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RESEARCH ARTICLE

Turning the rationale of cattle rabies surveillance and control in Latin America: from rabies case to vampire bat aggression-based program

*Ricardo Augusto Dias[1], Mariana Figueira Dornelas[2], Vitor Salvador Picão Gonçalves[2]

[1]University of Sao Paulo, Butanta, São Paulo - State of São Paulo, Brazil
[2]University of Brasilia, UnB - Brasilia, Federal District, 70910-900, Brazil

*ricardodias@usp.br

Abstract

In Brazil and in most of the Latin America countries, the control of the cattle rabies relies upon the indiscriminate culling of the *Desmodus rotundus* inside a radius of 12 km around an outbreak. The culling is performed by applying warfarin paste in the back of the bats, in the hope that when it returns to its roost after foraging, its conspecifics would ingest the paste during social grooming and die of hemorrhage. This control approach is performed in absentia with the surveillance effort, since if bats die indiscriminately, the effects in the social structure of the colonies are unknown. It is believed that the indiscriminate culling helps the rabies virus spread among bats and consequently, the spillover to livestock. For this reason, any sampling effort in bats and even the identification of cattle rabies outbreaks transmitted by bats is useless to predict future outbreaks or even mitigate current outbreaks. Even though the tendency of the cattle rabies outbreaks is decreasing in Brazil, this should be carefully considered, since rabies surveillance efforts are heterogeneous and decreasing. Even so, the nationwide space-time cattle rabies outbreak shows a wave pattern, increasing the urge of the revision of the current surveillance and control actions. The present work proposes a new approach aiming at decreasing the spillover to livestock by incorporating ecological features of the *D. rotundus*, most importantly turning the surveillance-control rationale which is currently reactive to livestock rabies cases to a surveillance system reactive to changes in the incidence of vampire bat attacks on the livestock and selective bat population control. For example, estimating the roosts' carrying capacity and contact networks allows the interruption of rabies virus spread by reducing the bat population of target individuals in selected roosts or roost communities. Moreover, the terrain slope dependency of the bat foraging behavior allows to find more efficiently the roost from which bats are attacking a farm or conversely, to find attacked farms if an occupied bat roost is known. These practices could increase the efficiency of the surveillance and control and the cost-effectiveness of the current cattle rabies control program.

Keywords: common vampire bat, *Desmodus rotundus*, rabies, control, surveillance, biology.

Introduction

In Brazil and most of the Latin American countries, cattle rabies is an insidious disease that causes severe socio-economic impact[1]. Although the disease is one of the longest known zoonotic diseases, it was not until the beginning of the 20th century that transmission by the common vampire bat *Desmodus rotundus* was described. In 1908, the first cattle rabies outbreak was recorded in Brazil, the most severe cattle illness ever since, but only in 1934 the transmission of the rabies virus (RABV) by common vampire bats was confirmed. Until then, only the transmission by dogs was accepted[3].

Cattle rabies transmitted by vampire bats occurs only in Latin America, where the only three hematophagous bat species occur, but only one (*D. rotundus*) is associated with rabies transmission to cattle. Mortality is the main direct cost of cattle rabies along with vaccination. This burden is significantly higher in developing countries such as in Latin America, especially in regions where small farmers are more prevalent[3].

In Brazil, the National Cattle Rabies Control Plan (PNCRH) was implemented in 1966 and reformulated in 2002, but roughly the same surveillance and control measures are made since its creation. The surveillance is passive, relying on the communication of suspicious cases by public or private veterinarians or the farmers, to a local veterinary service. An official veterinarian then visits the farm, collects epidemiological information and biological samples to confirm the suspicion. If the infection is confirmed, the control is based on indiscriminate culling of common vampire bats in a Euclidean radius of 12 km around the outbreak, using anticoagulant paste applied in the bat's back, in the hope that when returning to its roost, other bats would ingest the anticoagulant during social grooming and die of hemorrhage. Moreover, vaccination of susceptible animals is only suggested. Once mandatory nationwide, some Brazilian States no longer require it since 2008, despite the fact that the farmers were always responsible for the vaccine payment and delivery.

Conversely, the surveillance of rabies virus circulation in bats is not representative. It is currently based on opportunistic samples collected mainly during the bat captures carried out to administrate the anticoagulant paste[4]. Some attempts to predict the rabies circulation proved to be susceptible to the quality of the surveillance data[5]. This design makes the PNCRH reactive to reported cattle rabies outbreaks, but incapable to determine the circulation of the RABV in bats and to predict or even describe the evolution of cattle rabies.

Some authors state that indiscriminate vampire bat culling may be not only ineffective to control bat rabies, but also helps to spread the RABV by disrupting the colonies and subsequently increasing the infectious contacts among the vampire bats[6-7]. For this reason, the knowledge of the common vampire bat biology aligned with the demands for cattle rabies control, must prioritized, for example using precise and selective culling only when and where is needed[8-9].

In this work, we aimed to estimate the current state of the cattle rabies surveillance and control through (1) the probability of occurrence and probable geographic distribution of *D. rotundus* roosts; (2) the effort of the veterinary services in recording bat roosts; and (3) the incidence of cattle rabies outbreaks in Brazil. We performed an ecological niche model for vampire bats distribution and a space-temporal analysis of reported outbreaks, as a means to improve RABV surveillance in *D. rotundus* and control measures. Moreover, a reflection of the future development of the PNCRH is debated, comparing the surveillance effort nationally and proposing a new approach based on bat attacks on cattle, as a way of spatial-time monitoring of the vampire bat population, using as proxies the relief slope dependency on foraging behavior[8] and carrying capacity of roosts in a contact network[9]. This turn in the rationale of the surveillance and control of cattle rabies is essential, if one consider the execution of rabies surveillance field work as one of the most expensive actions of animal health activities and cattle rabies is not as economic appealing as other diseases such as foot-and-mouth disease, tuberculosis or brucellosis.

Material ant Methods

Geographic distribution of D. rotundus

An ecological niche model for the common vampire bat *D. rotundus* was elaborated to estimate the association between the climatic conditions of the known presence and absence of this species. This process included (1) the geolocation of the *D. rotundus* presence (and absence); (2) extraction of the environmental predictors of these locations; (3) adjustment of the similarity model to the environmental parameters of the occurrence locations; (4) utilization of the adjusted model to predict the occurrence of the common vampire bat in Brazil and Latin America.

To achieve that, we used the geographic coordinates of the recorded vampire bat roosts obtained by the local veterinary services and compiled by the Ministry of Agriculture, Livestock and Food Supply (MAPA). Files of the locations of the roosts were compiled in a single national data base and imported to R software. The *D. rotundus* roosts were classified as harem (occupied mostly by females and pups), bachelors (occupied mostly by young males) and overnight (temporary resting stop during foraging and digestion), assuming for those locations the status of known presence of *D. rotundus*. As for the status of absence of *D. rotundus* two approaches were compared: (1) geographic location of empty roosts and (2) a set of 500 random points, denominated as background. The choice of the best model was based on the ROC curves.

The geographic parameters were obtained as GeoTIFF (raster) files from www.worldclim.org (version 2. with historical data from 1970-2000) and imported to R software using the *dismo* package. The variables included:

- BIO1 - Annual mean temperature;

- BIO2 - Mean diurnal range (mean of monthly (maximum temperature - minimum temperature));
- BIO3 - Isothermality (BIO2/BIO7) (×100);
- BIO4 - Temperature seasonality (standard deviation ×100);
- BIO5 - Maximum temperature of warmest month;
- BIO6 - Minimum temperature of coldest month;
- BIO7 - Temperature annual range (BIO5-BIO6);
- BIO8 - Mean temperature of wettest quarter;
- BIO9 - Mean temperature of driest quarter;
- BIO10 - Mean temperature of warmest quarter;
- BIO11 - Mean temperature of coldest quarter;
- BIO12 - Annual precipitation;
- BIO13 - Precipitation of wettest month;
- BIO14 - Precipitation of driest month;
- BIO15 - Precipitation seasonality (coefficient of variation);
- BIO16 - Precipitation of wettest quarter;
- BIO17 - Precipitation of driest quarter;
- BIO18 - Precipitation of warmest quarter;
- BIO19 - Precipitation of coldest quarter.

The climatic parameters of the known presence and absence points (bat roosts) were extracted using the R function 'extract'. which were later used as predictors in the ecological niche model. After the extraction of the predictors, the collinearities were removed.

A general linear model (glm) was implemented, where all extracted environmental parameters were considered, but being kept in the final model only those with $p < 0.05$. Two models were tested, the first trained with the absence data (empty roosts) and the second, trained with the set of 500 random points (background). The predictive model of the *D. rotundus* distribution was obtained using the function 'predict' of the *dismo* package of R software. The obtained GeoTIFF (raster) maps were used for the subsequent analyses in the QGIS software, where the probability of occurrence of the *D. rotundus* was shown as varying from 0 to 100%.

Using the results of the ecological niche model for the *D. rotundus*, it was also possible to determine the probability of occurrence of the vampire bat in each cattle raising farm in Brazil. The register of cattle raising farms in Brasil farm was kindly provided by MAPA. The probability of *D. rotundus* occurrence was extracted from the raster of the ecological niche (above) to each cattle raising farm using the 'Point sampling tools' of the QGIS software. The obtained values were continuous and could be reclassified according to the analytic interest.

Density of D. rotundus roosts and evaluation of their recording in Brazil

The density of the roosts used by the *D. rotundus* (harem, bachelor and overnight) recorded by the local veterinary services and compiled by MAPA was calculated in the QGIS software using the 'heatmap' function, with an analysis radius of 100 km. Sao Paulo was the Brazilian State showing the highest number of monitored bat roost and for that reason, the maximum density value observed in this State was used as benchmark for the whole country by considering this value as 100% and normalizing the national results between 0 to 100%.

The evaluation of the effort of the vampire bat roost recording was made by subtracting the raster map of the probability of *D. rotundus* occurrence by the raster map of the normalized bat roost density. This operation was made in QGIS software using the 'Raster calculation' tool. The resulting GeoTIFF (raster) map represented the deficiency of the recording effort of vampire bat roosts. varying from 0 to 100%. The 0% value corresponded to the highest effort (benchmark) and 100%, the absence of *D. rotundus* roost recording.

Incidence of cattle rabies outbreaks in Brazil

The annual cumulative incidence of cattle rabies was calculated by using the number of bovine and buffalo (cattle from now on) rabies outbreaks recorded by MAPA at Continental System of Epidemiological Surveillance (SIVCont) (WHO/PAHO/Panaftosa) from 2010 to 2019 as numerator and the number of cattle raising farms in Brazil as denominator, since parameter was more stable than the cattle population itself during the time series.

The graphical representation of the cattle rabies outbreaks between 2010 and 2019 was made by using the outbreaks reported by MAPA to SIVCont, and completing the missing geographic coordinates with the coordinates from the city center. Moreover, the signs of the coordinates were checked and changed if needed. The graphical representation of the annual cumulative incidence of cattle rabies outbreaks between 2010 and 2019 was represented in a panel of thematic maps made in QGIS software.

Spatial relative risk of cattle rabies in Brazil

A space-time analysis of the cattle rabies outbreaks reported by MAPA to SivCont was made by using the geographic coordinates of the cattle rabies outbreaks (considered cases) and the coordinates of the cattle raising farms (considered controls). The analysis was made in R, using the package *sparr*. The calculation was based in the ratio between the estimated kernel densities of cases and controls, using the cases stratified by year (annual cumulative incidence) and considering a variable and adaptive bandwidth, generating continuous surfaces of relative risks in thematic maps. The contours of the asymptotic tolerance ($p = 0.05$) were obtained to assign areas of increased and significative relative risk ($RR > 1$).

Decomposition of the time series of cattle rabies in Brazil

The time series of cattle rabies outbreaks (farm with at least one positive animal) was analyzed using the weekly reports made by MAPA to SivCont between 2010 and 2019. The years 2010 and 2016 had 53 weeks, and for them, data from the 53rd week were added to the 52nd week data.

To decompose the time series, a multiplicative method based on Cryer and Chan[10]. The first step was the determination of the seasonal index, calculated from the division of the weekly number of outbreaks by the mean number of outbreaks of the corresponding year. After that, the mean weekly values of the entire time series was calculated, obtaining the seasonal index. The next step was the removal of the seasonality, calculated from the division of the weekly number of outbreaks by its correspondent seasonal index. From the resulting series, a tendency line (linear regression) was obtained. From the equation of this line, one could determine if there was an increased, decreased or constant tendency of growth of outbreaks. Following the decomposition of the time series, the next step was the removal of the tendency, obtained by the division of the values obtained with the removal of seasonality (previous step) by the values obtained by the equation of the tendency line. Moreover a moving average of 6 months has been obtained to smooth the obtained results.

Finally, a control chart for a typical year, based in the time series, was elaborated. The control chart was elaborated from the weekly records of cattle rabies, the mean weekly values (denominated endemic level) and the upper limit of the endemic level, given by the standard deviation of the mean values.

Results

Geographic distribution of D. rotundus

In the final model of the geographic distribution of *D. rotundus*, the parameters BIO1, BIO5, BIO6, BIO7, BIO8, BIO12, BIO16 and BIO17 were significant. The model using the climatic parameters extracted from the known absence of *D. rotundus* (empty roosts) produced an AUC = 0.58 and the model using the set of 500 aleatory points (background) produced an AUC = 0.92, this being chosen as the final model. The obtained *D. rotundus* distribution ranged from Northern Argentina to Northern Mexico with low, but present, probability of occurrence in Southern United States. Although the model indicated the presence of the vampire bat in the oceanic islands, no record of this species has ever been made in these locations (Figure 1).

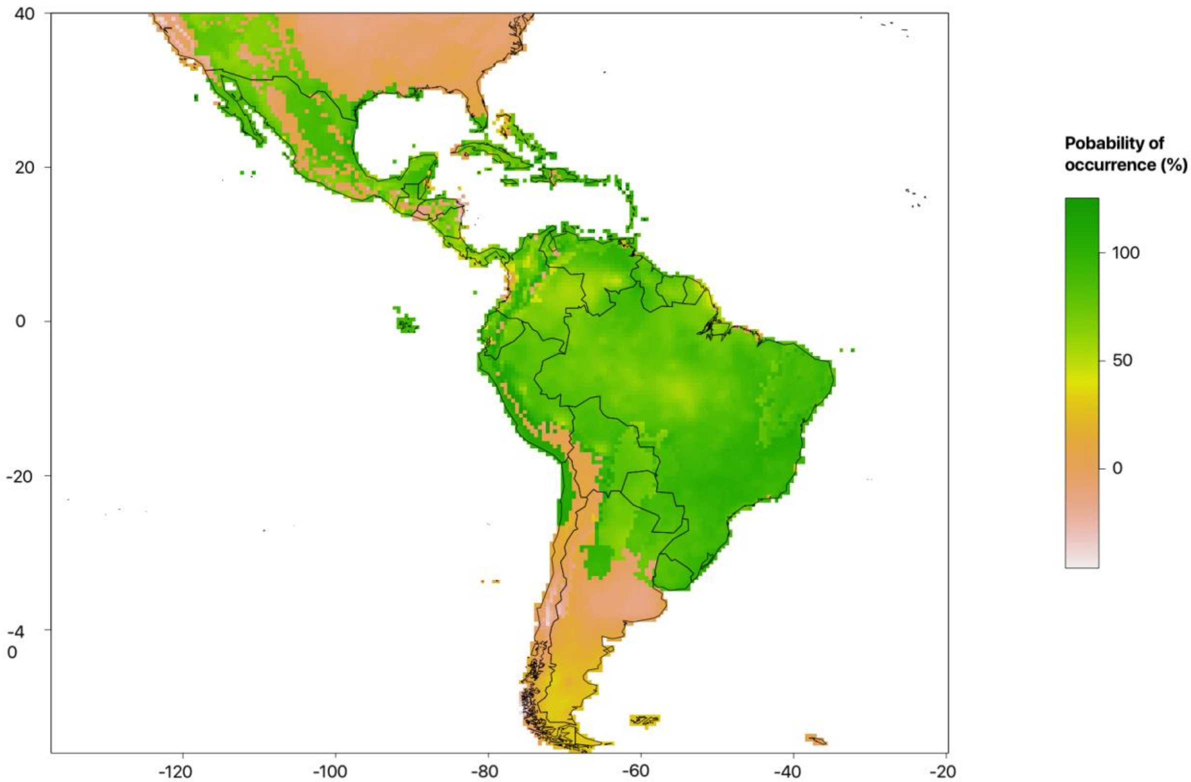

Figure 1. Geographic distribution model of the *Desmodus rotundus* in Latin America.

In continental Brazil, the probabilities of occurrence of the *D. rotundus* are variable, being highest in the Atlantic Rain Forest, Central and Northern Brazil (Roraima) and lowest in the Amazon, Semi-Arid Northeastern Brazil (Caatinga) and Pantanal (Figure 2).

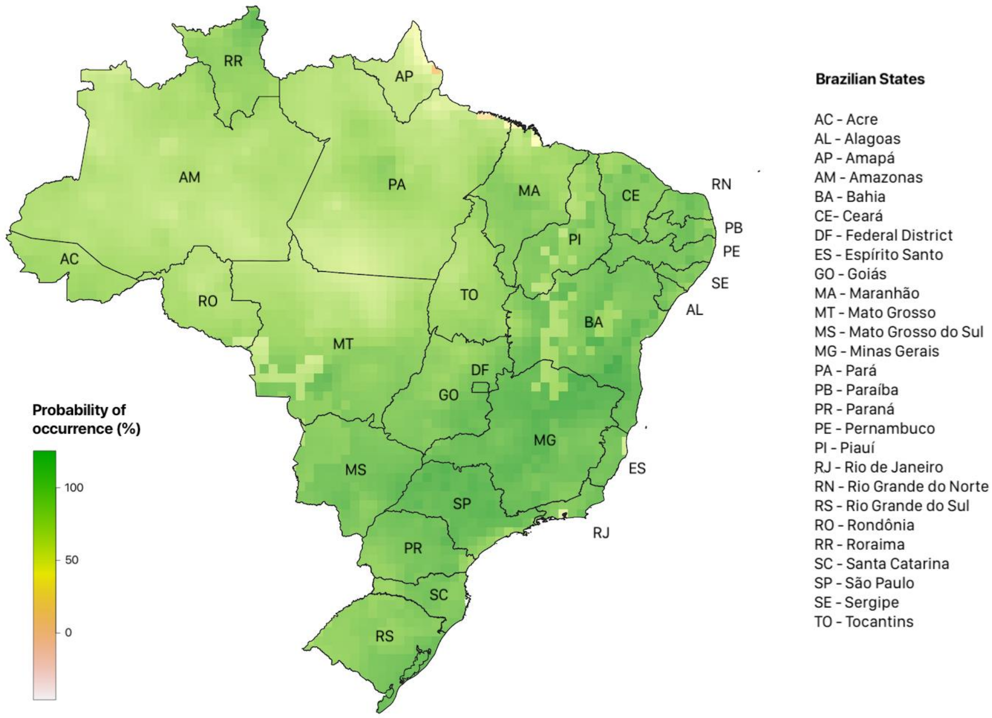

Figure 2. Geographic distribution model of the *Desmodus rotundus* in Brazil estimated in probability of occurrence.

The probability of occurrence of *D. rotundus* (receptivity) in each cattle raising farms of Brazil is shown in Figure 3.

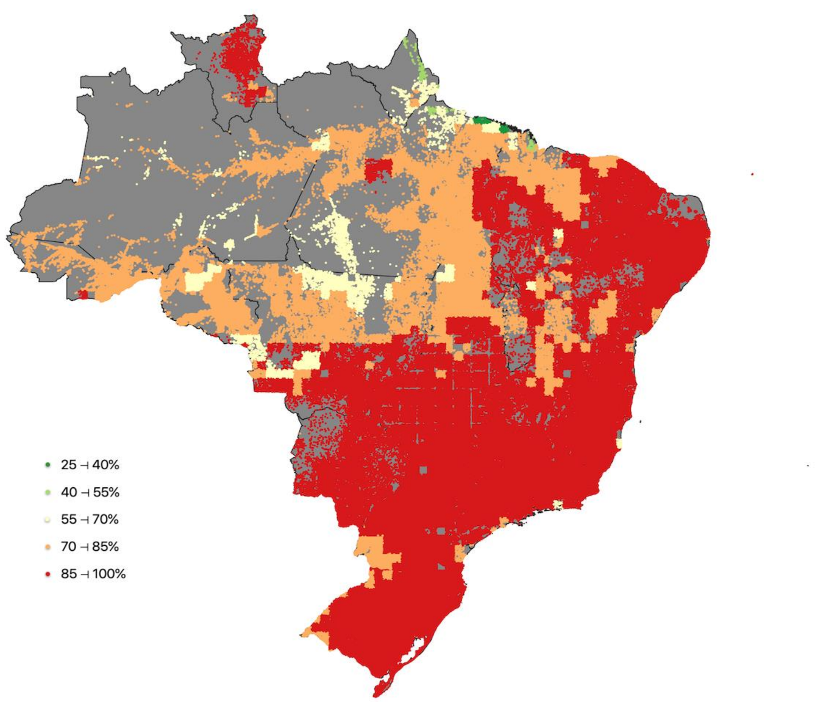

Figure 3. Probability of occurrence (receptivity) of the *Desmodus rotundus* in cattle raising farms in Brazil.

Density of D. rotundus roosts and evaluation of their recording effort

The normalized *D. rotundus* roost density was represented in Figure 4 and the deficiency of the recording effort of vampire bat roosts was represented in Figure 5. In general. the *D. rotundus* roost recording was roughly nonexistent in the Amazon, excepting a few spots in some States. Other spots of nonexistent efforts of vampire bat roost recording were large areas in the Northeast (between Piauí and Maranhão and Eastern Pernambuco States) and Central Brazil (Western Goiás and Northern Minas Gerais States). Excepting Central and Eastern Sao Paulo and Southern Minas Gerais, the rest of the country showed, at most, intermediary efforts of vampire bat roost recording.

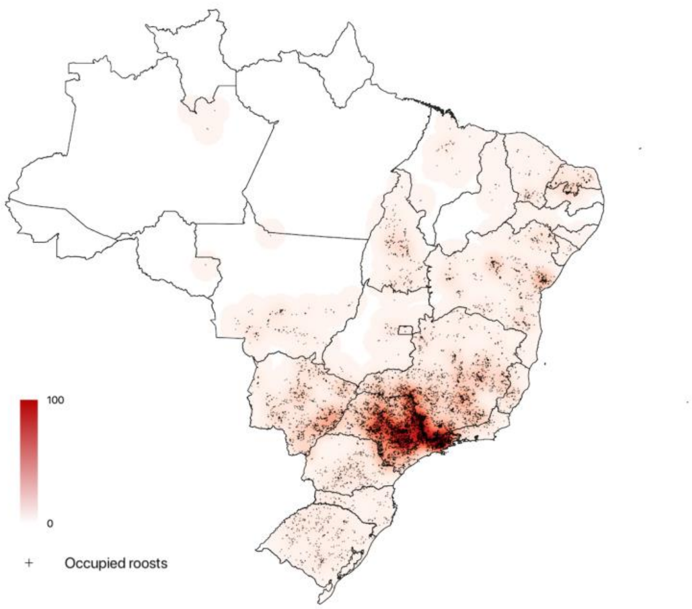

Figure 4. Normalized density of *Desmodus rotundus* roosts, using Sao Paulo State as benchmark.

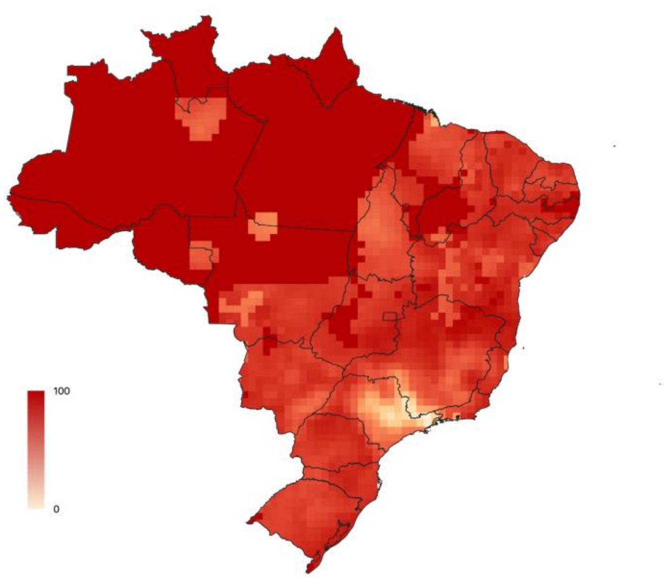

Figure 5. Deficiency in *Desmodus rotundus* roosts recording, using Sao Paulo State as benchmark.

Incidence of cattle rabies outbreaks in Brazil

A total of 5,999 cattle outbreaks have been recorded in Brazil from 2010 to 2019, of them 5,980 (99.7%) in bovines and 19 (0.3%) in buffaloes. The number of reported cattle rabies outbreaks and incidences were compiled in Table 1.

Table 1. Annual cumulative incidences of cattle rabies in Brazil (and States) from 2010 to 2019.

(continue)

State	2010		2011		2012		2013		2014		Farms[2]
	Outbreaks[1] (N)	Incidence (per 1,000)	Outbreaks[1] (N)	Incidence (per 1.000)	Outbreaks[1] (N)	Incidence (per 1.000)	Outbreaks[1] (N)	Incidence (per 1.000)	Outbreaks[1] (N)	Incidence (per 1.000)	
RO	7	0.07	2	0.02	1	0.01	8	0.08	3	0.03	102,089
AC	1	0.04	0	0	3	0.12	10	0.40	1	0.04	25,133
AM	1	0.06	0	0	2	0.12	0	0	0	0	16,208
RR	0	0	0	0	0	0	0	0	0	0	13,258
PA	11	0.09	10	0.08	10	0.08	17	0.14	20	0.16	122,884
AP	0	0	0	0	0	0	0	0	0	0	1,647
TO	10	0.13	17	0.22	1	0.01	7	0.09	17	0.22	76,637
MA	7	0.05	6	0.04	10	0.07	14	0.10	5	0.04	137,641
PI	6	0.03	8	0.04	7	0.03	2	0.01	1	<0.01	221,155
CE	6	0.04	1	0.01	7	0.05	2	0.01	4	0.03	137,697
RN	5	0.11	5	0.11	7	0.15	2	0.04	19	0.42	45,460
PB	17	0.12	9	0.06	3	0.02	6	0.04	3	0.02	144,923
PE	29	0.15	28	0.15	7	0.04	15	0.08	24	0.12	191,695
AL	8	0.13	13	0.21	8	0.13	7	0.11	5	0.08	62,389
SE	6	0.15	8	0.21	4	0.10	6	0.15	3	0.08	38,682
BA	0	0	0	0	1	<0.01	4	0.01	26	0.09	297,741
MG	102	0.26	112	0.28	112	0.28	131	0.33	152	0.38	398,588
ES	82	3.05	53	1.97	64	2.38	46	1.71	60	2.23	26,918
RJ	35	1.06	57	1.72	41	1.24	44	1.33	23	0.69	33,111
SP	36	0.17	51	0.24	98	0.46	65	0.30	128	0.60	214,915
PR	63	0.36	83	0.47	97	0.55	60	0.34	26	0.15	176,121
SC	28	0.15	32	0.17	90	0.48	54	0.29	35	0.19	188,569
RS	48	0.16	47	0.15	118	0.39	124	0.41	138	0.46	302,841
MS	13	0.23	10	0.17	17	0.30	6	0.10	16	0.28	57,321
MT	57	0.29	82	0.42	62	0.31	37	0.19	33	0.17	196,514
GO	21	0.16	10	0.08	4	0.03	13	0.10	13	0.10	127,671
DF	0	0	0	0	0	0	1	0.35	0	0	2,852
Brazil	599	0.18	644	0.19	774	0.23	681	0.20	755	0.22	3,360,660

(continued)

State	2015		2016		2017		2018		2019		Farms[2]
	Outbreaks[1] (N)	Incidênce (per 1.000)	Outbreaks[1] (N)	Incidênce (per 1.000)	Outbreaks[1] (N)	Incidênce (per 1.000)	Outbreaks[1] (N)	Incidênce (per 1.000)	Outbreaks[1] (N)	Incidênce (per 1.000)	
RO	2	0.02	1	0.01	2	0.02	5	0.05	4	0.04	102,089
AC	4	0.16	0	0	0	0	2	0.08	1	0.04	25,133
AM	5	0.31	4	0.25	0	0	0	0	2	0.12	16,208
RR	0	0	1	0.07	0	0	0	0	0	0	13,258
PA	17	0.14	6	0.05	20	0.16	29	0.24	21	0.17	122,884
AP	0	0	0	0	0	0	0	0	0	0	1,647
TO	47	0.61	40	0.52	38	0.50	20	0.26	14	0.18	76,637
MA	9	0.06	3	0.02	0	0	4	0.03	7	0.05	137,641
PI	0	0	6	0.03	2	0.01	1	<0.01	3	0.01	221,155
CE	35	0.25	9	0.06	13	0.09	18	0.13	4	0.03	137,697
RN	14	0.31	5	0.11	4	0.09	2	0.04	3	0.07	45,460
PB	6	0.04	1	0.01	0	0	0	0	1	0.01	144,923
PE	25	0.13	3	0.02	7	0.04	23	0.12	13	0.07	191,695
AL	5	0.08	4	0.06	3	0.05	3	0.05	16	0.26	62,389
SE	3	0.08	4	0.10	1	0.03	3	0.08	1	0.03	38,682
BA	11	0.04	20	0.07	54	0.18	19	0.06	17	0.06	297,741
MG	99	0.25	95	0.24	72	0.18	92	0.23	94	0.24	398,588
ES	44	1.63	18	0.67	25	0.93	12	0.45	20	0.74	26,918
RJ	12	0.36	20	0.60	8	0.24	10	0.30	12	0.36	33,111
SP	63	0.29	42	0.19	25	0.12	13	0.06	94	0.44	214,915
PR	34	0.19	38	0.22	41	0.23	35	0.21	73	0.41	176,121
SC	14	0.07	8	0.04	16	0.08	50	0.26	56	0.30	188,569
RS	80	0.26	48	0.16	28	0.09	47	0.15	47	0.15	302,841
MS	8	0.14	7	0.12	37	0.64	18	0.31	35	0.61	57,321
MT	42	0.21	27	0.14	51	0.26	16	0.08	58	0.29	196,514
GO	18	0.14	10	0.08	13	0.10	18	0.14	26	0.20	127,671
DF	0	0	1	0.35	1	0.35	3	1.05	2	0.70	2,852
Brazil	597	0.18	421	0.12	461	0.14	443	0.13	624	0.19	3,360,660

1Cattle rabies outbreaks recorded by MAPA at SIVCont (PANAFTOSA).
2Cattle raising farms by State in 2019.
Grey cells represent annual cumulative incidence above the national values of each year.

The cumulative annual incidence of cattle rabies was stable in Brazil throughout the time series, varying from 0.12 to 0.24 outbreaks per thousand cattle raising farms. As for the Brazilian States, Minas Gerais, Espírito Santo and Rio de Janeiro (all located in Southeastern Brazil) showed incidences consistently above the national values throughout the time series. The highest incidence was recorded in Espirito Santo in 2010 (3.05 outbreaks per thousand farms). In the Federal District, the incidences above the national values were, most of the times, due to a single outbreak. Most of the incidences above the national values were observed in Southeastern, South and Central Brazil.

The graphical representation of the annual cumulative incidence of cattle rabies outbreaks between 2010 and 2019 is shown in a panel of thematic maps (Figure 6). A total of 1,205 (20.1%) records (mostly in Minas Gerais and Paraná) had missing geographic coordinates, which were completed by the location of the corresponding city's downtown. Moreover, 86 (1.4%) original coordinates had the signs of latitude and/or longitude changed.

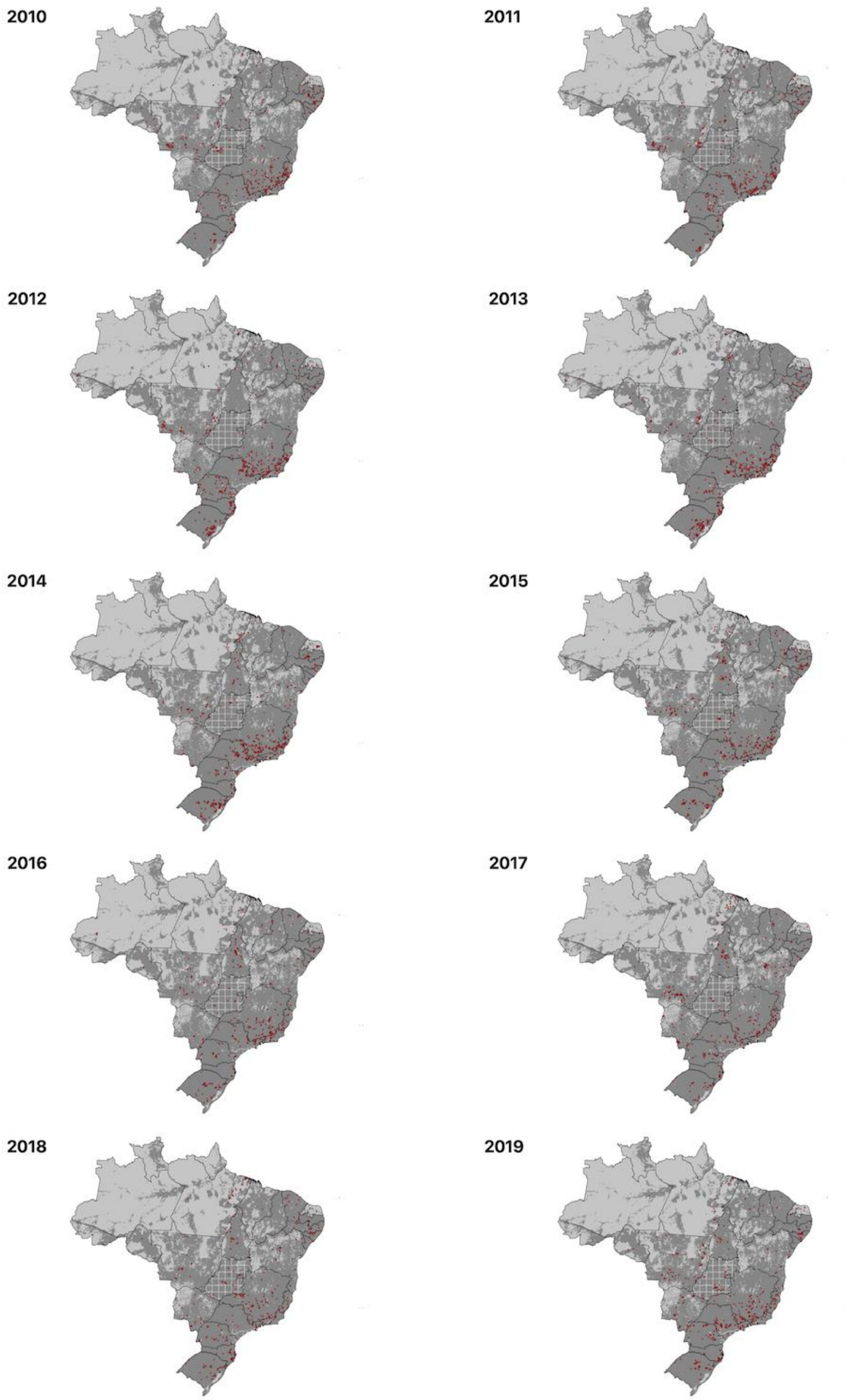

Figure 6. Graphical representation of the annual cumulative incidence of cattle rabies between 2010 and 2019. Grey dots represent cattle raising farms and red dots, cattle rabies outbreaks.

Spatial relative risk of cattle rabies in Brazil

A panel with thematic maps of the spatial relative risk of cattle rabies is shown in Figure 7. Areas of increased relative risk (RR > 1) were observed in Western Mato Grosso do Sul (border with Bolivia and Paraguay), Eastern Paraná and Southeastern Brazil (Sao Paulo, Minas Gerais, Rio de Janeiro and Espirito Santo States) consistently throughout the entire time series. These areas may be considered endemic. Moreover, the same situation, but in shorter periods were observed in Eastern (2010-11) and Southern (2011-13) Mato Grosso, Southern Rio Grande do Sul (2011-16), Western Amazonas and Acre (2013 and 2015-16), Eastern Ceará (2014-15), Tocantins (2015-19), Eastern Bahia (2016-18), Northern Pará (2017-19) and Eastern Rio Grande do Sul and Santa Catarina (2018-19).

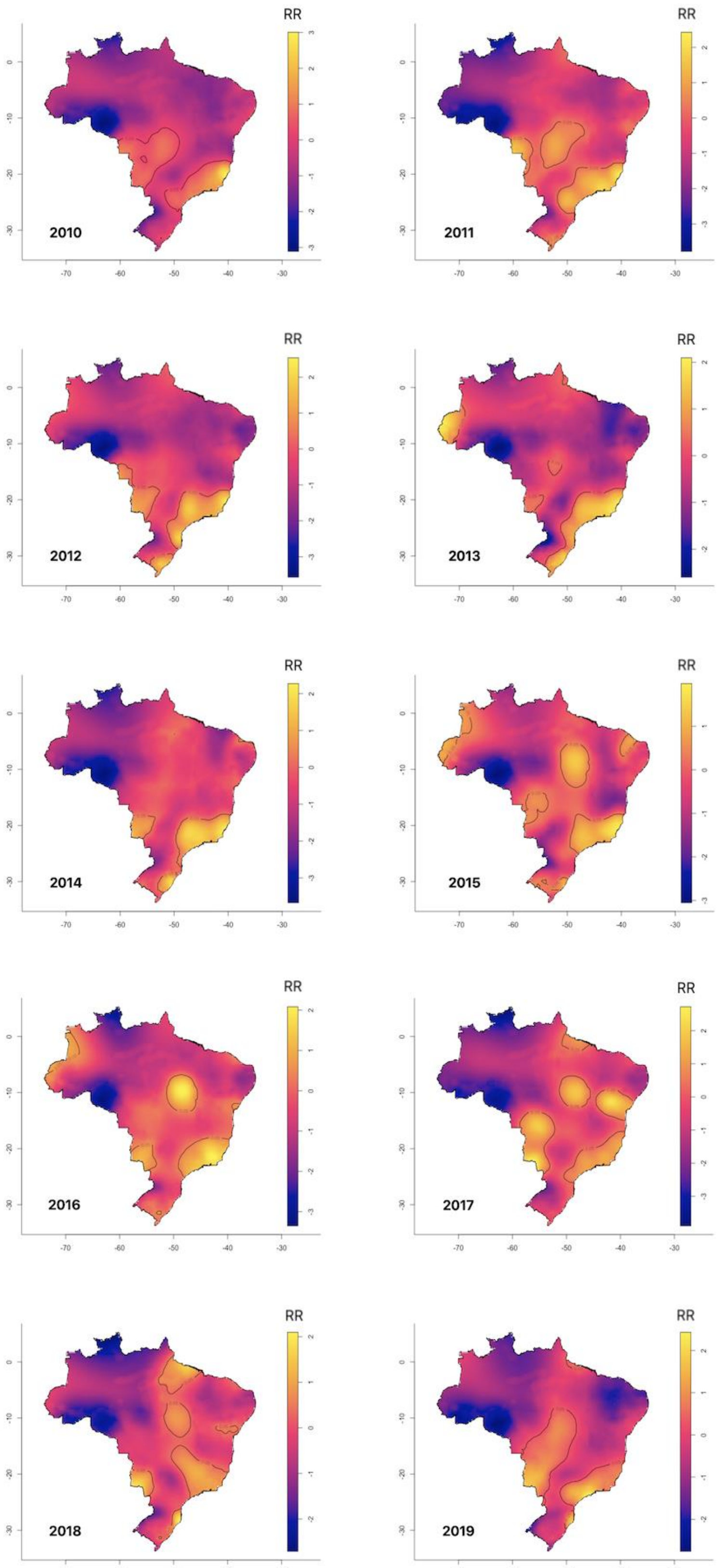

Figure 7. Panel of the spatial relative risk of cattle rabies in Brazil between 2010 and 2019.

Decomposition of the time series of cattle rabies in Brazil

From the raw data of the weekly reports of cattle rabies outbreaks between 2010 and 2019 (Figure 8), no epidemiological pattern could be observed. Moreover, from the seasonal index graph (Figure 9), no accumulation of outbreaks has been observed, but a single peak of outbreak reports has been observed in week 34 (September). A tendency of reduction of cattle rabies outbreaks has been observed throughout the time series (Figure 10). A cyclical variation of cattle rabies outbreaks was observed in the time series, with an interval of 7 years from peak to peak (Figure 11).

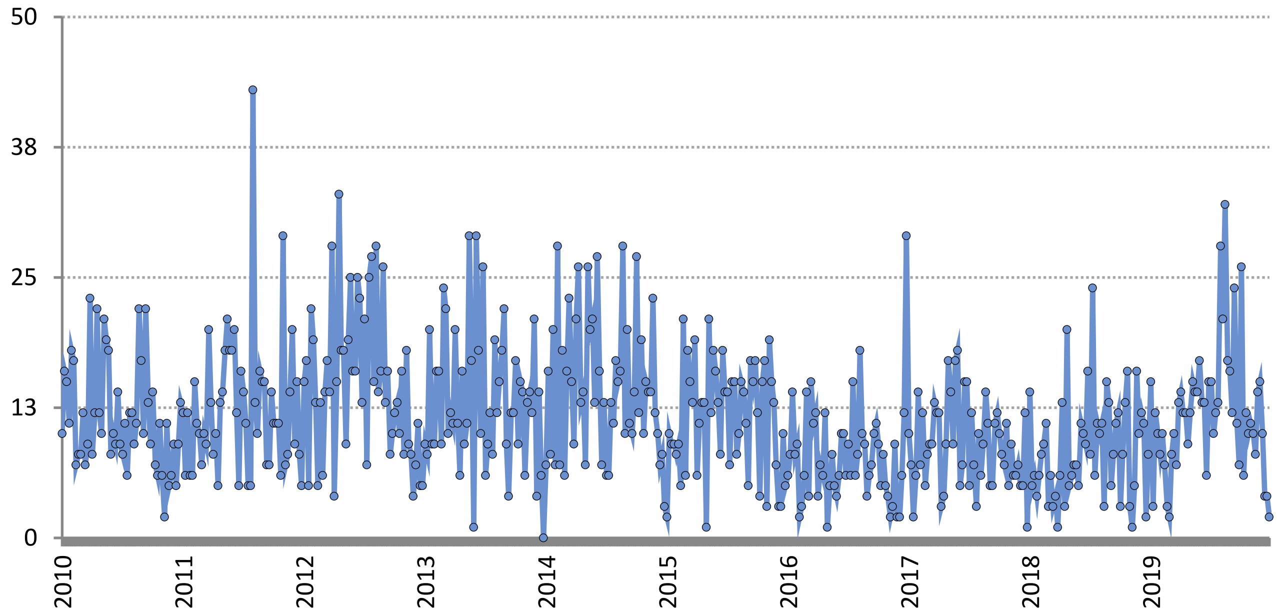

Figure 8. Cumulative weekly incidence of cattle rabies outbreaks in Brazil between 2010 and 2019.

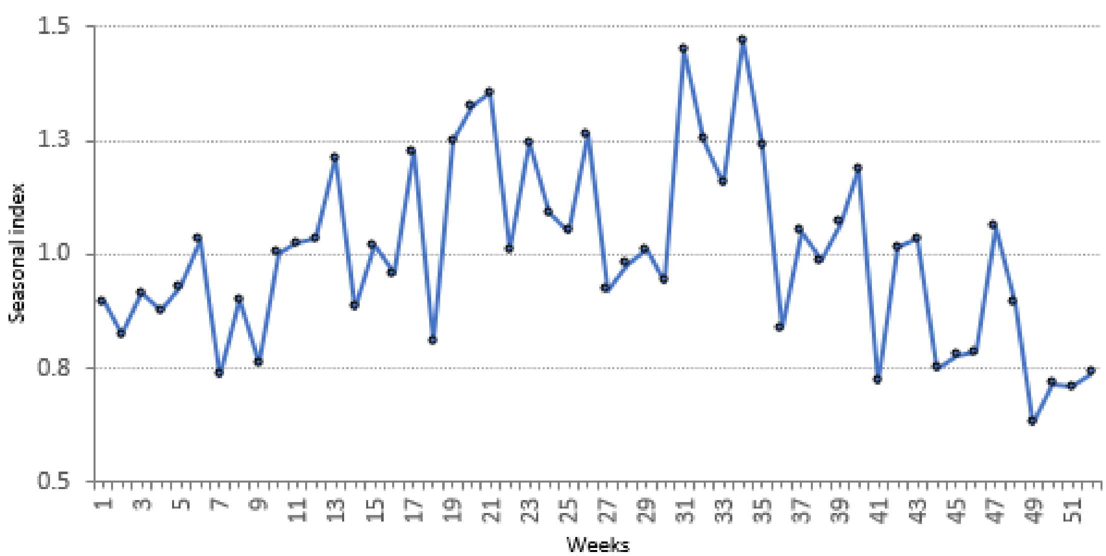

Figure 9. Seasonal index of cattle rabies outbreaks in Brazil between 2010 and 2019.

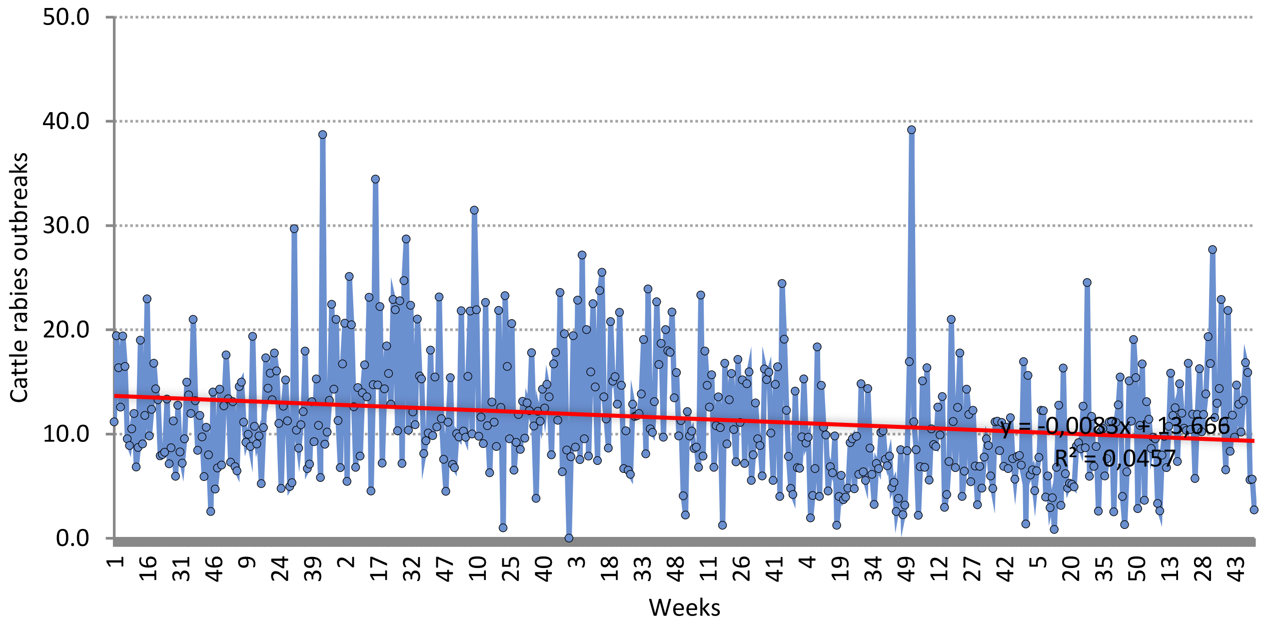

Figure 10. Tendency line (red) obtained by the linear regression of the series with seasonality removed (blue line) from the time series of cattle rabies outbreaks in Brazil between 2010 and 2019.

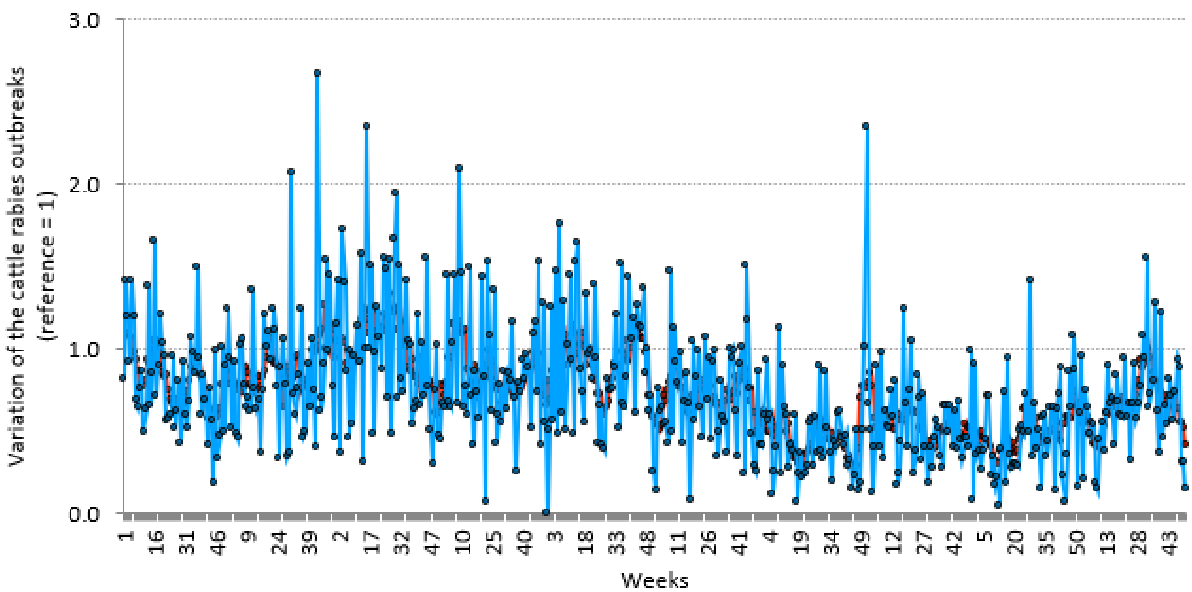

Figure 11. Removal of tendency (blue line) and smoothing by moving average (red line) of the time series of cattle rabies outbreaks in Brazil between 2010 and 2019.

As an example, the control chart of the year 2019 is shown in Figure 12. This chart represents the entire time series, with an endemic behavior of the cattle rabies, despite some weekly epidemic peaks, followed by endemic behavior. Curiously, the endemic peaks occurred around the week 34 (mid September). Despite this, the behavior of the cattle rabies in the time series between 2010 and 2019 was considered endemic.

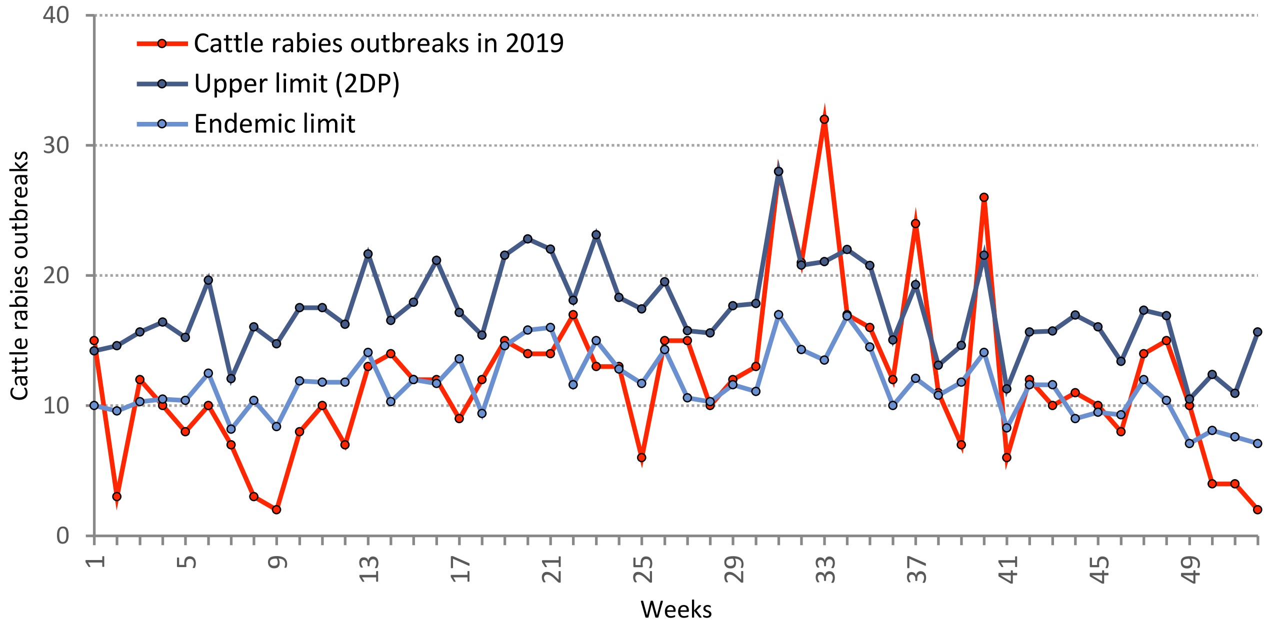

Figure 12. Control chart for the cattle rabies outbreaks in Brazil between 2010 and 2019.

Discussion

The logic of the Brazilian cattle rabies control program currently aims at reducing the cattle rabies incidence by promoting indiscriminate culling of the vampire bats in the vicinity of a reported cattle rabies case. The reduction of the vampire bat population is performed with the pretense expectation of reduction of the spillover of RABV to livestock[4,11]. The system is passive, triggered by cattle rabies cases, even being a dead end in the transmission of the RABV as they do not pass on the virus. After the notification of a cattle rabies case, official veterinarians visit a 12 km Euclidean radius around the outbreak trying to capture vampire bats and apply anticoagulant paste in their backs, hoping to kill as many as possible though hemorrhage[4].

If the main control strategy of cattle rabies is the indiscriminate culling of vampire bats which appointed by some authors as being associated with RABV spread[6-7] and the main prevention strategy, i.e., the vaccination of susceptible livestock against rabies, is no longer mandatory since 2008, turning into farmer responsibility ever since, the Brazilian cattle herd is currently at risk of rabies outbreaks. Moreover, even sending high numbers of vampire bats captured during the control actions to the official laboratories, this opportunistic sample is not even nearly as representative of the RABV circulation in bats and do not allow the prediction of the RABV circulation in vampire bats nor the spillover to cattle, the same happening in the case of dog rabies[12].

The present work aimed at describe the probability of *D. rotundus* occurrence, the effort of vampire bat surveillance and the spatial time behavior of the cattle rabies waves, in light of ecological features of vampire bats that could improve the efficacy of the program[8-9]. When the *D. rotundus* ecological niche model (ie., continuous approach) is considered alone, probable high densities are expected in Atlantic Rain Forest, Central and Northern Brazil and low densities in the Amazon, the semi-arid Northeast and Pantanal. The approach of the present work is in line with other published models, especially the one from Lee et al[13]. But when this probability is extracted from the ecological niche model to the coordinates of the Brazilian farms (ie., a discrete approach), roughly all farms, excepting those in Amazon and some spots of semi-arid Northeast, are exposed to high probability of occurrence of *D. rotundus* and for instance, rabies.

The registration of vampire bat roosts is a key feature in the surveillance of rabies, but not in the way it is currently performed. The importance of this feature is discussed below. Using the State of Sao Paulo as benchmark, we observed that the registration effort of vampire bat roosts is low in the rest of the country, and should be increased in Southern, Central and Northeast Brazil, precisely where most of the herd is located. In Amazon, in addition to the difficulty of finding the roosts, the cattle population is sparse and vaccination should be encouraged to prevent spillover from bats.

Even though rabies surveillance is higher in the State of Sao Paulo, epidemic waves are observed throughout the country in the entire study period, especially in Central and Southeastern Brazil, as observed in other Latin American countries, such as Peru[14-15]. If we compare the sequence of space-time relative risk with the map or probability of occurrence of *D. rotundus* in farms, epidemic waves were expected in other parts of Brazil, and are probably underestimated due to low surveillance efforts.

The decreasing tendency of the cattle rabies outbreaks in the 2010-2019 time series is another parameter that must have been influenced by the surveillance effort. Ideally, the cumulative annual cattle rabies incidence calculation should have been adjusted by the surveillance effort throughout the time series. This effort is given by the number of veterinarians and field staff of each State who work in rabies surveillance. Since this number was not available for each State in each year of the time series, this adjustment was not made in the cattle rabies incidence calculations nor the time series decomposition. Besides the number of staff working in rabies surveillance and control, it would be necessary to inform their work regime. For example, in Sao Paulo State, these workers could not accumulate more than 50% of their monthly salary in workday payments after the year 2008 (State Decree 48.292/2003 - 1st Article, paragraph 3rd). Since most of the activities included traveling to the countryside to investigate bat roosts, make bat captures and visit farms with suspect rabies cases, the resulting situation was a significant reduction of the (cattle and bat) rabies surveillance system sensitivity. Along with the fall of the number of staff from 55 in 2008 to 32 in 2018 (a reduction of 36.4%), the surveillance effort has fallen from 105,600 workers * hour to 22,560 workers * hour (a reduction of 78.6%). It is noteworthy that the accumulation of workaday payments is more related to the bat captures (night activities) than surveillance of cattle rabies outbreaks (daytime activities), but since the work regimes may vary between each Brazilian State, this elucidation would be pertinent. These results are therefore incompatible with a decreased surveillance effort, due to decreased number of field staff and work regime, with the high probability of occurrence of the *D. rotundus* in most of the Brazilian territory.

Despite the decreasing tendency of the incidence of cattle rabies, the 2018 control chart (Figure 12) shows an epidemic state of the disease. The peak of incidence in mid-September must be a result of the resources contingency of the fiscal year, which occurs precisely at this time. The resources must be executed to this date, otherwise they would be collected, resulting in a concentrated surveillance effort.

The circulation of the RABV in vampire bats and its spillover to other species depends on several factors related to the ability of the *D. rotundus* to establish in the environment (receptivity) and the circulation of the RABV (vulnerability), as described by Dias et al[16]. However, that predictive model was highly dependent not only on good cattle rabies surveillance data, but also wildlife (especially bat) rabies surveillance data, which should be structured and risk orientated in order to provide accurate and useful predictions to control cattle rabies.

The parameters related to the receptivity are temporarily stable, if compared to the vulnerability. This stability facilitates not only the collection and organization of the information not only by the local veterinary services, but also by other sectors such as the environmental protection agencies. Among the parameters that should be obtained by the local veterinary services, the main sources are the register of cattle raising farms and the register of *D. rotundus* roosts. However, the effort of registration of *D. rotundus* roosts is low and heterogeneous in Brazil. If these data were used in predictive models such as the one proposed by Dias et al[16], would produce inaccurate results, especially if the aim was to define interstate or regional strategies.

Atemporal information should be continuously improved to more precisely predict the occurrence of vampire bats as the roost register increases. The ecological niche allowed this approach since even with disturbances, the vampire bat would tend to reoccupy the most suitable areas. The proposed analysis allows not only the observation of regional patterns but also the adequacy of control measures, aspects pursued by Braga et al[5].

Still referring to the receptivity, the role of the cattle herds as feed sources to *D. rotundus* has been elucidated by Rocha et al[8]. Regardless of the type of farm, each group of cattle works as a single feeding unit, in beef, dairy or mixed herds. Based in the results of the present work, the receptivity key proposed by Dias et al[16] could be replaced by the probability of occurrence of the *D. rotundus* in cattle raising farms (Figure 3).

As for the vulnerability, the parameters are mainly the incidence of bat rabies and environmental changes. The main information is related to the circulation of the RABV in bats, information that should be obtained in a structured way and with appropriate statistical criteria, especially with regard to the sample design. These aspects inevitably refer to a local interest, that is, field actions that can elucidate not only the source of infection, but the control measures to be used locally.

Rocha et al[8] also observed a topographical dependence on the location of *D. rotundus* roosts in relation to food sources, i.e., the roosts from which bats leave to forage are always located at higher altitudes than the attacked farms. Thus, when bat bites are observed on a particular farm, the bats involved in these attacks come from roosts located at altitudes higher than this farm. Conversely, when identifying roosts occupied by *D. rotundus*, their feed sources would likely be located at lower altitudes. This information is of paramount importance in the surveillance and control of rabies transmission from bats to cattle. In this regard, the main information for rabies surveillance would be the incidence of bites and not the findings of the rabies virus in bats or cattle. This approach also allow the construction of contact networks between roosts and between roosts and farms, as described by Rocha and Dias[9].

Finally, with regard to herbivore rabies control, it is possible to act in specific roosts and strategically targeting certain individuals, in order to break the chain of transmission of rabies to herbivores. As demonstrated by Rocha and Dias[9], the circulation of the virus among bats occurs in communities, given by the network of roosts used by *D. rotundus*. When describing these networks, one can proceed in selected shelters with the capture and euthanasia of specific individuals, in order to break the transmission network or to decrease the prevalence of rabies virus in bats before transmission to herbivores can occur. The number of managed target bats can be defined by the historical data of the bat attack incidence, with the objective of keeping this parameter below a transmission threshold. The description of the roosts network therefore depends on the increased effort to register *D. rotundus* roosts. Even so, this network can be built gradually, step by step, as surveillance and control actions are implemented.

It is therefore recommended to set a system to register the incidence of bat attacks in cattle and to improve the register of roosts, nationally, to the detriment of the indiscriminate capture of *D. rotundus* for diagnostic tests or management with warfarin paste, as currently performed. Of course, in addition to targeted management, it is recommended to establish vaccination programs aimed at areas with the highest risk of transmission to cattle such a system could be implemented in a scalable way, and in a recursive way (Figure 13). If implemented like proposed, the predictability of the RABV circulation would improve.

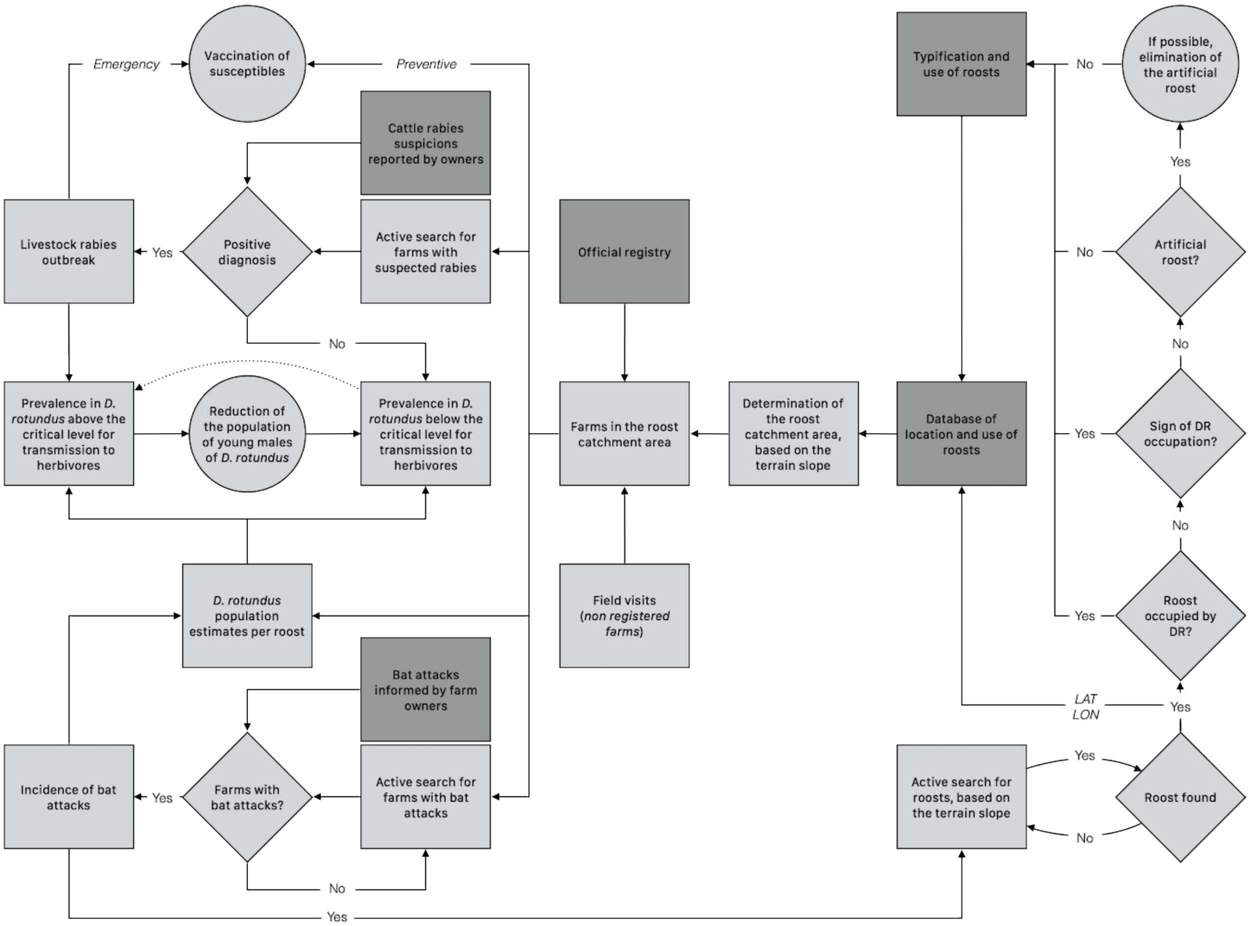

Figure 13. Flowchart of cattle rabies surveillance and control based on vampire bat attacks.

Finally, another point of discussion is the comparison between mass vaccination of cattle versus strategic vaccination in risk areas, associated with the reduction of the risk of RABV circulation in bats, through euthanasia focused on individuals at higher risk (young male vampire bats). In addition, to associate surveillance of other RNA viruses in euthanized bats, in order to provide some information on emerging viruses in bats, since there is no such effort in place in Brazil, even though the country may be a hotspot for emerging viruses in bats[17] and the rabies surveillance service already has national capillarity.

Conclusions

The present work proposes to change the logic of the cattle rabies passive surveillance system, currently based on cases and suspicions of rabies in livestock, to the monitoring of the incidence of bat attacks on cattle, as the main parameter. It is important to remember that the surveillance system would benefit from the estimation of the circulation (or areas of high circulation) of the RABV in bats to reduce the risk of spillover.

Moreover, this work could raise some questions, like: Why bother registering vampire bat roosts? Or is a National Cattle

Rabies Control Plan (PNCRH) necessary? This reflection is oriented not only to the optimization of the financial resources designated to rabies control, but to One Health, since rabies is still 100% lethal in humans, and it still circulates in Latin America, mostly transmitted from bats. Moreover, by monitoring and managing selected individuals of *D. rotundus* when necessary could mitigate the risk of RABV spillover to cattle.

Most importantly, indiscriminate culling of vampire bats must be halted, as this alone could lead to an epidemic state. This is a proposal of scalable improvement of the quality of the surveillance of bat and cattle rabies to improve the effectiveness of the rabies risk mitigation actions.

Corresponding author:
Ricardo Augusto Dias
University of Sao Paulo, Butanta
São Paulo - State of São Paulo, Brazil
Email: ricardodias@usp.br

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Conflict of Interest:

The authors have no conflicts of interest to declare.

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