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Research article

Using geostatistics to better understand the epidemiology of animal rabies in Morocco: what is the contribution of the predictive value?

Mounir Khayli [a,*], Youssef Lhor [a], Mohammed Bengoumi [b], Khalil Zro [c], Mehdi El Harrak [d], Abdenacer Bakkouri [e], Mohammed Akrim [f], Reda Yaagoubi [g], Ikhlass El berbri [h], Faouzi Kichou [k], Jaouad Berrada [h], Mohammed Bouslikhane [h]

[a] National Office of Food Safety (ONSSA), Rabat-Instituts, Po. Box 6472, Rabat, Morocco
[b] FAO Subregional Office for North Africa, Po. Box 107, 1053, Tunisia
[c] Biopharma, Po. Box 4569, Rabat, Morocco
[d] OIE-FAO Consultant, Rabat, Morocco
[e] FAO-HQ, 00153, Roma RM, Italy
[f] National School of Public Health, Rabat-Instituts, Po. Box 6329, Rabat, Morocco
[g] Hassan II Institute of Agronomy and Veterinary Medicine, School of Geomatics and Surveying Engineering, Po. Box 6202, Madinat Al Irfane, Rabat, Morocco
[h] Hassan II Institute of Agronomy and Veterinary Medicine, Microbiology Immunology and Contagious Diseases Unit, Po. Box 6202, Madinat Al Irfane, Rabat, Morocco
[k] Hassan II Institute of Agronomy and Veterinary Medicine, Pathology and Veterinary Public Health Department, Po.Box 6202, Madinat Al Irfane, Rabat, Morocco

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ABSTRACT

This study aims to characterize the spatial distribution of animal rabies in Morocco in order to provide appropriate control approaches. Descriptive analyses of the epidemiological data show that the number of reported canine rabies cases greatly underestimates the true incidence of the disease. Underreporting subsequently affects the coherence of its spatial distribution. To perform accurate geographic distribution mapping of the disease based on interpolation methods, a data set was created using data between 2000 and 2018 to compare the derived disease cases with known true values in order to identify disease clusters. The subsequent interpolation was conducted using Ordinary Kriging regression methods and the semi variogram to focus on short distances and reduce uncertainty. The estimated clusters of rabies were evaluated using a cross validation step which revealed predicted cases close to the true values. To improve the precision of analysis, the authors displayed georeferenced dog and human rabies cases reported during the last three years, demonstrating reliable results that correspond to the estimated cluster areas similar to the true disease incidence on the field. This work highlights a strong correlation between infrastructure projects (i.e. railways, roads, facilities) and rabies epizootics for several specific locations. This study is the first attempt to use geostatistics to build upon the understanding of animal rabies in Morocco and shed light on the most appropriate strategies to sustainably reduce and mitigate the risk of rabies. There has been little literature on the use of kriging methods in animal health research. Thus, this study also aimed to explore a novel method in the veterinary sciences to establish kriging as a valid and coherent analysis tool to identify the extent to which the geostatistic area can objectively support understanding on animal rabies and saw it as being highly instrumental in coping with gaps in the data.

1. Introduction

Rabies is a fatal viral infection that can infect all mammals, but domestic dogs cause over 99% of all human deaths from rabies [1]. Rabies has a worldwide distribution [2]. As per a World Health Organization (WHO) estimate, annually about 59,000 human rabies deaths occur globally and of these 31,000 are from Asia and 24,000 from Africa [3]. In the Middle East and North Africa (MENA) region, dogs are the main reservoir for rabies. In this region, rabies affects more domestic carnivores (50% of cases) than farm animals (40% of cases) [4]. Most industrialized countries have eliminated rabies from domestic dog populations. However, in the majority of developing countries, rabies remains endemic in domestic dog populations and poorly controlled [5]. Rabies is a notoriously underreported and neglected disease of

* Corresponding author.
E-mail address: mounir.khayli@gmail.com (M. Khayli).

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low-income countries [6]. Official reporting of incidence data on rabies and rabies exposures remains desperately poor in most canine rabies-endemic countries and Experts are increasingly recognizing that reporting grossly underestimates the true number of cases [7, 8] and it can be assumed that more unreported cases occur in Asia and Africa [2].Within the last decade in Morocco, we have noticed a downward trend in the reporting of cases of canine rabies. This trend might suggest there has been significant progress in combatting the disease through mass vaccination campaigns of domestic dogs at a national scale beginning in 2003. However, this is a somewhat speculative trend hypothetical trend and the estimates should be considered on the low side due to limited data, which underestimate the true burden of the disease.

An in-depth analysis of the data over this period shows that although the number of cases of canine rabies has drastically reduced, those cases related to farm animal contamination remains high. A comparison of the reported prevalence of rabies today with the decades prior suggests that rabies is similarly prevalent despite the implementation of two control programs in 1986 and 2003, which have not significantly improved in the epidemiological indicators of this disease. These two control programs required a large number of resources but led to questionable results. The gap in the epidemiological profile of this disease is one of the main reasons for the failure of this control strategy and is indicative of the range of missing canine rabies data required to conduct comprehensive studies or program evaluation (Figure 1).

The factors affecting rabies transmission and control in Morocco are not sufficiently understood to design the most appropriate control strategy, and, as a result, efforts and resources may be wasted [9]. Despite the importance of dogs as vectors for human rabies, little is known about the spatial dynamics of rabies in this major reservoir species, or the processes responsible for its maintenance in specific geographic localities. In turn, decision-makers do not have tangible elements to guide the control of the disease. According to Tao et al. [10], multidisciplinary studies are required to improve rabies surveillance to identify potential alternative sources of human infection.

The few studies that have been conducted to understand the determinants of rabies in Morocco have highlighted the importance of geographical range on the transmission of rabies. Studies carried out for better understanding this issue are admittedly sparse, but all support this observation. Analytical approaches using linear regression to describe patterns of rabies virus transmission according to environmental characteristics have been applied and show that statistical models have a high capacity for discrimination but can not be used for predictive purposes [11].

Kriging is a regression method that gives a least squares estimate of data [12]. A strength of this type of interpolation is that it not only generates an interpolated spatial model, but it also generates an estimate of the uncertainty of each point in that model.

The research question emerging from this regression method is: what is the contribution of interpolation methods for reducing uncertainty in terms of rabies knowledge, and how does this inform interventions oriented to control the disease?

This question was the starting point in this research study to investigate methods which could bridge the gap in missing data due to unreported cases and allow us to map the geographical distribution of the disease as closely as possible to the context in the field. Strong evidence on the geographic distribution of rabies will help in advocating for resources for rabies control and would be in line with the lessons learned from a risk-based approach and alternative cost-effective control possibilities.

The overall aim of this research study was to better understand the spatial heterogeneity of canine and animal rabies in Morocco and to learn to what extent operational epidemiology can inform an effective control strategy for the disease.

As a result, this paper proposes an alternative method, using the Kriging based method that can compensate for data gaps in the reporting process. The Kriging method fully uses the reported spatial information of the disease to compute inferred data and thus gives an estimate to the missed data.

2. Methodology

The research objective has been explored in a number of data analyses. In accordance with the research design, the methods below are organised in terms of coverage and in-depth analysis.

We first conducted a review of the spatial distribution of animal rabies in Morocco by comparing and contrasting the epidemiological surveillance data of rabies across a range of periods: [2000–2008] and [2009–2018]. We then applied a predictive model using interpolation

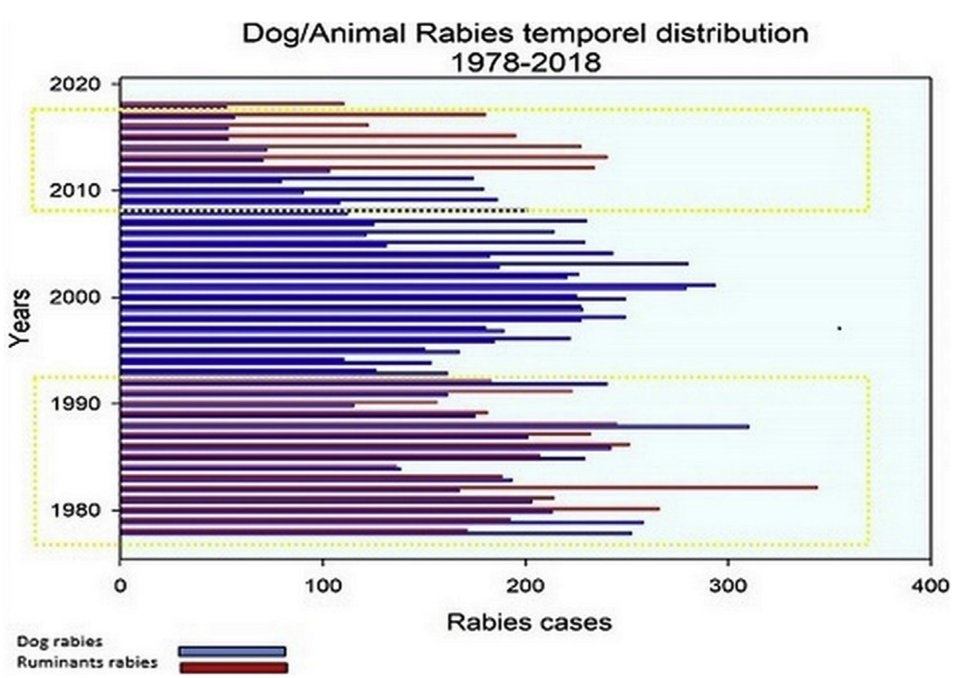


Figure 1. Annual distribution of rabies (Dogs and Ruminants)-Period 1978–2018 [20].

methods to explore rabies risk-based control approaches. Finally, we approached the geostatistical analysis in two stages: 1) characterizing the spatial variability of rabies through the semivariogram; and 2) optimizing interpolation of this variable using Kriging regression methods.

Kriging is a linear estimation method that guarantees minimal variance. The method performs spatial interpolation of a regionalized variable by calculating the mathematical expectation of a random variable, using the interpretation and modeling of the experimental variogram. Such a method seems to be the best non-biased linear estimator since it takes into account not only the distance between the data and the point of estimation, but also the distances between the two-by-two data.

Kriging is a robust method to estimate by interpolation. It is based on the assumption that the spatial field of the variable studied is an achievement of a random function. The point estimate is written as the weighted sum of the values at the experimental points [13].

This study focuses on an exact interpolator which is Ordinary Kriging. Exact interpolation is desired when the input values are free of error. The number of points used for interpolation depends on the data set and the user's decision [14]. Detailed information about the used kriging methods are given for example by Cressie [15], Chilès and Delfiner [16], and Christensen [17]. Ordinary Kriging is an exact interpolator [15]. Exact interpolation is desired when the input values are free of error. The number of points used for interpolation depends on the data set and the user's decision [14]. Irregularly distributed observations may lead to distorted results, for example due to unwanted screening [16, 18] or spatial biases. The discontinuity at distances near zero is caused, for example, by limitations of the sampling density [16].

Unlike inverse distance weighted interpolation (IWD), Kriging interpolation is based primarily on empirical observations, the observed sample data points, rather than on a pre-assumed model. The interpolation gives more weight to sample points nearby a location than those further, and, in order to reduce sampling bias, weighs clusters less heavily than single points. The value of each point is calculated in such a way as to minimize the expected error for that particular point.

The basic idea of kriging is to predict the value of the regionalized variable studied at an unsampled site s0 by a linear combination of adjacent point data by the relationship below. In the example of rabies cases, each data point is referenced by its spatial location Sα = (Xα, yα).

$$\hat{z}(s_0) = a + \sum_{i \in V(s_0)} \lambda_i \, z(s_i)$$

The weights λi associated with each of the regionalised values observed are chosen so as to obtain an unbiased forecast with minimum variance [38].

Namely:

$$\sum_{i \in V(s_0)} \lambda_i \ = 1$$

The basic kriging model has the same form as the classical or local regression model, but the errors are now assumed to be spatially dependent. It reads as follows:

$$Z(s) = \mu(s) + \delta(s), \quad s \in D$$

where:

- μ (.): the deterministic structure for the expectation of Z (.);
- δ (.): a stationary random function, of zero expectation and of known dependence structure.

In addition, the dependence structure of the random function δ (.) must be specified. If it is not known beforehand, which is typically the case in practice, it is determined based on a trend data analysis before variographic analysis [19].

Variographic analysis makes it possible to describe the spatial variability of regionalized phenomena. The main tool for this analysis is the semi-variogram which describes the evolution of the semi-variance as a function of the distance between the measurements and thus makes it possible to study the spatial link between the data.

The cross-validation step for kriging takes one of our input data and throws it out of the data set. Using all of the remaining points, it runs the prediction back to that location. As the true value is known, this process uses all the remaining to predict that value.

3. Data source and study locations

In order to study the epidemiological profile of canid and animal rabies in Morocco, it was necessary to develop a data collection that could cover a broad range of landscapes, dog habitats and human activities. Employing both descriptive and analytic methodologies enabled us to conduct an in-depth analysis of the disease profile.

This study used data collected from national information system (SIPS) covering a period from 2000 to 2018. A total of 3236 rabies cases were recorded during this period.

This review covered a wide range of data edited on an annually basis. The data used in this study were collected from the Epidemiology and Health Surveillance Department (SEVS) under the National Office of Food Safety (ONSSA) and also from the Epidemiology and diseases control Direction (DELM) belonging to the Moroccan Department of Health. Data collection was carried out over a long period from 2000 to 2018, thus benefiting from an epidemiological window of long chronology.

In this study, we opted to analyze the data over two distinct periods to study changes in the epidemiology of animal rabies in Morocco. The main objective was to reflect on meaningful methods to identify risky areas of the disease. The first period (2000–2008) corresponds to the execution of the second national plan for the control of dog rabies. The second period (2009–2018) coincides with the launch of major infrastructure projects in the country as well as with the new reorganization of veterinary services in Morocco (creation of the National Office of Food Safety).

4. Research results

4.1. Descriptive spatial analysis approach

Investigation of spatial distribution usually reveals that the majority of animal rabies cases do not seem to have any particular geographic patterns because the disease affects most of the provinces. On the other hand, rabies incidence at the provincial level has varied over the years. However, it should be noted that the geographic pattern of rabies has changed significantly over the past decade. Indeed, it can be noted that since 2010 the incidence of rabies in larger cities has dropped a lot, while at the same time the disease has started to be observed high incidences in rural areas. As for the whole period, the majority (81%) of the cases of animal rabies occurred in the rural environment compared to 19% of the cases occurring in urban settings, suggesting the disease was often closely associated with rural habitat (Figure 2).

4.2. Geostatistical methods approach

The geostatistical approach occurred in two phases:

- The first characterizes the structure of the spatial variability of canine and animal rabies through the semivariogram
- The second is the optimal interpolation of this variable thanks to Kriging.

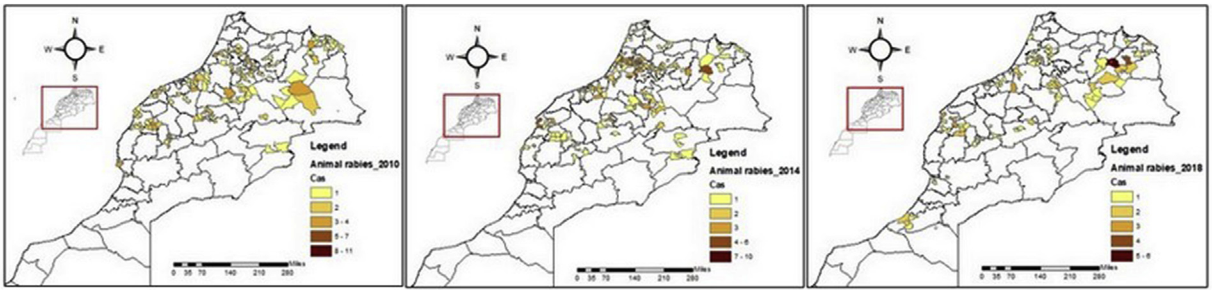


Figure 2. Rabies geographic distribution (period 2010-2014-2018).

The geostatistical wizard generates a semivariogram with blue crosses showing the average variation for each pair of points. The lag size is the size of a distance class into which pairs of locations are grouped. As a rule, we multiply the lag size by the number of lags for it to equal half of the largest distance among all points. As our points data are not clustered, we ran the “Average Nearest Neighbor” tool which tells the average distance between points. For our study area, we model data with a semi-variogram and the resulting outputs illustrated in Figures 3 and 4, it is a spherical semivariogram.

The shape of the variogram sample is presented according to the spatial scale. This variogram presents a minimum threshold of at least 05 cases, an almost nugget effect and the sharp increase at up to a range of 1.1°. This range corresponds to the maximum distance that allows measures to be taken into account. On the basis of these data it can be stated that rabies in the study area has no structure beyond 1.1°. On the other hand, the current data is not sufficient to represent rabies phenomena on a small scale, hence the presence of a nugget effect.

After fitting the semi-variogram, the wizard gives a preview surface with even more parameters to customize the output to map the model with Kriging weight. Using a weighted average with nearest neighbors, it predicts responses at each location. The results show speckled patterns in Figures 5 and 6 with the estimation of the interpolation errors represented in Figure 7. The spatial patterns do not only reflect on the existence of observations, but provide further guidance about areas with higher risk. The maps provide some comparison results and prove a general suitability of the ordinary kriging.

For cross validation, the model iterates through all of the input points until it was complete. Then, it creates this summary table of residuals comparing actual versus model's predicted values (Table 1). This table shows how robust our model is and how well does it fit the data. To put this in perspective, we checked the root-mean-square standardized, as it should be close to 1. In addition, root mean square error shown to be as small as possible. The accuracy of the results is assessed by the root-mean-square error (RMSE) over all points. Table 1 illustrates a nearly linear relationship between them, which confirms the visual assessment by the semi-variogram model in Figure 3.

To illustrate to what extent the spatial autocorrelation phenomenon could take in the analysis of both animal rabies and human activities data, an aggregation of affected municipalities has been analysed. The measures estimated for each distance have been projected into risk maps. Epidemiological data included the location and status of animals belonging to municipalities spread across the national territory but for some graphic reasons, authors have opted for a mapping on areas that appear as hot spots. Also, in order to give accurate analysis, we incorporate georeferenced dog and human rabies cases recorded during the last three years within the defined cluster areas (Figures 8 and 9).

To quantify the exposure of dogs to the rabies virus in relation to some identified risk factors in this study, a case-control approach seemed more feasible. For this purpose, authors included non-randomized comparison groups and the data used correspond to a period of two years (2017–2018). Data reported in 2019 have been excluded because there is less control group records to respond to the basic ratio of one case to one control individual.

The definition used for the case (rabid dog) was mainly based on laboratory (biological tests) and/or clinical criteria. Only dogs diagnosed as rabid during the period (2017 and 2018) were included as cases. The constitution of the control group is a key element of this investigation because of selection bias. The definition of controls was also based on biological criteria revealed by the laboratory or clinics. Thus, our control group is formed from dogs whose laboratory results or from a veterinary observation reveal a negative result. The control group was matched with

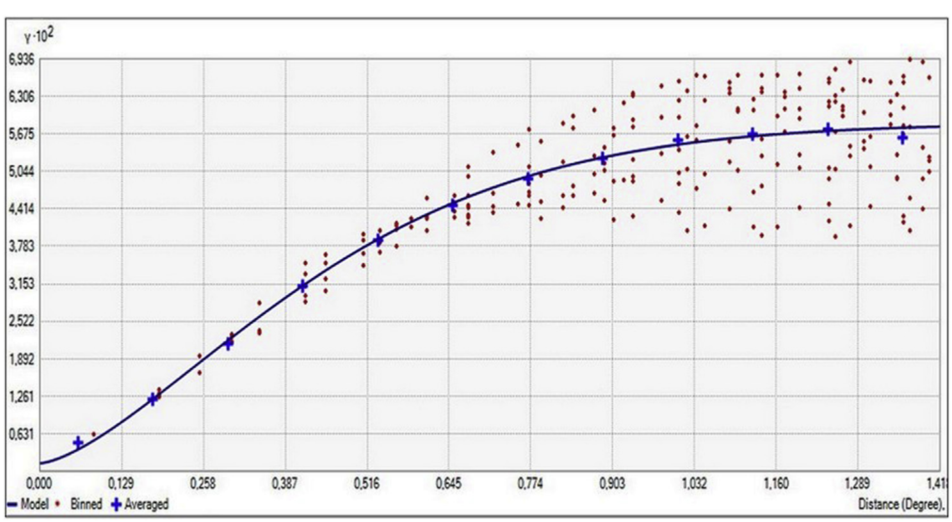


Figure 3. Average semivariogram of animal rabies cases.

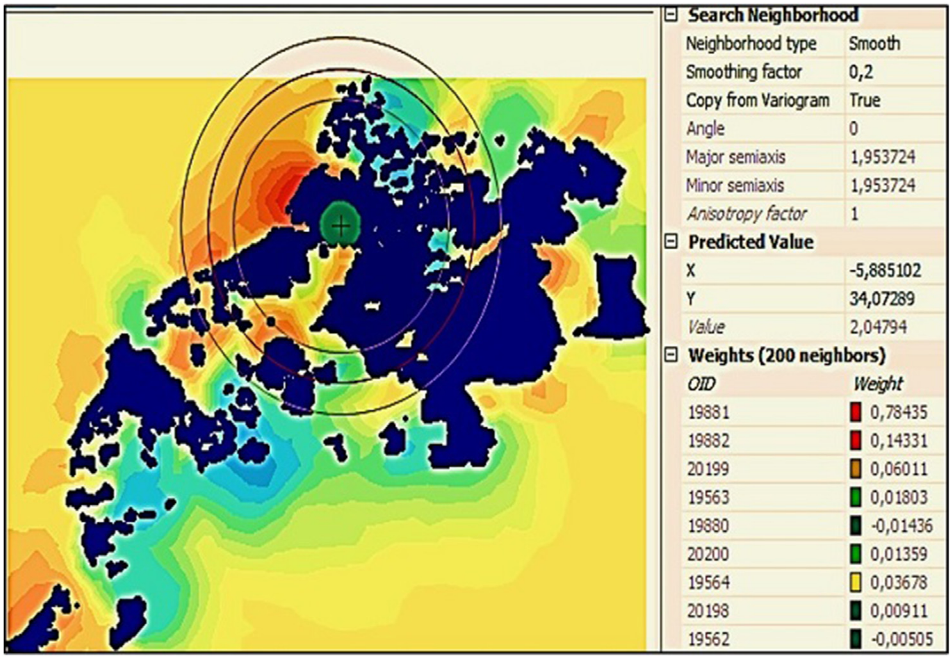


Figure 4. Average Nearest Neighborhood search.

cases group on criterias as the geographic unit (same commune), the age group and the time unit (same season).

The risk was estimated by the paired odds ratio (OR) and proportions were compared using the Chi^2 test or Mantel-Haenszel test.

5. Interpretation

Based on the spatial distribution of rabies it appears that the disease is endemic in Morocco, with all provinces except for the southern region being affected. The distribution of rabies in Morocco is geographically variable.

From descriptive analysis of the data, it is clear that the number of reported canine rabies cases greatly underestimates the true prevalence of the disease which, accordingly, affects the coherence of its spatial distribution. The insights on objective assessment of estimation of disease burden are lacking.

Campaign suggests the identification of geographic patterns. Its complexity arises from the need to identify in which given locations rabies occurs systematically more than in others. This highlights the need to go through in-depth studies to identify eligible areas for effective control actions, instead of descriptive epidemiological studies with only some cross-understanding of the true context of the disease.

At this level, any meaning attributed to “risk zone” is to be left open because it is dependant to quality and completion of data gathered. It is not resolvable on a singular scale and will necessitate other analysis options as the Kriging to shape the whole spatial spectrum of the disease.

To this end, it should be noted that the kriging method was not explicitly designated for animal health in the literature consulted during this study. It is exclusively applied here to spatialize discrimination of animal rabies cases. Therefore, it leads to better results than the normal geographic distribution of cases and it seek to link these new understandings to specific operational interests. The importance of finding suitable maps for disease surveillance and control is well demonstrated

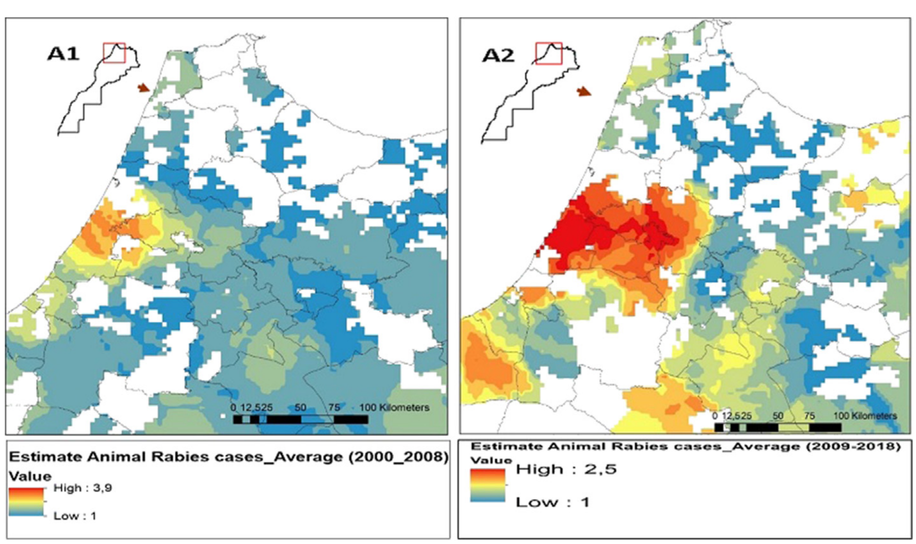


Figure 5. Maps of the annual average of animal rabies for two periods: A1 (2000–2008) and A2 (2009–2018).

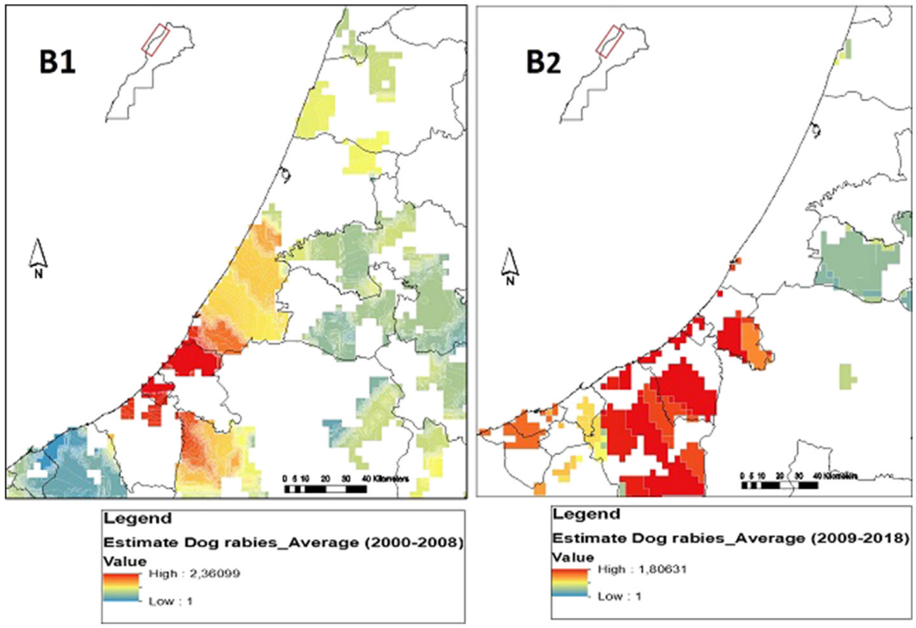


Figure 6. Maps of the annual average of canine rabies for two periods: B1 (2000–2008) and B2 (2009–2018).

here. As the difference between the apparent geographic distribution of the disease and interpolation distribution estimates is self-evident and reflect the true gaps, this model assumes there are unreported cases and thus allows for implementation of an effective control strategy.

The data analysis of two periods spanning over 18 years makes it possible to establish risk maps with a more precise reading of the spatial distribution of the disease, including the identification of the geographic clusters of rabies and an understanding of the evolution of the disease in these areas.

The changes observed from these maps highlight and confirm that cases of dog rabies have been underreported. The geographic distribution of animal rabies contamination between the two periods contrasts with dog rabies statistics and demonstrates an upward trend in reported animal rabies cases. When we know that dogs are the main reservoir and vector of rabies in Morocco, it is obvious to conclude on the underreporting.

As seen previously, rabies is confined to rural areas. The analysis of dog rabies data over the two periods has shown that interesting changes start to occur from this initial habitat towards the cities due to the pressure of urbanization and human activities.

From the above, the resulting clusters of rabies are approved by cross validation which gives predicted cases close to actual values. Also, in order to conduct an accurate analysis, we integrate georeferenced rabies cases in dog and human recorded during the last three years (2017–2019) to the defined cluster area. The analysis clearly revealed the influence of the construction sites on dog's ability to be infected by the rabies virus. The study was complemented by a qualitative study.

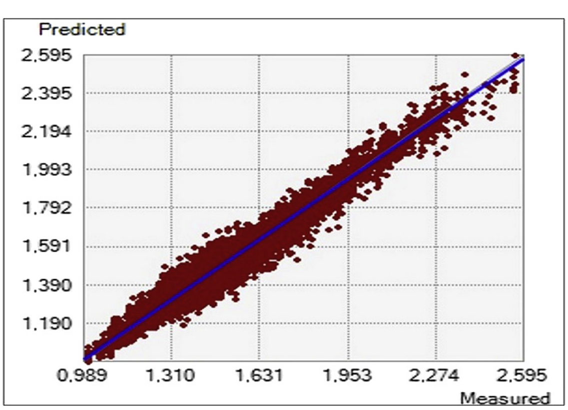


Figure 7. Cross-validation of the model.

To statistically and robustly assess the role of infrastructure development, we used a case-control study for the two years (2017 and 2018), and found a strong association between the infrastructure development, including railways, highways, etc., and dog rabies (OR = 6.74 [2.09–22.34], p-value <0.00017). The results obtained are reliable, support the above findings and suggest that the spatial patterns identified through geostatistical analysis reflect close similarities to field context and would contribute to built understanding for an oriented control approach, its provision and its uptake.

6. Discussion

Without reliable data on rabies it is difficult to assess the full impact of the virus on human and animal health, leading experts to substantially underestimate the scale of the problem [21, 22, 23]. Some reassessments are therefore encouraged.

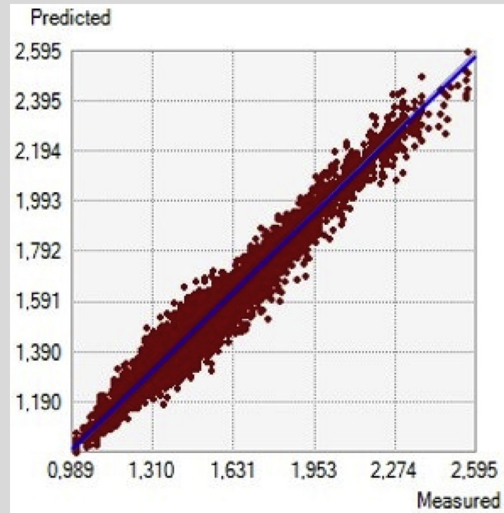
Incomplete reporting prohibits experts from understanding key insights on the coherence of the spatial distribution of the disease and, consequently, from defining appropriate control configurations.

Data collection and analysis are necessary in order to learn lessons from the past and to propose future actions to be included in new control strategies [24]. In a previous study on animal rabies in Morocco, the dog's habitat and anthropogenic data were included as explanatory variables. The study found that suburban and rural habitats, public health management infrastructure (pounds, landfills, slaughterhouses, livestock markets), and road accessibility are determinant factors of rabies in Morocco [25]. This finding is supportive to the results of this study demonstrating the impact that human activities would have on the distribution of rabies in Morocco.

Geostatistical predecting models for rabies are very recent and to-date, none have been found in the scientific literature. This study provides the first example of an applied interpolation methods to map the spatial risk distribution of canine and animal rabies in Morocco. The use of spatial autocorrelation reflects the tendency that geographically close locations have similar characteristics [26]. For this purpose,

Table 1. Comparison between measured and predicted values and standard errors.

Source ID	Induded	Measured	Predicted	Standard Error	Standardized Error
179	Yes	1.3607	1.364	0.05520908	0.06967301656
496	Yes	1.3608	1.365	0.04252427	0.11631296008
497	Yes	1.3607	1.355	0.04421446	-0.1221826403
813	Yes	1.3608	1.368	0.04496568	0.15965068402
814	Yes	1.3607	1.361	0.03925363	0.01276097612
1125	Yes	1.3336	1.425	0.05589804	1.64804186099
1131	Yes	1.3608	1.370	0.04137051	0.2244464138
1132	Yes	1.3607	1.360	0.04068797	0.00469264573
1436	Yes	1.5427	1.541	0.05382055	-0.0225160258
1437	Yes	1.5426	1.536	0.04385763	-0.13533438705
1438	Yes	1.5424	1.538	0.04320404	-0.0944496365
1439	Yes	1.5420	1.515	0.05231231	-0.50921110788
1442	Yes	1.4169	1.410	0.04647096	-0.1393425104
1443	Yes	1.4167	1.389	0.03982229	-0.6826886831
1444	Yes	1.4166	1.395	0.04650635	-0.4586765049
1449	Yes	1.3608	1.376	0.04188457	0.38077088524
1450	Yes	1.3606	1.300	0.03614579	-1.6737377418
1754	Yes	1.5427	1.551	0.05489480	0.15551018437
1756	Yes	1.5423	1.537	0.05297678	-0.0870731915
1760	Yes	1.4168	1.474	0.04470759	1.27833884698
1761	Yes	1.4167	1.430	0.04134219	0.34326615732
1762	Yes	1.4165	1.407	0.04685942	-0.1987558006
1767	Yes	1.3607	1.270	0.03718060	-2.4287031650
1768	Yes	1.1941	1.328	0.04467683	2.99926156158



Prediction Errors	
Samples	15681 of 15681
Mean	0.0002182868
Root-Mean-Square	0.03935841
Mean Standardized	0.004012242
Root-Mean-Square Stantardized	0.9476973
Average Standard errors	0.04308677

multidimensional analysis methods are a powerful tool for highlighting geographic clusters of the disease and then specific features of rabies contribute to the problem of underreporting [6]. Based on the data collected from 2000 to 2018 from the sanitary national records, the authors present a synthesis of territorial patterns of rabies.

The graphic representation of the processed data obtained is a series of risk maps. The semivariogram shows that the correlation between cases of animal rabies is only effective if cases are in close proximity to each other, hence the advantage of having georeferenced records of each notified case for better spatial analysis of the data. As a result, the predicted or simulated values would have the same statistical characteristics as the reported epidemiological data.

Through those predicted models, the different geographic pattern of dog and animal rabies identified shows the importance that some specific locations play in the magnitude and severity of the disease. This suggests that an oriented control on these areas would prevent rabies epizootics to spread at a large scale.

A recent study has shown that the suburb landscape is also starting to play a role in “recruiting” dog rabies cases, most likely because of the changes that begin to take place on the outskirts of cities [25]. The Suburb landscape becomes more « ruralized » due to cities's attractiveness (industrialization and rural exodus). Rabies is a prime example of an infectious disease in which dispersal can be exacerbated by animal movement mediated by humans. This is illustrated by raccoon rabies in Virginia, USA [27], dog rabies in Indonesia in Flores Island [28] and in parts of Europe [29].

Toward the objective of understanding the role of humans in the dispersal of canine rabies in Morocco, this study allows us to assess the health impact of human activities in terms of rabies occurrence in areas that were not previously a stronghold of the disease. It seems obvious that human activities (e.g infrastructure projects) can take over in terms of being a source of recruitment for dog rabies cases in outlying district of cities or urban agglomerations. The disease could also spread then along the project sites to reach once again the rural landscape, perpetuating a vicious cycle of the disease.

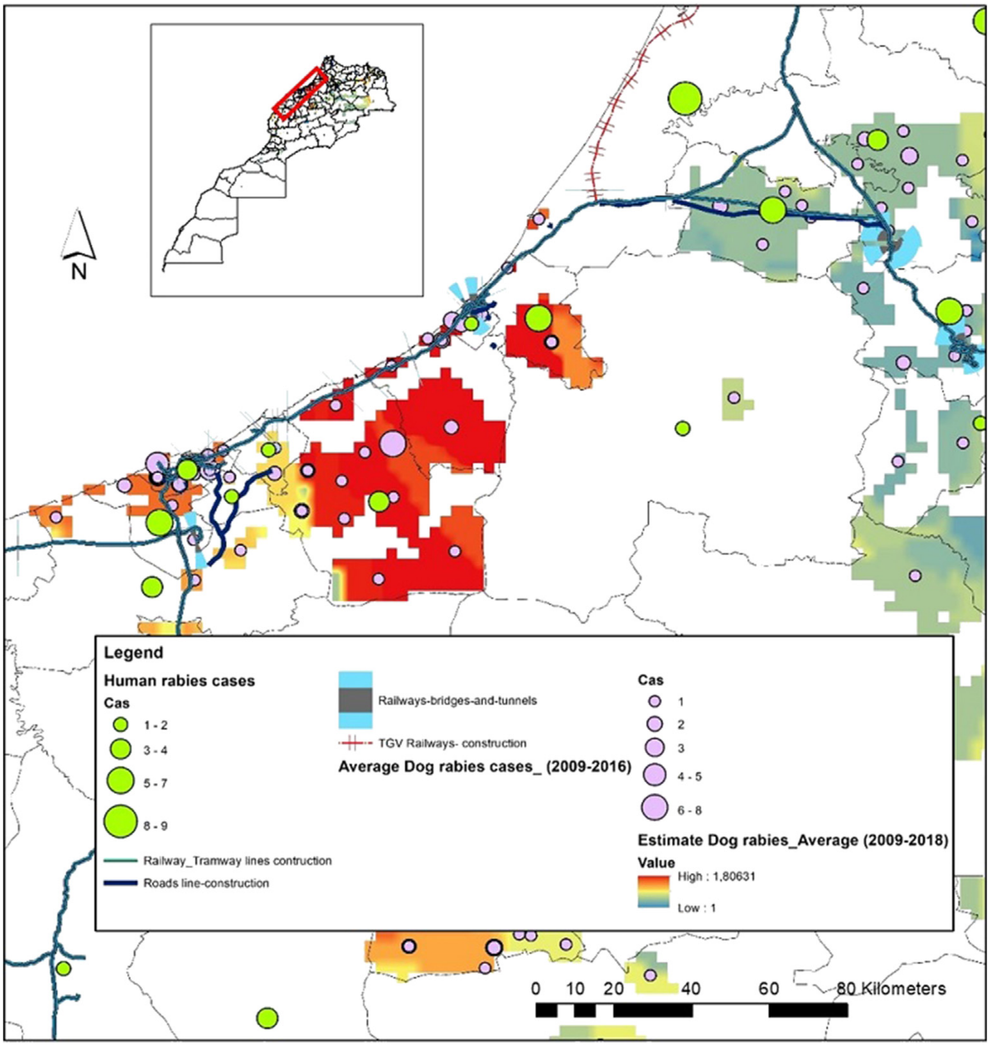


Figure 8. Correlation between dog rabies cases and estimate canine rabies distribution (2009–2018).

Another interesting finding of this study is the new urban and suburb rabies forms in Morocco; the study identified new habitats of dog rabies due to the extension of urbanization or the outright ruralization of the urban habitat following exodus of people. The comparison of the geographic patterns of the disease over the two periods showed a clear discrimination of the cases with an apparent recrudescence of the cases over the period 2009–2018 which coincides with the decade of major infrastructure projects in Morocco (Railways, motorways, urban real estate compounds and dams, etc.).

Those sites have greatly required guard jobs, which expressly require a dog's presence. Interestingly, the study found case clusters along the railways (e.g. LGV high speed train and highway roads projects) which were sites of construction projects for at least 8 years.

The presence of dog rabies clusters in municipalities hosting large infrastructure projects could provide an explanatory hypothesis on the factors determining the endemicity of the disease in these areas.

These results are also strongly supportive of human-mediated dispersal, and demonstrate how geostatistical methods will turn epidemiological data into a powerful asset for predicting, and potentially controlling, the spatial spread of pathogens. Talbi et al [30] suggest that the human-mediated dispersal of infected dogs is likely to continue to play a major role in the transmission of rabies in geographical areas where it has been present for many years. Authors used newly developed Bayesian phylogeographic methods to unravel the dynamics and determinants of the spread of dog rabies virus in North Africa. Road distances proved to be better predictors of the movement of dog rabies than accessibility or raw geographical distance, with occasional long distance and rapid spread. Such results support our findings regarding factors that may explain the spread of rabies.

This study thus contributed to a better understanding of the spatial distribution of two types of rabies in Morocco (dog and farms animal), with their associated socio-economic landscapes. It also highlighted the limits of an analysis approach based on incomplete data. The use of geostatistical analyses methods as Kriging is better adapted to enabling a vast array of data analyses and to compensate the gaps while recording data is often lacking.

Success in tackling the disease is contingent on investment in dog rabies control, which we show has been severely lacking. However, innovative financing models are required to overcome institutional barriers [6]. Long-term mass dog vaccination efforts could reduce medical sector and societal costs, and elimination is feasible with currently available control methods [31, 32].

Owing to limited resources and poor coordination between the different stakeholders, rabies control strategies are only partially implemented [4]. The risk maps obtained by this research would make it possible to better target the surveillance and control zones. Urgent strategies need to be implemented because rabies elimination is an achievable goal in Morocco [24].

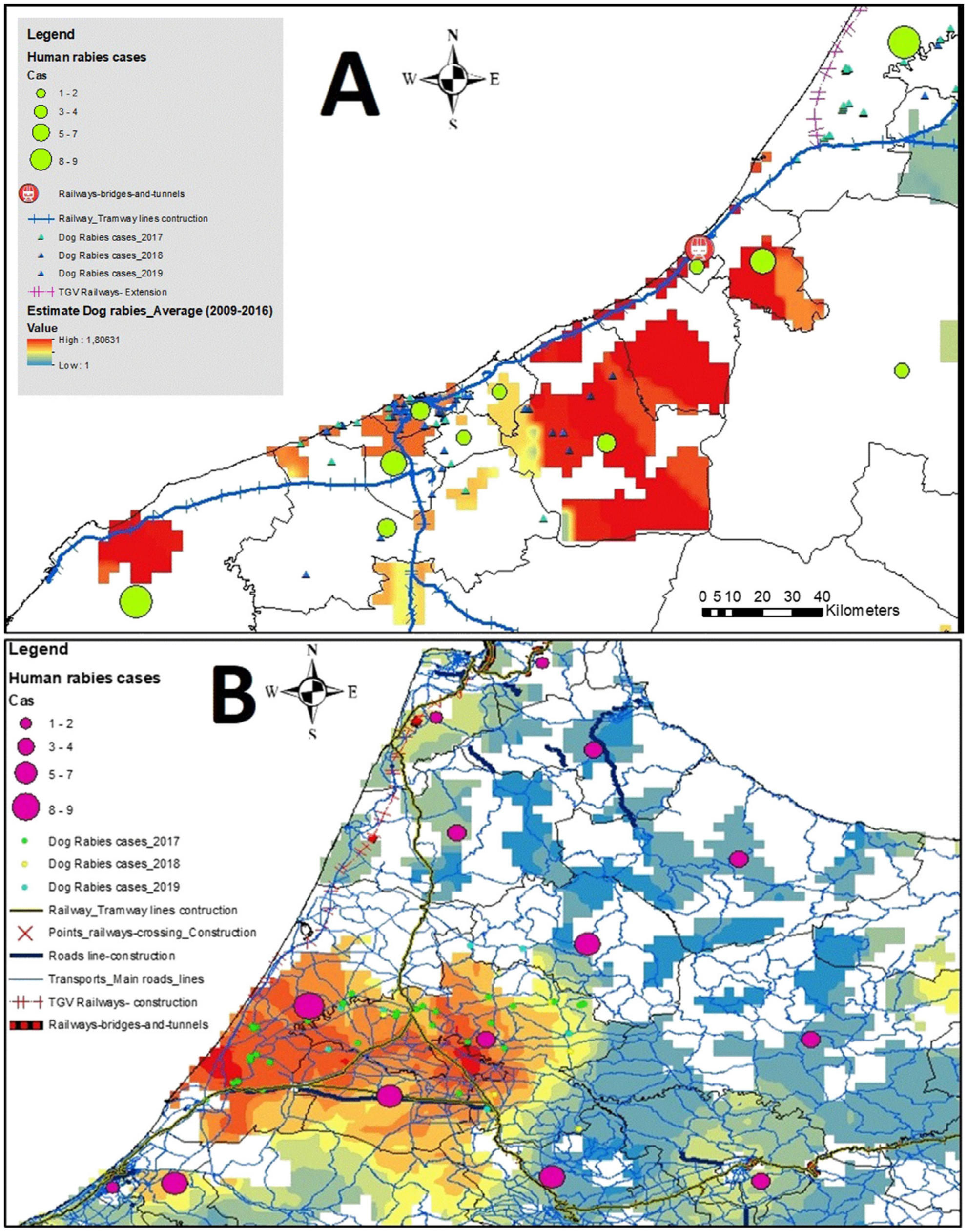


Figure 9. Georeferenced dog rabies cases correlation with estimates canine rabies (A) and estimates animal rabies (B).

7. Conclusion

Despite the importance and challenges of animal rabies, our current knowledge is insufficient to fully understand and predict the dynamics of its transmission. The analysis of animal rabies data in Morocco shows that its incidence neither proportionately distributed nor clearly complete. Therefore, suitable interpolation methods are strongly recommended to address distorted geographic patterns. The development of new decision support tools is essential to streamline disease prevention and to better target surveillance.

Starting to build reliable spatial screening of the disease, mainly in areas where data are severely missing or case reporting can not be immediately improved, would reduce uncertainty, enhance accuracy of the analysis and, eventually, lead to the implementation of risk-based control approach.

The aim of the study was to apply predictive geostatistical tools considering the potential of reflective practice in dog's control and its impact on exploring new rabies control approaches. The geostatistical method (Kriging) is valued and is seen as interesting spatial tool analysis when it addresses the needs of identifying rabies clusters in the country. The resulting geostatistical analysis models contribute above all to a better understanding of the landscape determinants of the disease (rural, urban or suburb).

The findings highlight a new variable which appears to be decisive for rabies control: the role of construction sites and infrastructure projects. Calling upon veterinary services for the vaccination of dogs alongside site employees and guard dogs before breaking ground on new construction sites may be an effective strategy in breaking the transmission cycle and preventing further spread of rabies once construction activities cease at a given site.

Based on this study, further research that heavily relies on other interpolation methods could expand the application of these results. Additionally, the inclusion of further content and data sets related to rabies risk determinants are worth considering to provide meaningful guidance. It is therefore imperative that we explore and focus upon the development of content knowledge about interpolation methods in animal health to shape alternative options for epidemiological analysis. These findings should be used to determine public health priorities and address the needs of decision-making tools where data are incomplete.

Declarations

Author contribution statement

Mounir Khayli: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Youssef Lhor, Mohammed Bengoumi, Khalil Zro, Mehdi El Harrak, Abdenacer Bakkouri, Mohammed Akrim, Reda Yaagoubi, Ikhlass El Berbri: Contributed reagents, materials, analysis tools or data.

Faouzi Kichou, Jaouad Berrada, Mohammed Bouslikhane: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

The authors do not have permission to share data.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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