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Modeling and Spatial Distribution of Peste des Petits Ruminants in South Kivu, Democratic Republic of Congo

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Abstract

Small ruminant farming, despite its nutritional and economic benefits, faces significant challenges, particularly regarding animal health. Peste des Petits Ruminants (PPR), a viral disease caused by a Morbillivirus, frequently infects herds, highlighting the need for a better understanding of its spatial distribution, risk areas, and control strategies. A study was conducted on 210 farms in three agro-ecological zones of South Kivu province (Mwenga, Uvira, and Kalehe), with 70 farms surveyed per site. Data collected focused on production systems and disease-related information. Data from the field were processed using Microsoft Excel and analyzed with XLSTAT software. The Pearson chi-square test was employed to determine the association of potential factors with PPR seropositivity, while univariate and multivariate logistic regression analyses were used to explore the relationship between PPR seroprevalence and risk factors at two sites (Mwenga and Kalehe). The Uvira site lacked sufficient serological data. Using the Maxent model, the study predicted the potential distribution of PPR based on environmental data and identified two types of niches: the fundamental niche, where species can theoretically exist, and the realized niche, which reflects real-world conditions influenced by environmental interactions. Key results revealed that farm characteristics such as water source, watering method, rearing system, species type, sex, age, and cleaning frequency significantly influenced PPR seroprevalence. Risk factors for infection included animal sex (OR = 91.73; CI = 21.15 - 39.60). This very high odds ratio reflects the fact that females have a longer life cycle than males, agro-ecological zone (OR = 8.28; CI = 4.75 - 14.42), and farming system (OR = 0.42; CI = 0.19 - 0.905). The highest prevalence (31.11%) was found in the high-altitude agro-ecological zone, and animals in the agropastoral system were most susceptible to infection (31.85%). Mapping of the study sites revealed three types of grazing lands based on infection risk. Uvira and Kalehe territories had more high-risk pastures than Mwenga. The study concluded that the MaxEnt model, incorporating Euclidean space and livestock farming systems as factors, is useful for controlling PPR in South Kivu and regions with similar farming and pasture conditions.

Keywords

Pasture Mapping, Risk Factors, Epidemiology, Modelling, Peste des Petits Ruminants, South Kivu

1. Introduction

Peste des Petits Ruminants (PPR) is a highly contagious viral disease, caused by morbillivirus (PPRV), which mainly affects goats and sheep [1] [2]. In the Democratic Republic of Congo (DRC), small ruminant farming plays an essential role in the economy of smallholder farmers, providing income via the sale of products such as meat, milk, and hides [3]-[5]. However, this livestock farming faces major challenges, including inadequate infrastructure, poor nutritional intake, limited veterinary care, and lack of hygiene [3] [6]. These conditions leave animals highly exposed to disease, particularly PPR, the repercussions of which can be devastating for livestock farmers.

In the DRC, and particularly in South Kivu province, PPR poses a serious threat to small ruminants. Since it was first officially declared in 2012, PPR has caused the deaths of more than 300,000 goats, leaving nearly a million more at risk [7]. In 2018, more than 30,000 goats died following new outbreaks in South Kivu [8]. This has a direct economic impact on small farmers, disrupting local and international markets [9] [10]. Despite calls for urgent vaccination campaigns, PPR control efforts remain sporadic and ineffective [8] [11]. Porous borders and the uncontrolled movement of livestock also favor the spread of the disease.

PPR is caused by a morbillivirus that enters through the respiratory tract and affects the respiratory and gastrointestinal systems, leading to severe immunosuppression that predisposes animals to secondary infections [1]. Clinical signs include fever, nasal and ocular discharge, oral ulcers, coughing, diarrhea, and severe dehydration, often resulting in the death of animals, particularly those never exposed to the disease [12]. Transmission occurs mainly through direct contact with infected animals via body secretions (saliva, urine, etc.), or indirectly via contaminated water and feed. Animal mobility and the absence of biosecurity measures accelerate the spread of infection in affected areas [7].

The need for this research is accentuated by the major economic and health impact of PPR on small ruminant livestock farming in South Kivu. By providing crucial information on the prevalence, risk factors, and spatial distribution of PPR, this study will help develop targeted management strategies to better control and, potentially, eradicate the disease. The proposed epidemiological framework will also optimize the use of the limited resources available to combat this threat, with positive implications for food security and the livelihoods of small-scale farmers in the region.

2. Materials and Methods

2.1. Data Collection

The data on the seroprevalence of PPR were generated by [13] after laboratory analysis and confirmation of positive cases. Briefly, serum samples were used to assess the existence of anti-PPRV nucleoprotein (N) antibodies with a competitive enzyme-linked immunosorbent assay (cELISA) using the Innovative Diagnostics kit (ID vet, France) from France (ID Screen® PPR competition, https://www.innovative-diagnostics.com/) following the manufacturer's instructions. Stratified random sampling was applied in the high, medium, and low altitude territories of Kalehe, Mwenga, and Uvira, respectively. Farms were divided into different strata according to the agro-ecological zones of these territories, notably the Ruzizi plain and the high plateaus, to capture the variability of breeding practices and environmental factors. Within each stratum, a list of farms was drawn up based on local records and information collected in the field. A random draw was then made to select 70 farms per territory, for a total of 210 farms studied in the seroprevalence analysis. The questionnaire included both closed- and open-ended questions on husbandry practices, animal characteristics, water and feed sources, disease history, and vaccination. Geographical coordinates were collected by GPS, as well as information on distances between farm and bush, farm and water point, animals using these points and their origins, distances between farm and neighboring farm, origin of animals, and disease control techniques applied at the farm level.

The questionnaire was administered in a structured manner during field visits. A total of 210 questionnaires were completed, one for each farm. Results relating to the prevalence of PPR in the target environments were generated in the study conducted by [13].

A total of 319 serum, tracheal, and cloacal swab samples were collected from animals on the selected farms. Animals that had never been vaccinated against PPR were randomly selected for sampling. Samples were sent to the BecA ILRI laboratory for diagnostic testing using c-ELISA to detect the presence of anti-PPRV antibodies.

In order to correlate the seroprevalence results with associated risk factors, this study involved a survey through which a questionnaire was submitted to 210 small ruminant farms selected at random from 5 May to 19 July 2021, with 70 farms per territory in the Babulinzi, Bulinzi, and Wamuzimu groupings (in Mwenga territory), in the groupings of North Mbinga and South Mbinga (Kalehe territory), and in the groupings of Kiliba, Runingu, Sange, Luberizi, and Itara (Uvira territory) to collect information on clinical profiles of small ruminants and potential risk factors for PPR.

They were later encoded in Excel (version 14) and saved in CSV (Comma Separated Values) format to be imported into ArcGIS software version 10.8.1. The shapefile of South Kivu province from the MONUSCO DR Congo database was used to locate the different pastures visited according to the degree of exposure to the disease.

2.2. Data Treatment

The collected data coordinates were used to illustrate on a map the network of contacts between herds in the area. This network was one of the tools used to obtain a precise idea of the intensity of the health risk presented by each pasture. Specifically, the health risk of a pasture was calculated by combining information on the itinerary of each herd and the prevalence of PPR in the farms on the pasture, such as the distances between the farm and the pasture, the farm and the water point, the animals using these points and their origins, the distance between the farm and the neighboring farm, the origin of the animals, the disease control techniques applied, the seasonality, and the carrying capacity. As for the spatial distribution of the disease, this was done using GIS software (ArcGIS version 10.8.1). Physiographic information, distance to farms, water sources, and pastures were used for spatial modelling. Maps depicting the distribution pattern of the disease were produced and interpreted.

The influence of season on disease prevalence provided information on the temporal aspect of the dynamics of PPR transmission in different farms in the territories of Kalehe, Mwenga, and Uvira.

During the survey in the territories, the different geographical points (latitudes, longitudes, and altitudes) were taken and associated with the seroprevalence of each environment studied.

The meteorological data included in the analysis were rainfall (R), relative humidity (H), mean wind speed (W), monthly maximum temperature (T1), monthly minimum temperature (T2), monthly temperature range (T3), and monthly mean temperature (T) [14]. These data were collected from the WorldClim database (http://www.worldclim.org).

Eight potential risk factors were considered in this study. These included 1) age (proportion of animals in the flock aged less than 4 months, 4 - 8 months, 8 - 12 months, or more than 12 months), 2) species type (proportion of goats and sheep in the flock), 3) sex (proportion of males and females in the flock), 4) water source in the pasture, 5) breeding system, 6) breed type, 7) feeding method, and 8) territory. The corresponding data were collected from the local agricultural statistical yearbook and linked to the information revealed by the survey.

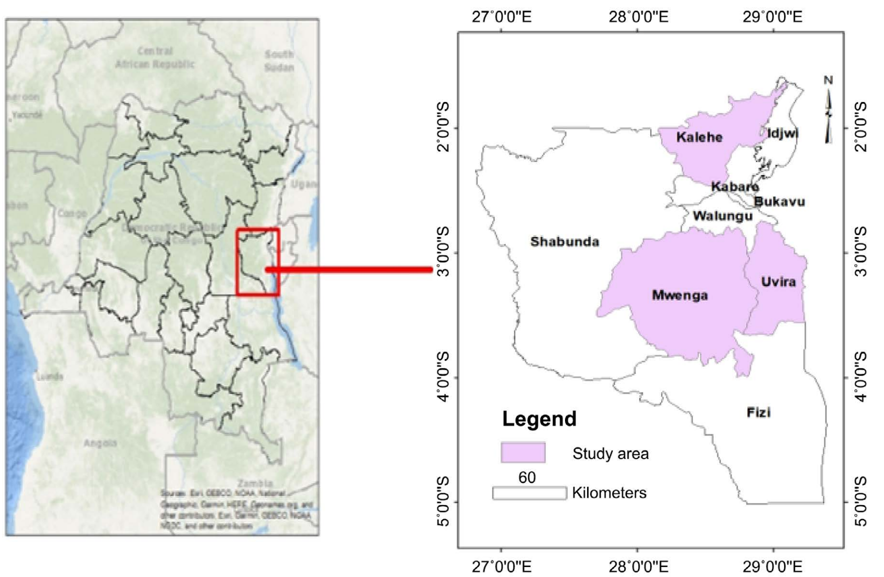

Figure 1. Study areas in South Kivu.

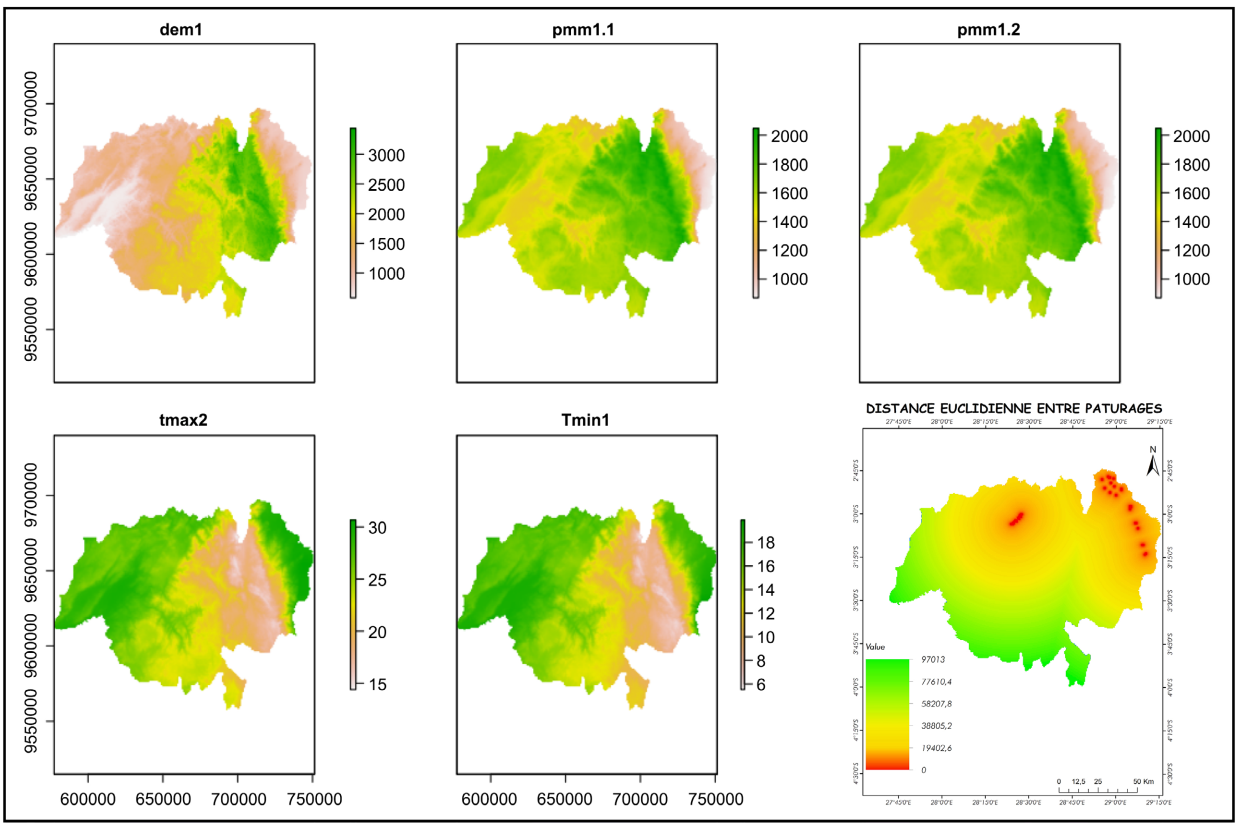

Figure 2. Bioclimatic variables included in the model.

In order to eliminate the influence of multicollinearity on the modelling process and to select the best-fitting variables with high degrees of contribution to the model, a Pearson correlation analysis of 16 environmental, topographical, and risk factor variables was performed using XLSTAT software version 2017.1. Highly correlated variables with Pearson correlation coefficients (g) above 0.8 were removed to improve the accuracy of the model simulation [15].

For a good determination of the main environmental and epidemiological risk factors of PPR disease, a binary logistic regression model was used. According to [16], logistic regression is a model to express the relationship between a qualitative variable Y and variables Xi, which can be quantitative or qualitative. The general writing of the method is as follows:

$$LogitP = \alpha + \sum_{i=1}^{p} \beta iXi$$

α : is the estimate of the change in the dependent variable.

βi : is the estimate of the variation of the dependent variable with respect to the variable Xi.

$LogitP$: is the probability of Y occurring as a function of the values of Xi. Logistic variable and multivariate regression analyses were used to establish the level of association between PPR seroprevalence and risk factors in the study sites (Mwenga and Kalehe) due to the non-existence of serological data in Uvira territory. The characteristics of the farms and pastures in this area gave the status of the disease prevalence through the risk factors considered. Factors with a p-value ≤ 0.25 in the univariate and multivariate regression analysis, comparable frequencies, and potential risk factors were selected. The univariate regression analysis, comparable frequencies, and non-collinear frequencies were passed on for multivariate logistic regression analysis. Associations were considered significant at p-value ≤ 0.05. In addition, a confidence interval at the 95% threshold was used for prevalence.

Description of the Maxent model

The data collected during this study were analysed using the maximum entropy model (Maxent). This model provides information on the potential distribution of a biological species, taking into account environmental factors. The distribution niche is therefore the basis of the model. An ecological niche is the environmental space occupied by a species under natural conditions [17]. But [18] makes a distinction between a fundamental niche and an effective niche. A fundamental niche is the range of environmental conditions in which a species can theoretically exist, while an effective niche is defined by the combination of negative interactions that restrict the presence of a species and positive interactions that can extend the environmental range in which a species is able to thrive. Unfortunately, the data collected do not always cover the entire natural range of a species. The Maxent model is therefore a species distribution modelling programme that approximates the potential distribution of a species [19]. It is a practical tool for identifying the areas in which a species is likely to be found. The aim of Maxent is to make predictions from incomplete information on a statistical basis [18] [20]. It is a new model that offers many advantages and few constraints [19] compared with those that already exist. This study required climate data imported from the http://www.worldclim.org/bioclimlink. These are environmental variables that can have an influence on the distribution of species. For each farm and pasture whose distribution was analyzed using Maxent, we compared the geographical harvest data with the various bioclimatic variables for the DRC. One of the parameters used to assess the predictive capacity of a model generated by Maxent is the AUC (Area Under Curve), which is the area under the ROC (Receiver Operating Characteristic) curve [21]. The AUC can then be interpreted as the probability that a randomly selected point of presence is located in a raster cell with a higher probability of occurrence of the species than a randomly generated point [19]. To finalize the maps generated from the maximum entropy model, we used the extension files (.asc) that present maps in pixels to produce maps in isoeets to indicate areas with high disease prevalence or risk with mapping software (ArcGIS).

3. Results and Discussion

3.1. Risk Factors Associated with Peste des Petits Ruminants Disease

Table 1 shows that the sex of the animal, the rearing system, the feeding method, the breed, the presence of a water source in the pasture, as well as the territory, would have an effect on the probability of infection (p-value < 0.05) and would significantly influence the presence of Peste des Petits Ruminants. This higher susceptibility in young animals is consistent with findings from other studies, which suggest that the immature immune system of younger animals makes them more prone to infections [22].

In addition, gender was a risk factor (OR = 91.73; CI = 21.15 - 39.6), and females were more exposed to infection (89.7%) than males (10.2%). Similarly, territory had an influence on the distribution of infection (OR = 8.29; CI = 4.76 - 14.43), and the highest prevalence was observed in Mwenga (31.11%) and the lowest in Kalehe (10.37%). In addition, the farming system was a risk factor (OR = 0.42; CI = 0.19 - 0.90), and animals raised in agropastoral systems were more exposed to infection (31.85%) than those raised in a pastoral system (9.63%). The infection rate also varied with the feeding mode (CI = 0.37 - 18.13), where animals on pasture would be more susceptible to infection; the same is true for breed (OR = 25.74) and the presence of a water source in the pasture. This is likely due to increased exposure to contaminated environments, including pastures shared with other infected herds [23]. Likewise, breed also influences the seroprevalence (p-value = 0.03 and OR = 1.30), where sheep are more infected (22.96%) than goats (18.52%).

Risk factors strongly associated with PPR infection were animal sex and environment. The results found by [24] conducted in Bangladesh are contrary to those of this study; however, they are similar to those found by [25] conducted recently in DRC, where high prevalence was observed in Mwenga. They further reported that females are susceptible to the disease. Our findings are also in agreement with [26], for whom females were more affected than males. This would be due to the fact that females have a longer life cycle than males as a result of their retention in the farm for breeding reasons, and thus they are exposed to several diseases due to production and breeding stresses [27]. In extenso, the time of risk for infection for females is much longer, resulting in a higher long-term seroprevalence of antibodies.

Table 1. Correlation between Peste des petits ruminants seroprevalence and predisposing factors.

Variable	Modality	Negative (%)	Positive (%)	Total (%)	Pr > chi²	Odds Ratio	95%
Age	4 months	15.19	13.33	28.52	**0.68**	2.62	0.37 - 18.13
	4 to 8 months	15.56	11.11	26.67			
	8 to 12 months	15.93	10.00	25.93			
	More than 12 months	11.85	7.04	18.89			
Territories	Kalehe	42.96	10.37	53.33	**<0.00**	8.29	4.76 - 14.43
	Mwenga	15.56	31.11	46.67			
Sex	Female	7.04	89.70	40.83	**<0.00**	91.70	21.15 - 39.76
	Male	92.90	10.20	59.17			
Species	Sheep	42.22	22.96	34.81	**0.03**	1.30	0.23 - 0.98
	Goat	16.30	18.52	65.19		0.62	
Feeding mode	Feeding	2.22	0.74	2.96			
	Tied to the stake	19.26	7.41	26.67			0.37 - 18.13
	In the pasture	20.74	14.81	35.56	**0.00**	2.62	
	Along the road	16.30	18.52	34.81			
Breeding system	Agropastoral system	34.07	31.85	65.93	**0.02**	0.42	0.19 - 0.90
	Pastoral system	24.44	9.63	34.07			
Breed	Exotic	1.48	1.48	2.96	**0.01**	25.74	9.9 - 51.20
	Hybrid	7.41	8.89	16.30			
	Local	49.63	31.11	80.74		0.94	
Availability of water source	No	21.48	24.44	45.93	**0.01**	0.62	
	Yes	37.04	17.04	54.07		1.54	

Infection likewise varies according to the species kept on the farm, where sheep are more affected than goats. These results are not in agreement with the results reported by [2] in an epidemiological survey on Peste des Petits Ruminants in Ethiopia, where it was reported that goats were more affected than sheep. This discrepancy is thought to be due to the higher recovery rate in sheep, resulting in a longer lifespan, which explains a larger population of sheep. Furthermore, these results would be in agreement with [28] in a previous study conducted in Tanzania; given that the DRC borders Tanzania, this would be due to trade between the two countries [28]. From this study, it was found that the livestock system is a predisposing factor and that animals raised in the agropastoral system are more exposed than those in the pastoral system. These results are contrary to those of [29] and [26], for whom the pastoral systems would have a high prevalence. However, this agropastoral system is common in some areas where farms lack the financial means to buy feed for animals and where the only source of food would come mainly from agricultural activities [30] [31]; thus, animals could contaminate each other through the soiled feed through the secretions of PPR-infected individuals [4].

The same is true for the presence of a water source in the pasture that would cause the presence of infection in the herd. These results are in agreement with those reported by [25] and [13], and this would be possible because the virus has the ability to be transmitted mechanically through water, but also orally through water and infected feed [4] [25]. These findings suggest that communal water sources may serve as vectors for disease transmission, reinforcing the need for water management as part of PPR control strategies.

Feeding pattern influences the presence of PPR; these results are in agreement with [32]. On a common pasture, animals can transmit the disease to each other either by direct contact with diseased individuals or by grazing soiled grass [33].

3.2. Contribution of the Various Factors in the Model

Table 2 below shows the contribution of each factor considered in the MaxEnt model.

Table 2. Contribution of the various bioclimatic and grazing-related factors.

Factor	KALEHE	MWENGA and UVIRA
Precipitation	14.32	11.4
Maximum Temperature	6.5	4.93
Minimum Temperature	4.45	7.48
Average temperature	10.84	9.21
Euclidean space between pasture	34.66	36.9
Radiation	8.66	2.23
Wind speed	13.67	14.3
Humidity	6.9	13.64
TOTAL	**100**	**100**

Table 2 above shows that of the 9 factors considered in the study, only Euclidean space between pastures contributes 34.66% in Kalehe and 36.9% in Mwenga and Uvira to the prevalence of PPR, followed by rainfall (14.32% and 11.3%) and wind speed (13.67% and 14.3%) in Kalehe and Mwenga-Uvira, respectively. At

medium and low altitudes, relative humidity (13.64%) also contributes to the prevalence of PPR. These findings align with similar studies, such as those by [34] [35], highlighting the importance of environmental and spatial factors in modeling disease prevalence. Additionally, Figure 1 and Figure 2 underscore that, aside from farming systems, Euclidean distance emerges as a critical explanatory variable in the maximum entropy model.

Thus, apart from the farming system, Euclidean distance is an explanatory factor in the results of the maximum entropy model, as shown in Figure 3 and Figure 4 below:

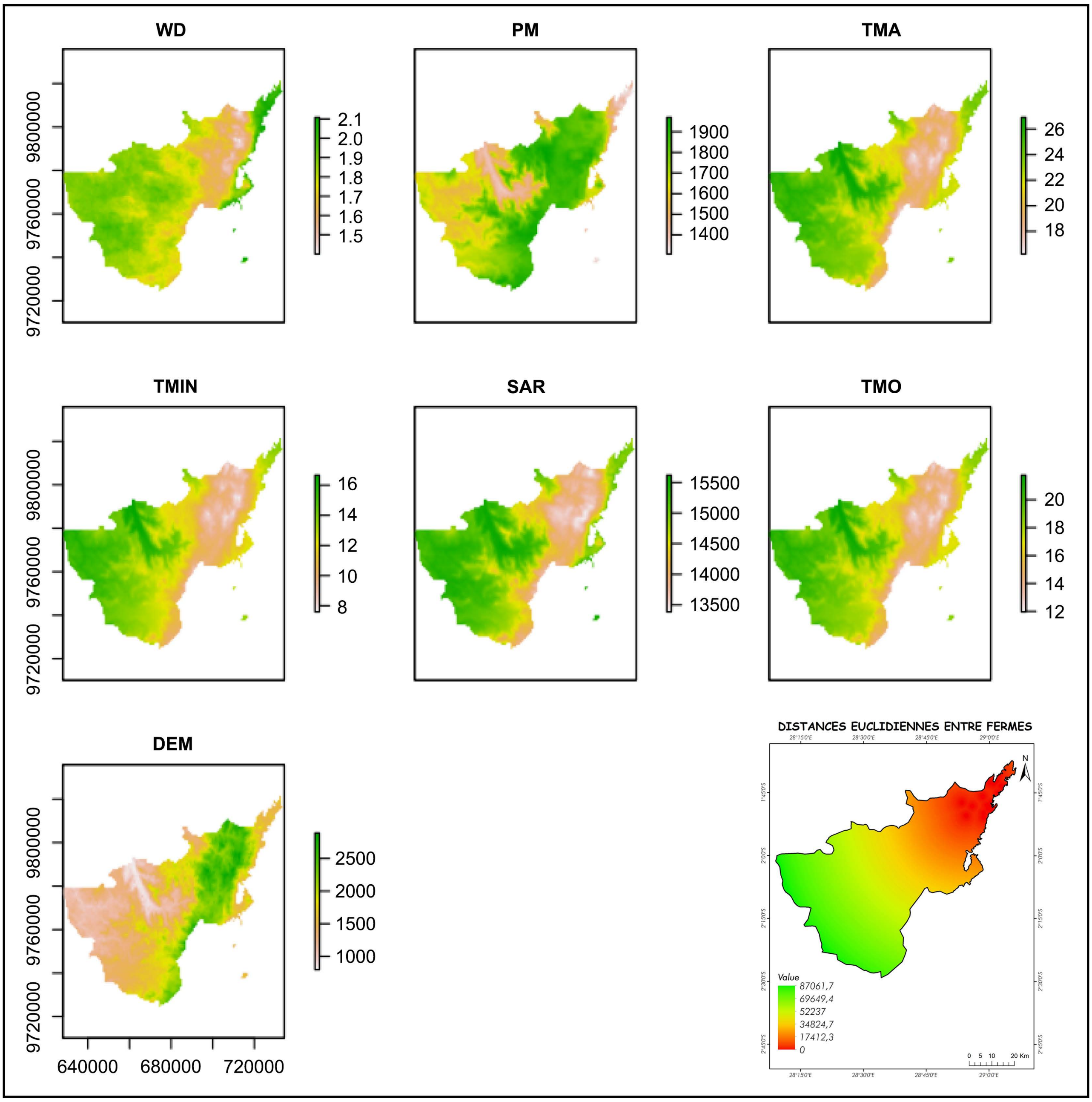

Figure 3. Euclidean distance between farms.

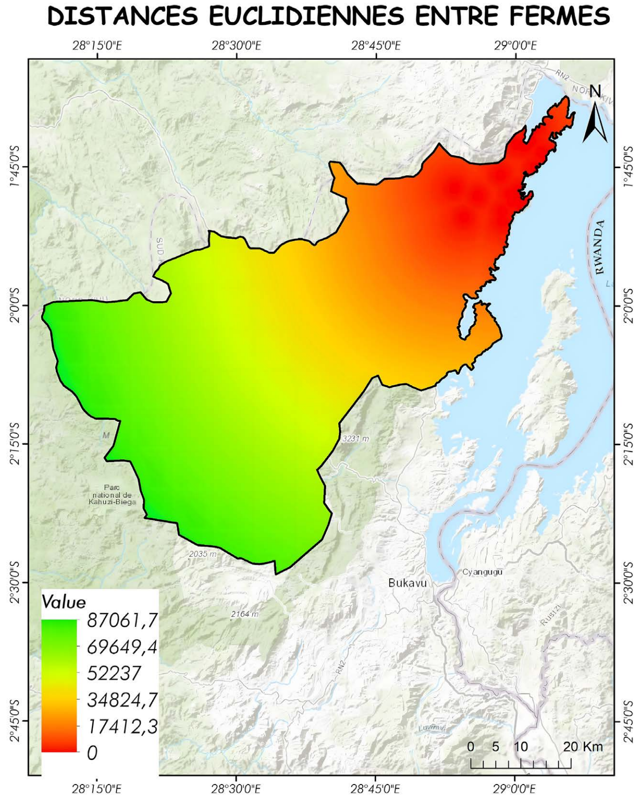

Figure 4. Euclidean distance between pastures.

The figure above illustrates that the closer the farms are to each other, the greater the risk of transmission of PPR disease.

3.3. Mapping of Grazing Lands in Kalehe, Uvira, and Mwenga Territories

From Table 3 and Figures 5-7, it is clear that Uvira territory has the highest proportion of high-risk pastures (90.52%) compared to Kalehe (35.62%) and Mwenga (28.74%).

Table 3. Area of grazing land in the territories of Kalehe, Mwenga, and Uvira.

Zone	KALEHE		MWENGA		UVIRA	
Pasture type	Surface area (Km^2)	%	Surface area (Km^2)	%	Surface area (Km^2)	%
Low-risk pasture	1054.50	31.75	2915.07	34.42	1.71	0.05
Medium risk pasture	1083.62	32.63	3119.81	36.84	305.81	9.43
High-risk pasture	1182.99	35.62	433.65	28.74	2934.78	90.52

The mapping of grazing lands was conducted using spatial data on animal movements, proximity to water sources, and herd interactions, combined with meteorological data. By overlaying this information with the seroprevalence data from different regions, we were able to identify high-risk areas for PPR outbreaks.

The risk thresholds were determined using the natural breaks (Jenks) optimization method, which is widely used in spatial analysis to classify data into meaningful categories by minimizing variance within categories and maximizing variance between categories [36] [37].

The figures below illustrate the mapping of the grazing areas of the different study areas according to the level of risk for PPR. The GIS analysis revealed that herds grazing in lowland areas near rivers or lakes, such as in the territories of Uvira and parts of Kalehe, had a higher prevalence of PPR. These areas showed increased disease risk due to higher animal density and limited access to controlled water sources. In contrast, the highland areas of Mwenga, despite having lower overall prevalence, showed localized clusters of outbreaks, particularly near seasonal water sources. This spatial differentiation is crucial for targeting disease control measures [38].

From **Figure 5**, it can be seen that the pasture areas of Kalehe territory are subdivided into three categories according to the level of risk for PPR: low-risk pasture covering an area of 1054.50 Km^2 representing 31.75% of the total area; medium-risk pasture covering an area of 1083.62 Km^2 representing 32.6% of the total area; and high-risk pasture covering an area estimated at 1182.99 Km^2 (35.62%).

The results of **Figure 6** reveal that the pastures in the Mwenga territory can also be classified into three categories depending on the level of risk for PPR: low-risk pastures covering an area of 2915.07 Km^2 (34.42% of the total area); medium-risk pastures with an area of 3119.81 Km^2 (36.84% of the total area); and high-risk pastures with an estimated area of 2433.65 Km^2 (28.74%).

Finally, **Figure 7** shows that the low-risk pastures for PPR in the territory of Uvira represent an area of 1.71 Km^2, representing 0.05% of the total area; those at medium risk have an area of 305.81 Km^2 (9.43% of the total area), while those at high risk cover an area estimated at 2934.78 Km^2 (90.52% of the total area). According to these results and the survey conducted in the study area, it is noted that environmental and topographical factors are strongly correlated and act in the same way on the dispersion and distribution of the disease.

The maps produced in this study serve as critical tools for identifying high-risk zones, which can help direct vaccination campaigns and other control measures. The incorporation of topographical data into the risk assessment provides insights into how geographical barriers, such as mountains or rivers, influence the movement of animals and thus the spread of PPR [39] [40].

Indeed, according to [41] [42], in tropical environments, climatic parameters such as rainfall, wind speed, and elevation are environmental factors playing quite an important role in the distribution of the disease and in the dissemination of the virus [43]; consequently, they will contribute in the same way to the model of the spatio-temporal distribution of the PPR [2]. For this study, it is observed that only the husbandry system and Euclidean space have a really significant effect on the distribution of the disease, which is not in agreement with the study by [44]; this would be due to the fact that the environmental conditions of the study settings are not similar and the management methods in the two settings are not the same [13] [24].

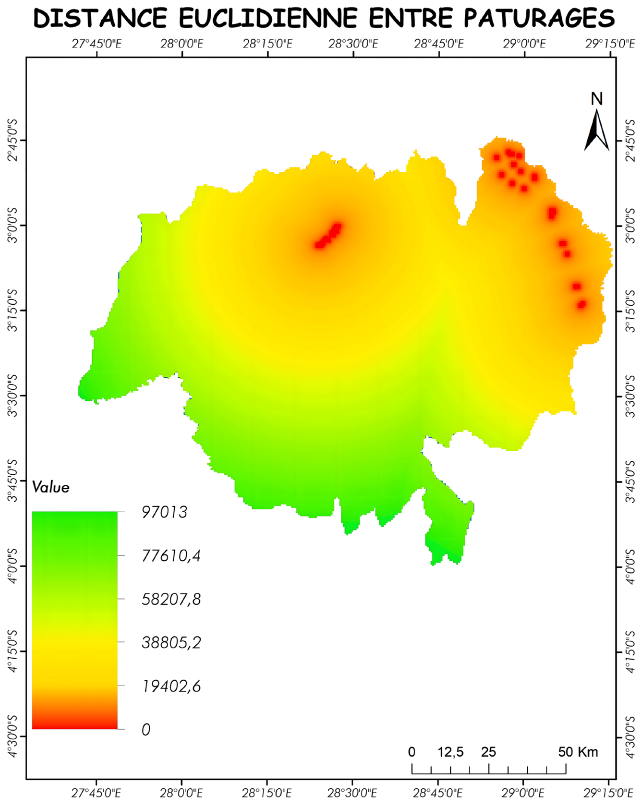

Figure 5. Types of pastures in Kalehe according to PPR risk.

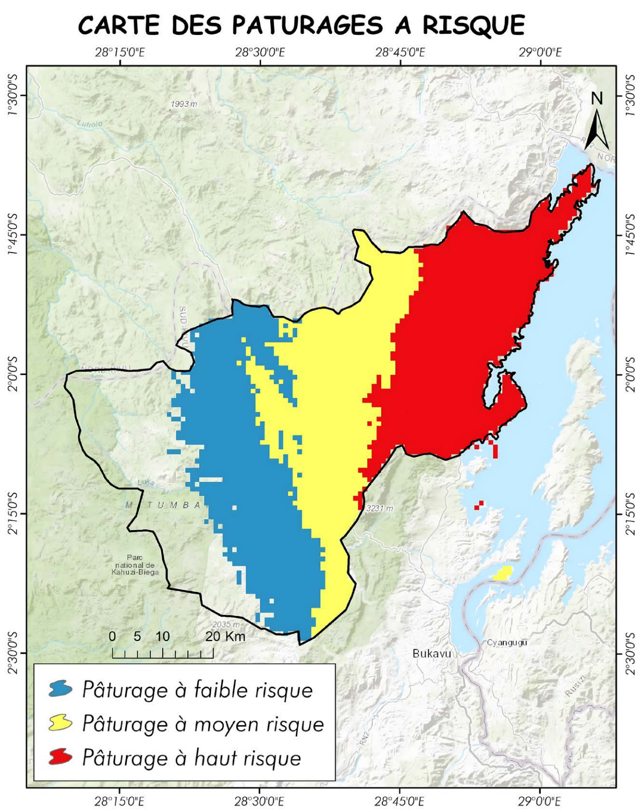

Figure 6. Types of pastures in Uvira according to the risk of PPR.

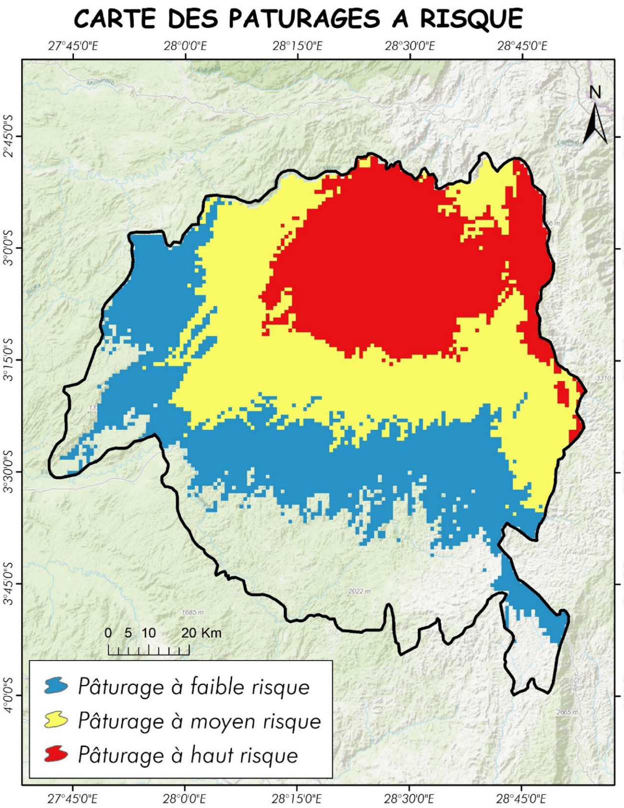

Figure 7. Mwenga pasture types according to PPR risk.

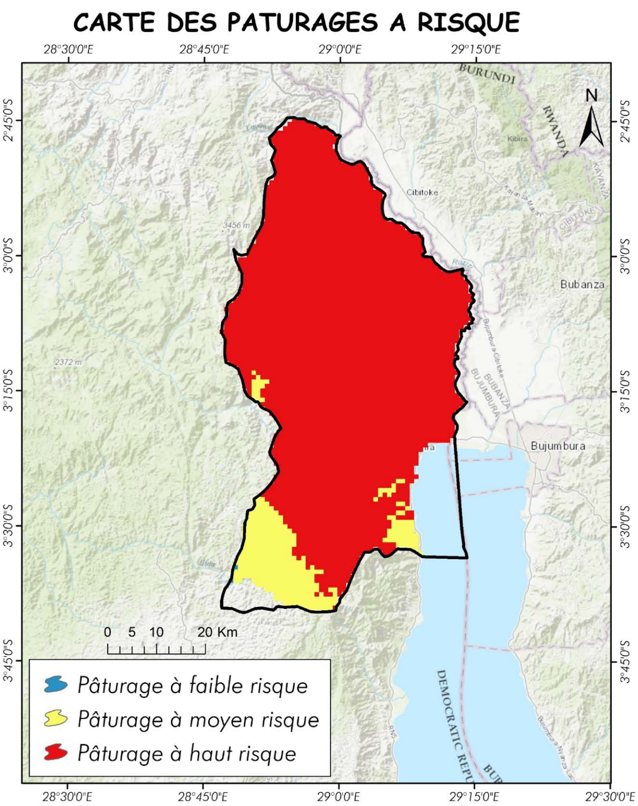

Figure 8. Types of pastures in Uvira according to the risk at PPR.

4. Conclusions

This study highlights that characteristics of pastures and farms, including the breeding system, water source, and watering method, are significantly associated with PPR seroprevalence. Mapping the study sites identified three agro-ecological zones with varying PPR infection risks in South Kivu: low, medium, and high-risk pastures, with Euclidean distance serving as the explanatory variable. The MaxEnt model developed in this research holds promise for controlling and eradicating PPR in South Kivu and other regions with similar agricultural systems. Its application could improve risk management and optimize resource allocation in vulnerable areas (Figure 8).

In practice, the study recommends establishing serological monitoring in high-risk areas to track the epidemiological dynamics of PPR and estimate its incidence. This monitoring would help refine vaccination strategies and control measures based on regional disease patterns. Future research should focus on testing the effectiveness of the MaxEnt model in other regions with comparable ecological conditions. Additionally, it would be valuable to examine the influence of specific pasture characteristics on PPR prevalence and their role in disease transmission dynamics.

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Patents

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Credit Authorship Contribution Statement

Bwihangane Birindwa Ahadi: Conceptualization, methodology, validation, formal analysis, resources, writing—preparation of the original project, writing—revision and editing, project supervision and administration. **Basengere Justin Amani:** Conceptualization, methodology, software, investigation, data retention, writing—preparation of the original project, visualization**. Azine Pascaline Ciza:** Methodology**,** validation, formal analysis, resources, writing—preparation of the original project, writing—revision and editing, writing—revision and editing, project supervision and administration**. Rodrigue Basengere Balthazar Ayagirwe:** Methodology, formal analysis**. Basimine Geant Chuma:** Software, investigation, data retention**. Dieudonné Shukuru Wasso:** Methodology, software**. Muderhwa Zagabe Christian:** Software, investigation, data retention.

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Data Availability Statement

The data presented in this study are available upon request from the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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