2), kindly provided by Cumming (1998, 1999, 2000). These records represent the total known distribution of this species in Sub-Saharan Africa (Lessard et al. 1990). A study on the diapause behaviour of *R. appendiculatus* (Madder et al. 2002) indicated that this tick features two phenotypes in Africa, largely determined by geographic distribution. In the tropical distribution, a long rainy season ensures favourable environmental conditions for *R. appendiculatus* all year round; bivoltine or even multivoltine life cycles can be

Fig. 1 Map of the study area

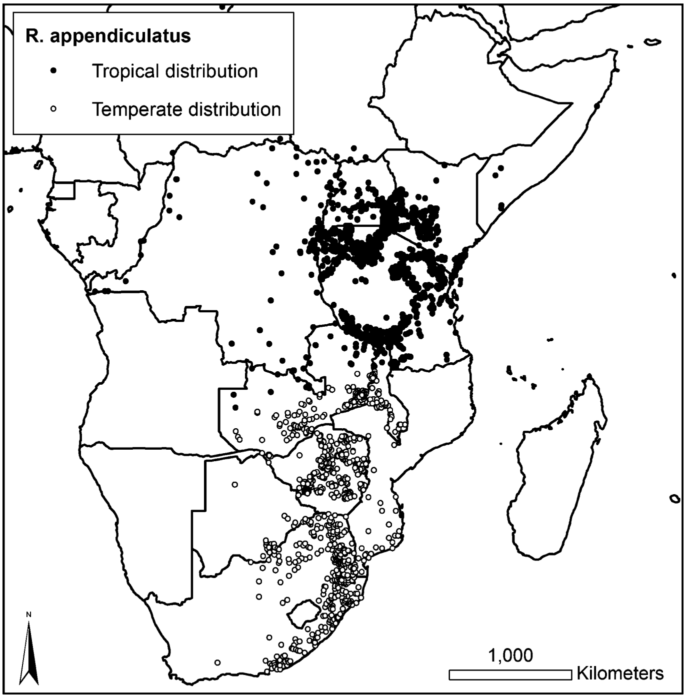

Fig. 2 The recorded distribution of *Rhipicephalus appendiculatus* in Sub-Saharan Africa (Cumming 1998, 1999, 2000)

sustained. This phenotype shows no diapausing behaviour. In the temperate distribution on the other hand, the phenotype of *R. appendiculatus* has the capacity to go into diapause, which enables it to survive longer periods of unfavourable climatic conditions and prevents for instance larval desiccation. In order to describe the climatic niche of both phenotypes, two models were run: one using only the records from the temperate distribution, and one using only the records from the tropical distribution.

Environmental data

To quantify the environmental conditions limiting the distribution of this tick, all 19 bioclimatic variables in the WorldClim dataset were selected (Hijmans et al. 2005). These raster layers have a spatial resolution of 30 arc-second (~ 1 km^2 per pixel) and were derived from monthly temperature and precipitation values observed in local weather stations during the period of 1950–2000. The WorldClim database was selected because it has both high spatial resolution and good quality, and it contains biologically meaningful variables (Table 1), making it a database frequently used for ecological niche modelling (De Meyer et al. 2010; Elith et al. 2010; Estrada-Pena et al. 2006a, b; Holt et al. 2009; Kulkarni et al. 2010).

Modelling approach

Habitat suitability was determined using the maximum entropy approach (MaxEnt). Maxent estimates species distributions by finding the probability distribution of maximum

Table 1 Description of the bioclimatic variables in the Worldclim dataset

Code	Description
BIO_01	Annual mean temperature
BIO_02	Mean diurnal range
BIO_03	Isothermality
BIO_04	Temperature seasonality
BIO_05	Max temperature of warmest month
BIO_06	Min temperature of coldest month
BIO_07	Temperature annual range
BIO_08	Mean temperature of wettest quarter
BIO_09	Mean temperature of driest quarter
BIO_10	Mean temperature of warmest quarter
BIO_11	Mean temperature of coldest quarter
BIO_12	Annual precipitation
BIO_13	Precipitation of wettest month
BIO_14	Precipitation of Driest Month
BIO_15	Precipitation seasonality
BIO_16	Precipitation of wettest quarter
BIO_17	Precipitation of driest quarter
BIO_18	Precipitation of warmest quarter
BIO_19	Precipitation of coldest quarter

entropy (i.e. closest to uniform), subject to a set of constraints imposed by information available regarding the species presences and the environmental conditions across the study area. It is a presence-only modelling technique that uses background samples of the environment rather than absence locations to estimate environmental relationships (Phillips et al. 2006; Phillips and Dudik 2008). This modelling technique was selected for use in this study because it performs well when compared with other modelling methods (Elith et al. 2006) and it does not require absence data. A detailed statistical explanation of Maxent can be found in the literature (Elith et al. 2011; Phillips et al. 2006). In this study MaxEnt version 3.3.3e was used.

Maxent was run using the default parameters. Both models were developed with the option "Auto feature" turned on. The Auto feature type allows the set of features used to depend on the number of presence records for the species being modelled using general empirically-derived rules (Stabach et al. 2009). Ten thousand background points were randomly sampled from the full study area. A regularization parameter of 1.0 was used to avoid over-fitting, the maximum number of iterations was set at 500 or until the convergence threshold fell below 0.00001. The form of replication used was tenfold cross-validation. For in total ten iterations, 90 % of the data was randomly selected and used to fit the model, and the remaining 10 % was used to assess the accuracy. A different random selection of data for fitting and testing the model is used in the respective iterations. The relative contributions of the environmental variables to the model were assessed based on MaxEnt's built-in Jacknife functionality.

The area under the receiver operating characteristic (ROC) curve (AUC) was used to measure the accuracy of the model. The AUC is the probability that a randomly chosen presence site will be ranked above a randomly chosen absence site. Since Maxent is a present only modelling technique, AUC is calculated by using background data (also called pseudo-absences) which are chosen uniformly at random from the study area, in place of true absences. In this approach the interpretation of AUC changes accordingly: it can be understood as the probability that a randomly chosen presence site is ranked above a random background site (Phillips et al. 2006). A random ranking has an AUC of 0.5, and a perfect ranking achieves the best possible AUC value of 1 (Phillips and Dudik 2008) and values </0.5 indicate performance worse than random (Elith et al. 2006).

Results and discussion

This paper outlines the predicted habitat suitability for *R. appendiculatus* in the Horn of Africa. *R. appendiculatus* has a wide, but patchy, distribution from the tropical regions of East Africa to the temperate regions of South Africa (Randolph 1997). This tick has different environmental preferences over its distribution range (i.e., in the tropical and temperate regions). When feeding the values for the bioclimatic variables of the occurrence records in a principal component analysis, it was apparent that both phenotypes occupy difference climatic niches (Fig. 3). The first and the second component of the climatic niche account for 72 % of the variation in the bioclimatic variables. Records from the tropical distribution are situated in the upper left part of the scatterplot, while records from the temperate distribution are situated in the lower right part of the scatterplot. The temperate records are thus characterised by a higher variability (BIO_02, BIO_4 and BIO_07) and the tropical records feature a higher precipitation (BIO_12, BIO_17 and BIO_19).

In this study, two models were developed to take this behaviour into account. The first model is based on the tropical distribution of *R. appendiculatus* and the second model is based on the temperate distribution of *R. appendiculatus*. The modes have an AUC_{test} value of 0.921 $\pm$ 0.006 and 0.950 $\pm$ 0.003 respectively, implying a very good fit of the model to the data.

Figure 4 shows predicted habitat suitability for *R. appendiculatus* in the Horn of Africa based on the occurrence records of this tick in its tropical distribution. The highest suitable habitat covers much of the highlands in the central, northern and southern Ethiopia and some patches in southern Eritrea. The whole Djibouti, the north eastern and south eastern Ethiopian lowlands, and majority of Eritrea and Somalia were found to be not suitable for the survival of this tick species.

The predicted habitat suitability for *R. appendiculatus* developed based on its temperate distribution in Sub-Saharan Africa was found to have a different range (Fig. 5). On contrary to the first model, Kenya and Ethiopia have a very low suitability. This is not a surprising result since this tick has a different environmental preference in its distribution range. Importation of this tick from the southern African countries will have a lower chance to establish itself in this region.

The bioclimatic variables which have major contributions to the models output are depicted in (Table 2). For the first model the most important predictor variables were temperature annual range, temperature seasonality and the maximum temperature of the warmest month collectively contributing 63.4 % to the model output. Mean temperature of the driest quarter, precipitation of the warmest quarter and temperature seasonality were the most important predictor variable for the second model collectively contributing 78.3 % to the model output. Temperature annual range, temperature seasonality and annual precipitation were listed as important predictor variables for both models. Most suitable

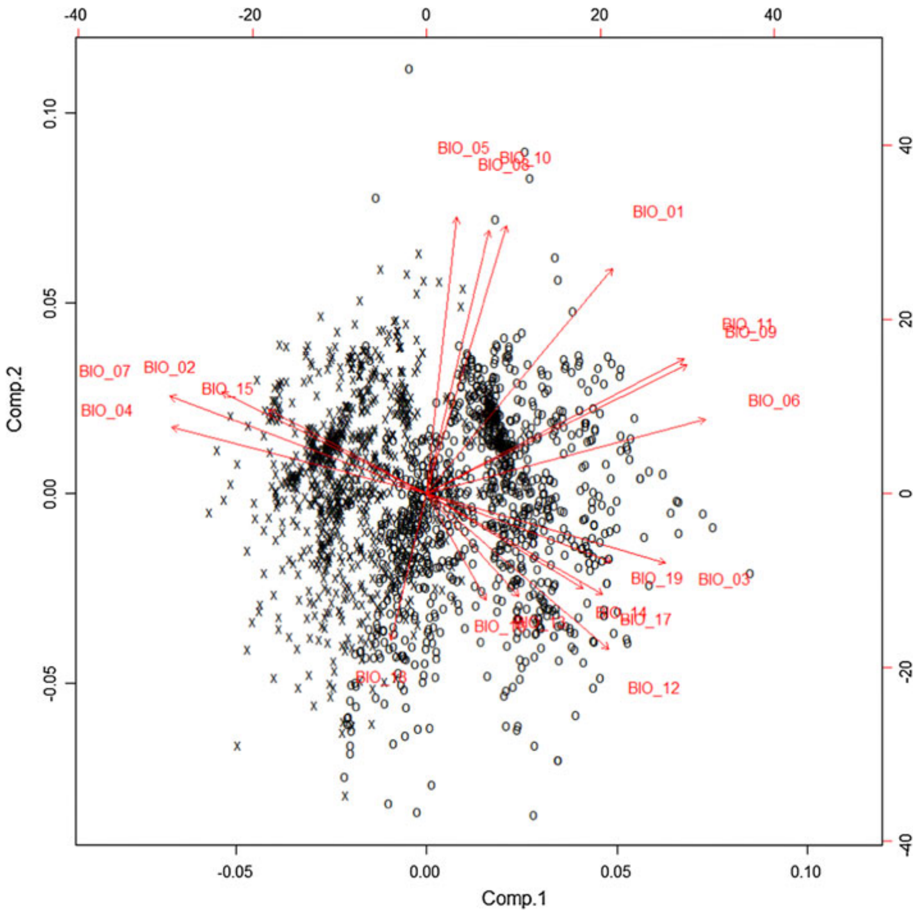

Fig. 3 Scatterplot of the *Rhipicephalus appendiculatus* records along the first and second principal component of the climatic niche. The symbol “o” stands for records from the tropical distribution, and the symbol “×” indicates records from the temperate distribution

habitat for *R. appendiculatus* was predicted in areas which have high precipitation and moderate temperature values.

It is very unlikely that *R. appendiculatus* was ever present in the Horn of Africa in general and in Ethiopia in particular. If this were the case, the tick would not have disappeared from such a highly suitable habitat where an adequate number of hosts and suitable environmental conditions co-exist. Introductions of *R. appendiculatus* into the Horn of Africa probably have been prevented by the natural barrier between the recorded *R. appendiculatus* distribution in East Africa and the Horn of Africa. An extensive unsuitable area exists between the known *R. appendiculatus* distribution range in neighbouring Kenya and South Sudan, and the suitable Ethiopian areas. Based on both models, the arid and semiarid areas of northern Kenya are clearly unsuitable for this tick survival and development. The unsuitable arid and semiarid areas of northern Kenya are protecting Ethiopia as a natural buffer zone. Even though there is an extensive cross border animal movement in this area, the chance for the tick to survive in this arid area is very unlikely

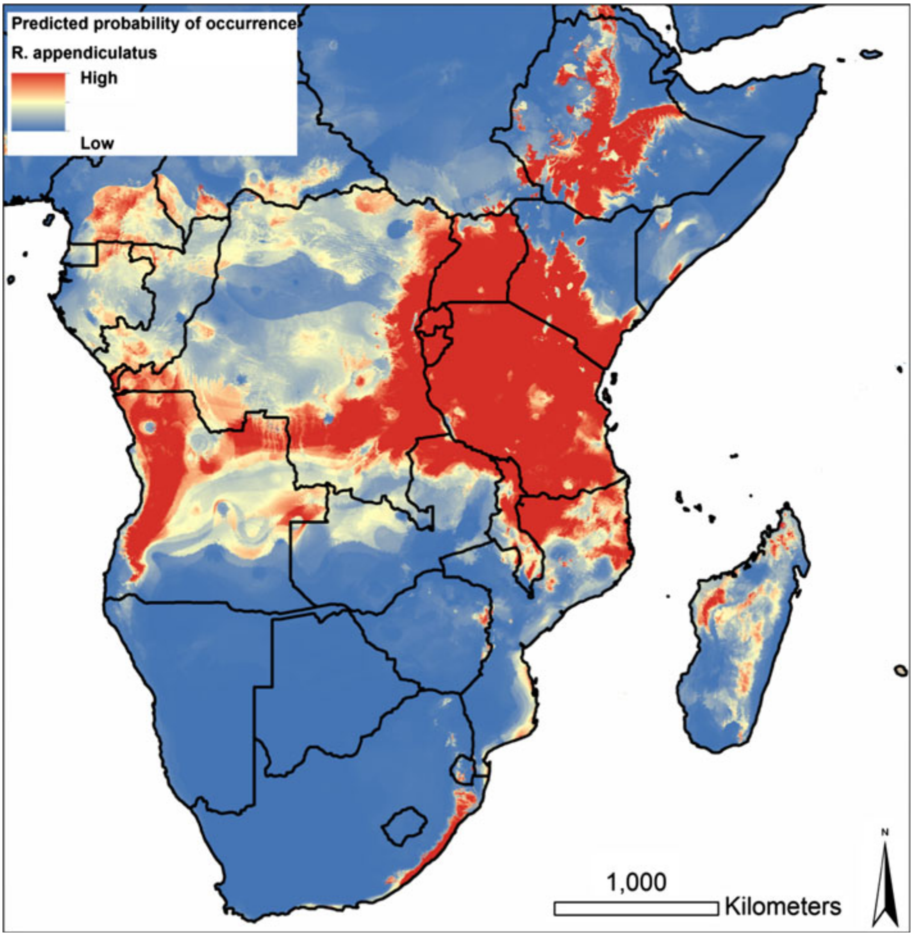

Fig. 4 Predicted habitat suitability for *Rhipicephalus appendiculatus* in the Horn of Africa based on tropical occurrence records

since this tick species spend on average less than a week on the animal in each life cycle stage. Furthermore, 20 years ago the Ethiopian government banned the importation of live animals from Kenya. The ban still exists and no animal is being transported live from the Kenyan highland to Ethiopia. The ban is also believed to contribute a lot in the prevention of the introduction of this tick species to the suitable Ethiopia areas.

Two decades ago Norval et al. (1991) proposed that the wider spread of the tick in southern Sudan in 1990s could result in the introduction of *R. appendiculatus* into Ethiopia. These authors used a climate-matching model (CLIMEX) at 25 km^2 spatial resolution to predict the habitat suitability for this tick in the Horn of Africa. They described the suitability of the Ethiopian highlands for this tick species. However, they used a spatial resolution of 25 km^2 (coarse-resolution) which lack adequate spatial resolution and this could prevent their model to capture a fine-scale suitable and/or unsuitable habitat. A previous study (Estrada-Pena et al. 2006c) demonstrated that a coarse-resolution climate driven model might be unable to adequately map the distribution of ticks over a wide

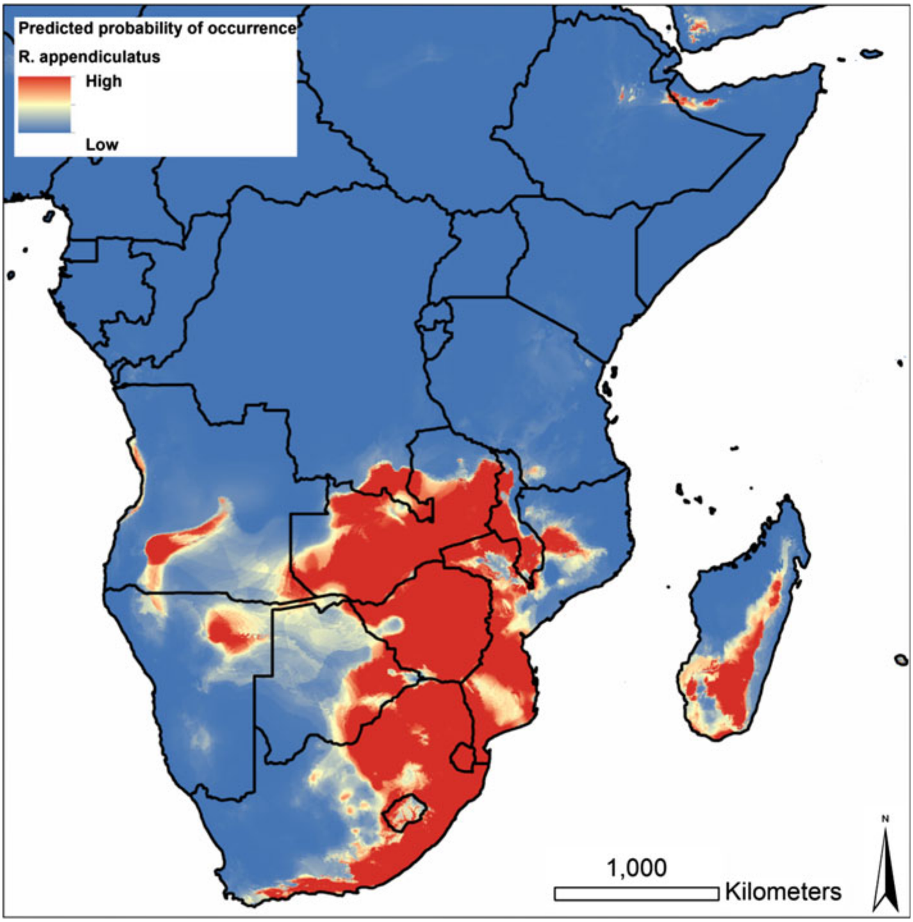

Fig. 5 Predicted habitat suitability for *Rhipicephalus appendiculatus* in the Horn of Africa based on temperate occurrence records

region. In this study high spatial resolution (30 arc-second) was used which can capture a fine-scale suitable and unsuitable areas.

In another study (Julla 1985) reported the presence of this tick species in Palotaka, Ikotos and Hilieu areas of southern Sudan east of Juba. According to the author ECF had caused cattle deaths in those areas. These areas are around 300 km from the Ethiopian border. The outspread of this tick from this area due to any reason could result in the introduction of *R. appendiculatus* into the suitable Ethiopian areas. *R. annulatus* was thought to be introduced to Ethiopia from southern Sudan because of extensive livestock movement due to social and civil unrest in that area in late 1980s (Norval et al. 1991). *R. annulatus* is a one host tick spending three weeks on its host from larva until engorged female, making it more likely to cross longer distances when carried on its host. However, *R. appendiculatus* is still believed to be absent from Horn of Africa in general and the Ethiopian in particular, even though no recent country-wide tick survey was conducted.

The risk of introduction of *R. appendiculatus* into this region will be high if livestock are moved long distances by motorized transport or by air from tropical Sub-Saharan

Table 2 The relative contributions of the environmental variables to the Maxent model (top 5)

Based on the records of *Rhipicephalus appendiculatus*			
Tropical distribution		Temperate distribution	
Variable	% contribution	Variable	% contribution
Temperature annual range (BIO_07)	27	Mean temperature of driest quarter (BIO_09)	31.6
Temperature seasonality (BIO_04)	22.3	Precipitation of warmest quarter (BIO_18)	30.3
Max temperature of warmest month (BIO_05)	14.1	Temperature seasonality (BIO_04)	16.4
Mean temperature of warmest quarter (BIO_10)	9.2	Annual precipitation (BIO_12)	8.3
Annual Precipitation (BIO_12)	6.8	Temperature annual range (BIO_07)	4.3

African countries. The effect of an introduction of *R. appendiculatus* and thereby ECF into the Horn of Africa could be catastrophic since the cattle population in this area has no immunity against this disease, and the mortality might be considerable. In the highlands of this region cattle are the sole source of draft power for ploughing; if the disease is introduced it may result in the deaths of large numbers of cattle which would severely limit agricultural production.

Conclusion

Habitat suitability prediction for *R. appendiculatus* shows positive environmental suitability for this tick species in the highlands of the Horn of Africa. This part of the world is one of the most food insecure regions in the world. The majority of the peoples livelihood is based on subsistent agriculture in which livestock has a key role. The introduction of this tick species into the region may worsen the food insecurity problem which the people of the region are facing. To avoid the introduction of this tick into this region the following measures are highly recommended: (1) Strict trans-border animal movement control and acaricide treatment of cattle crossing into the suitable highlands (2) Tick import risk assessment for *R. appendiculatus* shall be conducted before importation of any livestock into the region by any means of transport, and (3) Wider surveillance of the ticks in the region is crucial to make sure that there are no foci of infection.

In summary, it is of paramount importance to apply intensive surveillance and control in order to protect the livelihood of the already vulnerable population in the Horn of Africa.

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