# Development of the first georeferenced map of *Rhipicephalus (Boophilus)* spp. in Mexico from 1970 to date and prediction of its spatial distribution

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## Abstract

The tick genus *Ripicephalus* (*Boophilus*), particularly *R. microplus,* is one of the most important ectoparasites that affects livestock health and considered an epidemiological risk because it causes significant economic losses due, mainly, to restrictions in the export of infested animals to several countries. Its spatial distribution has been tied to environmental factors, mainly warm temperatures and high relative humidity. In this work, we integrated a dataset consisting of 5843 records of *Rhipicephalus* spp., in Mexico covering close to 50 years to know which environmental variables mostly influence this ticks' distribution. Occurrences were georeferenced using the software DIVA-GIS and the potential current distribution was modelled using the maximum entropy method (Maxent). The algorithm generated a map of high predictive capability (Area under the curve = 0.942), providing the various contribution and permutation importance of the tested variables. Precipitation seasonality, particularly in March, and isothermality were found to be the most significant climate variables in determining the probability of spatial distribution of *Rhipicephalus* spp. in Mexico (15.7%, 36.0% and 11.1%, respectively). Our findings demonstrate that *Rhipicephalus* has colonized Mexico widely, including areas characterized by different types of climate. We conclude that the Maxent distribution model using *Rhipicephalus* records and a set of environmental variables can predict the extent of the tick range in this country, information that should support the development of integrated control strategies.

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Key words: *Rhipicephalus (Boophilus)* spp.; Georeference; GIS; Maxent; Species distribution model; Mexico.

Acknowledgments: climate data provided by the Research Program on Climate Change, Agriculture and Food Security (CCAFS) in this work is greatly acknowledged as well as weekly reports of Is spp. provided by SENASICA-SAGARPA on its public website.

Contributions: the authors contributed equally.

Conflict of interest: the authors declare no potential conflict of interest.

Funding: the authors are grateful to DGAPA-PAPIIT IT200816 for the financial support of this project.

Received for publication: 12 September 2017.
Revision received: 30 January 2018.
Accepted for publication: 7 February 2018.


*Geospatial Health 2018; 13:624*
*doi:10.4081/gh.2018.624*



## Introduction

Ticks are distributed worldwide, from the Arctic region to the tropical areas. Most of these species are important disease vectors that affect animal and human health (Wang *et al.*, 2015). Infestation of cattle by ticks of the genus *Rhipicephalus* (*Boophilus*) has been reported to negatively impact economy and animal health, mainly because the parasite transmits tick-borne pathogens such as *Babesia bovis, B. bigemina* or *Anaplasma marginale* (Rodriguez-Vivas *et al.*, 2017), reduces weight gain, decreases milk and meat production (Jonsson *et al.*, 2008; Mondal *et al.*, 2013), injects toxins, causes blood loss, stress and irritation (Manjunathachar *et al.*, 2014). Likewise, *Rhipicephalus* spp. interferes with domestic and international trade due to restrictions in the export or introduction of infested cattle to areas or countries that have official regulations to control this parasite, for example, the United States (Pérez de León *et al.*, 2012; Giles *et al.*, 2014).

One of the most important factors that determines the survival and distribution of this tick species is climate. In general, regions with warm and humid conditions are suitable for the occurrence and development of *Rhipicephalus* spp. (Estrada-Peña *et al.*, 2006b). Ecological and climatologic data, as well as mathematical models, are available to estimate the distribution of potential growth and development of a species. The use of these models increases the understanding of the most important factors that influence the presence or absence of a parasite in a given region (Estrada-Peña *et al.*, 2016; 2006b) and may shed light on the biological capacity of a species to establish and thrive in different climatic regions. This information can be useful to implement geographical planning of prevention activities by targeting areas that are suitable for *Rhipicephalus* spp. (Estrada-Peña, 2001).

Several previous studies have modelled ecological niches of species using approaches such as the maximum entropy (Maxent) algorithm to estimate the potential distributions of ixodid ticks in the United States, such as *Amblyomma americanum* (Raghavan *et al.*, 2016) in Kansas, *Ixodes scapularis* (Johnson *et al.*, 2016) in Minnesota and *Dermacentor variabilis* (St John *et al.*, 2016). *Rhipicephalus microplus* and *R. appendiculatus* distributions have been modelled in West Africa (De Clercq *et al.*, 2013; Leta *et al.*, 2013; De Clercq *et al.*, 2015) and the Horn of Africa (Leta *et al.*, 2013), respectively. The distribution of *A. cajennense* and *A. sculptum* in Brazil has been assessed under present-day and future climate models (Oliveira *et al.*, 2017); whereas suitable habitats for *D. marginatus, Haemaphysalis punctata, Ha. sulcata, Hyalomma lusitanicum, Hy. marginatum, I. ricinus, R. annulatus* and *R. bursa* have been predicted using the same algorithm (Williams *et al.*, 2015).

In Mexico, the official institution for the diagnosis and public reporting of occurrences of *Rhipicephalus*) spp. is the National Service for Quality, Safety and Agricultural Health of the Secretariat of Agriculture, Livestock, Rural Development, Fisheries and Food (SENASICA), which carries out this responsibility according to the Mexican official regulations for the control of this parasite (SENASICA, 2017). Several studies have published information about the areas in Mexico where the tick has been collected with and noted the different climatic patterns that support *Rhipicephalus* spp. (Galaviz-Silva *et al.*, 2013; Rodriguez-Vivas *et al.*, 2012; Rodríguez-Vivas *et al.*, 2014b; Sánchez, 2014). However, as far as we currently know, there is not a single dataset including countrywide georeferenced *Rhipicephalus* locations that would support further modelling studies and make it possible to predict potential spread of the tick prompting veterinarians to take up timely control measures. We report here, for the first time, the georeferenced locations of *Rhipicephalus* spp. in Mexico for the period 1970-2017 modelling the potential geographic distribution of the tick using its current distribution and data based on a range of environmental parameters.

## Materials and Methods

### Data

A dataset comprising 5751 localities, from where any of the known *Rhipicephalus* spp. had been reported, was compiled for the period 1970 to 2017. The records included published scientific articles, theses, proceedings from academic and scientific meetings (Solorio-Rivera *et al.*, 1999; Rosado-Aguilar *et al.*, 2008; Rosario-Cruz *et al.*, 2009; Aguilar-Tipacamú and Rodriguez-Vivas, 2003; Alonso-Díaz *et al.*, 2007a; Alonso-Díaz *et al.*, 2007b; Lopez *et al.*, 2008; Rodríguez *et al.*, 2009; Gaxiola-Camacho *et al.*, 2009; Pound *et al.*, 2010; Lohmeyer *et al.*, 2011; Rodriguez-Vivas *et al.*, 2011; Aguilar-Tipacamú *et al.*, 2011; Fernández-Salas *et al.*, 2012a; Fernández-Salas *et al.*, 2012b; Fernández-Salas *et al.*, 2012c; Rodriguez-Vivas *et al.*, 2012; Rodriguez-Vivas *et al.*, 2013; Miller *et al.*, 2013; Treviño, 2013; Morales, 2014; Rodríguez-Vivas *et al.*, 2014a; Rodríguez-Vivas *et al.*, 2014b; Sánchez, 2014; Alegria-Lopez *et al.*, 2015) as well as from weekly zoo-sanitary information published online (SENASICA, 2017). Only natural infections were included in the database and *Rhipicephalus* spp. occurrences were recorded a single time when reported at same location and date.

Nineteen bioclimatic layers representing mean annual temperature (MAT), mean annual precipitation (MAP), seasonality as well as other derived precipitation and temperature-linked variables (Tables 1 and 2) were extracted from the websites of Research Program on Climate Change, Agriculture and Food Security (http://www.ccafs-climate.org) and WorldClim (http://www.worldclim.org). Variables resulting from global land area interpolation of climate point data at the 30-sec spatial resolution were used to produce an ecological niche model for *Rhipicephalus* spp. distribution. Coordinates for the 5751 sampling localities were collected and subsequently georeferenced using DIVA-GIS version 7.5 (http://www.diva-gis.org), a software that can also predict species habitat suitability and range changes in response to climate (Hijmans *et al.*, 2001). *Rhipicephalus* spp. georeferenced occurrence points in Mexico were checked for bias and errors using the DIVA-GIS software.

### Species distribution modelling

The predicted distribution of *Rhipicephalus* spp. in Mexico under current climate conditions was modelled using Maxent software (Phillips *et al.*, 2006), wich is based on an algorithm that estimates the suitability/unsuitability of a location for the presence of a species based on the distribution of maximum entropy, *i.e.*, closest to uniform supported by the association between presence points and environmental variables (Fand *et al.*, 2014; Qin *et al.*, 2016; Suwannatrai *et al.*, 2017). One of the main advantages of Maxent is that it only requires presence data and environmental layers (continuous or categorical variables) for the study area (Phillips *et al.*, 2009; Stevens and Pfeiffer, 2011). The main rule of partitioning data for modelling the distribution of species dictates that the proportion of testing data follows the equation:

$$Dt = 1/\left[1 + (p-1)^{\frac{1}{2}}\right]$$

where $Dt$ is the percentage of test data and $p$ the number of predictor variables (Padilla *et al.*, 2017). The percentage for Maxent training of data consists of 75% presence points, whereas the remaining 25% of points are used for validation (Khatchikian *et al.*, 2011). We set the random test percentage to 25% in the current study to improve the model performance, while the parameters set were the ones included by default when using the Maxent approach. The logistic output format used in this study assigned each grid cell of the study area values ranging from 0 (completely unsuitable) to 1 (fully suitable).

To avoid over-fitting, a series of correlations were conducted to remove redundant variables by extracting the bioclimatic information from randomly generated points. A Pearson's correlation coefficient was estimated by SAS/STAT, v. 9.2 (SAS Institute, Cary, NC, USA) for the most ecologically relevant variables for *Rhipicephalus,* such as temperature and precipitation (Estrada-Peña *et al.*, 2006a). A threshold of |r|>0.7 was used to eliminate highly correlated variables (Dormann *et al.*, 2013), *e.g.*, precipitation in the driest quarter (bio14) and precipitation in the driest month (bio17). A subset of biologically representative and uncorrelated bioclimatic variables was selected to run Maxent. To evaluate the true predictive power of the model, 10 runs were performed with a 10-fold cross-validation procedure to get 10 independent subsets, each with the same number of occurrence points (McQuillan and Rice, 2015). Subsequently, the fit of the model to test data was evaluated with the Area Under the Curve (AUC) of the Receiver Operating Characteristic (ROC) (Fand *et al.*, 2014). The model performance was estimated by creating a ROC plot measuring the area with a range from a random accuracy (0.5) to a perfect discrimination (1.0), *i.e.*, an AUC with a value of 0.5 represents a random model, values between 0.8 and 0.9 represent models with a good fit and values over 0.9 means excellent fit (Stevens and Pfeiffer, 2011). Predictions of Maxent were mapped in DIVA-GIS.

## Results

### *Ripicephalus* spp. findings

A total of 5751 geographical coordinates for the locations of *Rhipicephalus* spp. were obtained and the georeferenced occurrences depicted in a map of occurrences reported before and after the year 2012 (Figure 1). Most locations were obtained from the publically available, official SENASICA dataset, whereas fewer references reporting natural infestations were extracted from the literature. The dataset was limited to records from 1970 to 2017 because no previous records of this parasite were available.

### Spatial distribution

The model projected by Maxent presented an AUC of 0.942, which represents a strong fit (Figure 2) and, in agreement with the measurement of variable importance, the highest contributions came from variables prec3 (the March precipitation), bio15 (the seasonal

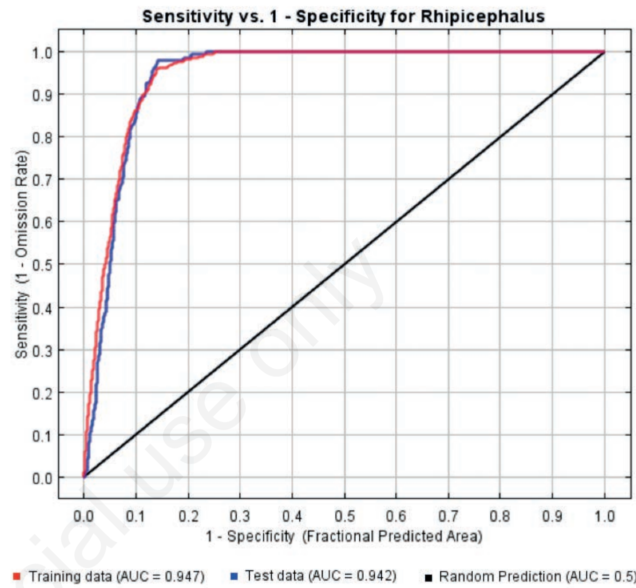


**Figure 2. The Receiver operating characteristic curve for training data.**
**AUC, Area under the curve.**

**Figure 1. *Rhipicephalus* spp. occurrences in Mexico from 1970 to 2017.**

precipitation) and bio4 (the seasonal temperatures (Tables 1 and 2), amounting to 36.0%, 15.7% and 11.1%, respectively (Table 3). In contrast, bio13 (the precipitation of wettest month), bio1 (the annual mean temperature) and tmean2 (the mean temperature in February), among other variables, neither contributed by percentage nor permutation importance to the distribution of *Rhipicephalus* spp. under the parameters of this model. The projection of the range distribution model onto Mexico is depicted in a map developed in DIVA-GIS (Figure 3). The most important abiotic factors (prec3, bio15, bio4) influencing the geographic distribution of *Rhipicephalus spp.* were considered to model the potential current spatial distribution of this parasite (Figure 3). The modelled distribution model showed that the predicted occurrence included the actual distribution of *Rhipicephalus* spp. in the country.

## Discussion

The climate classification (A–E) made by Enriqueta García (1981), governed by annual and monthly temperatures and precipitation patterns, where type A-climates are warm and humid, B corresponds to dry climates, C to temperate and humid ones, D to cold temperatures with intense winters and E to very cold or polar climates at high altitudes, play an important role for *Rhipicephalus* spp. occurrences. These ticks have traditionally been linked to climates classified as A and C, and this information is in good agreement with the current and predicted tick distribution map found. In addition, most of the literature reports locations with humid and warm climates (Aguilar-Tipacamú and Rodriguez-Vivas, 2003; Alvarez *et al.*, 2004; Rodríguez-Vivas *et al.*, 2007; Alonso-Díaz *et al.*, 2007b; Gaxiola, 2008). As shown here, the highest contribu-

**Table 1. Bioclim layers used in this study.**

| CODE | VARIABLE | CODE | VARIABLE |
|---|---|---|---|
| Bio1 | Annual mean temperature | bio11 | Mean temperature of the coldest quarter |
| Bio2 | Mean diurnal range (Mean of the monthly maximum temperature – minimum temperature) | bio12 | Annual precipitation |
| Bio3 | Isothermality (BIO2/BIO7) x 100 | bio13 | Precipitation of the wettest month |
| Bio4 | Temperature seasonality (standard deviation x 100) | bio14 | Precipitation of the driest month |
| Bio5 | Maximum temperature of the warmest month | bio15 | Precipitation seasonality (Variation coefficient) |
| Bio6 | Minimum temperature of the coldest month | bio16 | Precipitation of the wettest quarter |
| Bio7 | Annual temperature range (IO5-BIO6) | bio17 | Precipitation of the driest quarter |
| Bio8 | Mean temperature of the wettest quarter | bio18 | Precipitation of the warmest quarter |
| Bio9 | Mean temperature of the driest quarter | bio19 | Precipitation of the coldest quarter |
| Bio10 | Mean temperature of the warmest quarter | | |



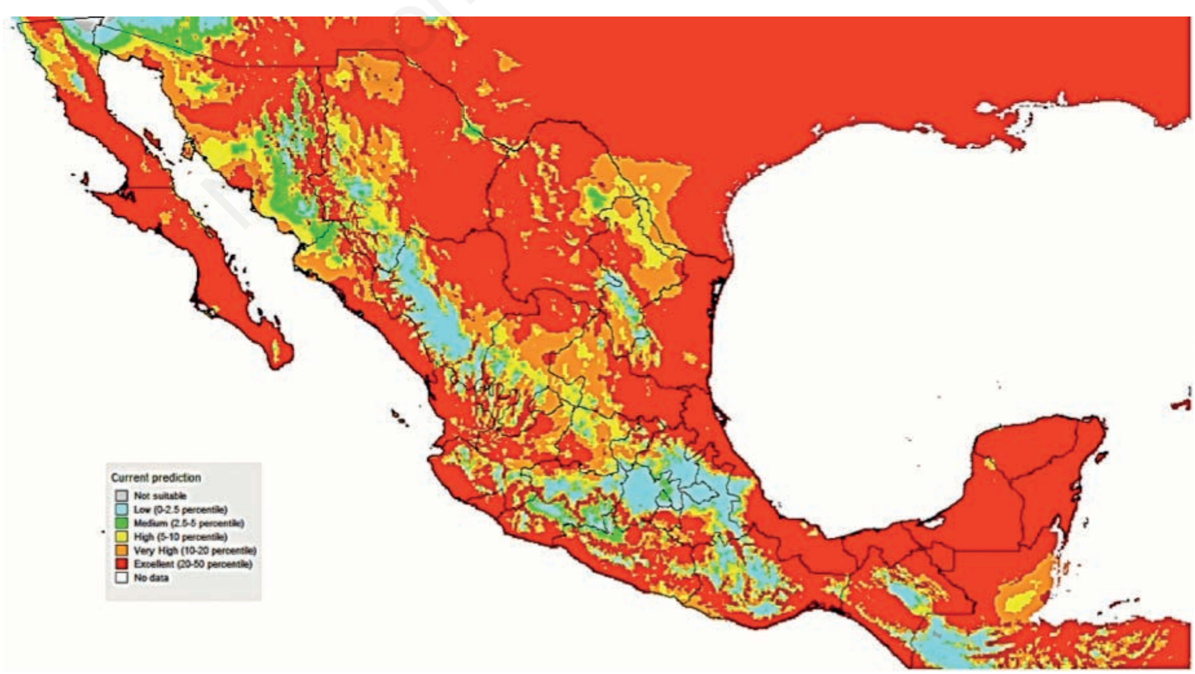


**Figure 3. Illustration of the predicted current geographic distribution of *Rhipicephalus* spp. in Mexico according to the environmental layers with the strongest influence.**

**Table 2. Codes for the monthly environmental variables referred to in this study.**

| Month | Precipitation | Minimum temperature | Maximum temperature | Mean temperature |
|---|---|---|---|---|
| January | prec1 | tmin1 | tmax1 | tmean1 |
| February | Prec2 | tmin2 | tmax2 | tmean2 |
| March | Prec3 | tmin3 | tmax3 | tmean3 |
| April | Prec4 | tmin4 | tmax4 | tmean4 |
| May | Prec5 | tmin5 | tmax5 | tmean5 |
| June | Prec6 | tmin6 | tmax6 | tmean6 |
| July | Prec7 | tmean7 | tmax7 | tmean7 |
| August | Prec8 | tmean8 | tmax8 | tmean8 |
| September | Prec9 | tmean9 | tmax9 | tmean9 |
| October | Prec10 | tmean10 | tmax10 | tmean10 |
| November | Prec11 | tmean11 | tmax11 | tmean11 |
| December | Prec12 | tmean12 | tmax12 | tmean12 |

tions came from abiotic variables, such as prec3 (March precipitation), bio15 (seasonal precipitation) and bio4 (seasonal temperatures (Tables 1 and 2), amounting to 36.0%, 15.7% and 11.1%, respectively, in determining the probability of occurrence of the species in Mexico (Table 3).

Nevertheless, it is indispensable to rule out the presence of biotic factors that interfere with habitat colonization or invasion potential by the above-mentioned parasites. For example, most of the north-eastern region of Mexico where *Rhipicephalus* spp. records were obtained is where cattle production has been traditionally carried out, and due to the animal health certifications that the United States of America requests to export cattle to that country, Mexican animal health authorities must perform several examinations to cattle in order to comply with international regulations that request tick-free animals (SENASICA, 2017). The understanding that both habitat suitability and cattle raising coincide with areas where most of the occurrences were reported should prompt researchers and animal health authorities to target risky areas for the geographic planning of preventive measures by *Rhipicephalus* spp. control programmes.

The evaluation of geographical distribution patterns of this species is important to decrease tick colonization in environmentally suitable areas. The dataset used in the current study included a comprehensive collection of georeferenced records for *Rhipicephalus* spp. to date (September 2017) and prediction findings identified that tmax5 (the May maximum temperature), bio15 (the precipitation seasonality), and bio5 (the maximum temperature of the warmest month) shape the species distribution patterns, which is a fundamental goal in the fields of ecology and biogeography.

Identifying the factors that shape *Rhipicephalus* spp. geographic distribution may shed light on where this parasite is able to establish and respond to environmental variables. Its presence in Mexico occurs in regions that, according to our results, can be considered as among the best suited for this tick to develop, *i.e.* Veracruz, Tabasco, Tamaulipas, Campeche, Yucatán, Quintana Roo and Chiapas. It would be unsafe to state that precipitation is the only factor that restricts habitat suitability of *Rhipicephalus* spp, yet this finding adds an ecological dimension to further studies aimed to model the potential distribution of this tick.

Therefore, predicting current and future species spatial distribution may improve the understanding of abiotic factors that provide insight into the suitability of this parasite to survive in several states of Mexico. In the present study, only bioclimatic abiotic factors were considered. Nonetheless, previous findings suggest that biotic factors will be more relevant at a species equatorial range limit; whereas these factors influence high altitude as well as latitude limits (McQuillan and Rice, 2015). While this hypothesis has been discussed in depth, this study did not include information to support or reject macroecological distributions. Still, the potential current distribution tendency of *Rhipicephalus* spp. shown in our results is consistent with actual locations where this parasite has been reported, such as the state of Tlaxcala and also some localities in Chiapas, where it has not been reported as far as we know.

**Table 3. Estimated relative contributions of the environmental variables to the Maxent model.**

| Variable* | Contribution % | Permutation importance |
|---|---|---|
| prec3 | 36 | 1.1 |
| bio15 | 15.7 | 16.8 |
| bio4 | 11.1 | 11 |
| bio13 | 0 | 0 |
| bio1 | 0 | 0 |
| tmean2 | 0 | 0 |

*Only the three strongest and the three less likely variables shown.

The fit of 0.942 as measured by the AUC, which is shown in Figure 3, indicates the strong ability of the Maxent algorithm to discriminate between suitable and unsuitable areas for *Rhipicephalus* spp. occurrence in Mexico (Fand *et al.*, 2014; Suwannatrai *et al.*, 2017). Albeit the best-fitting Maxent model predicts high probabilities of infection occurrence in several regions of the country, it would be unsafe to state that this species will colonize all predicted areas despite suitable climate, because there are variables such as vegetation, type of soil and altitude that will need to be addressed in further studies aimed to model the potential geographic distribution of *Rhipicephalus* spp.

Many assumptions and limitations are inherent in the present study. For instance, presence-only observations of *Rhipicephalus* spp. in Mexico collected from an array of sources differed in sampling effort and geographical focus. Therefore, the present results must be carefully interpreted as these differences could bias models toward areas with easier access for the collection of biological material, or localities with accessible laboratories where expert personnel can properly identify ixodid ticks according to molecular or morphological features. On the other hand, presence-only observations avoid the methodological drawback that absence of species is difficult to demonstrate. However, over- or under-sampling of *Rhipicephalus* spp. could skew the theoretical habitat preferences of the species (Estrada-Peña, 1999). It would be a mistake to see the current study as definitive. For example, one major limitation is the lack of a specific model for *R. microplus* and one for *R. annulatus.* The spatial distribution of *R. microplus* is influenced by climate mainly in tropical regions but temperate and arid environments can also provide a suitable habitat for this tick species; whereas the latter inhabits arid and temperate climates of Mexico (Rodriguez-Vivas and Domínguez-Alpizar, 1998; Estrada-Peña *et al.*, 2006a; Estrada-Peña and Venzal, 2006; Lohmeyer *et al.*, 2011; Wang *et al.*, 2017). Indeed, different models could provide more reliable results, yet the current database includes reports identified by the federal animal health authorities in Mexico as *Boophilus* spp. in weekly animal health reports (SENASICA, 2017) and federal regulations (SAGARPA, 2012). Although this aspect of our dataset is limited, we are convinced that this study could support the control of *Rhipicephalus* spp. in areas with environmental conditions that are highly suitable for the occurrence, development and population growth of this genus of ticks. Further studies should be conducted for assessing the impacts of abiotic factors to identify suitable habitats for *Rhipicephalus* spp. as well as to improve the predictive power of this species distribution model.

## Conclusions

The results of this study have implications for the enforcement of preventive and control measures aimed to reduce the prevalence of this parasite in endemic areas. Our georeferenced distribution of *Rhipicephalus* spp. occurrences support the fact that warmer climates and moisture-rich regions could be suitable for the potential distribution this parasite. In addition, these results demonstrate a reliable performance of the prediction model algorithm (Maxent) for this species according to our dataset. Findings support further geographical planning of preventive measures to interfere with the establishment of this parasite in areas that are ecologically suitable for its establishment and development.

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