World epidemiological meta-analyses of peste des petits ruminants (1997–2017)

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F. Bouchemla [(1)*], A. Sherasiya [(2)*], H. Benseghir [(3)] & A. Mimouni [(4)]

(1) Department of Animal Disease, Veterinarian and Sanitarian Expertise, Faculty of Veterinary Medicine, Vavilov Saratov State Agrarian University, 1 Theatral Square, Saratov, Russia

(2) Ex-Veterinary Officer, Star, Gulshan Park, NH-8A, Chandrapur Road, Wankaner-363621, Dist. Morbi, Gujarat, India. ORCID: https://orcid.org/0000-0002-1598-1820

(3) Ph.D. Student, National Veterinary School of Algeria, Issaad Abbes St. Oued Smar, Algiers, Algeria

(4) Potomac Animal Hospital, 10020 River RD, Potomac, Maryland 20854, United States of America

*Corresponding authors: faysselj18@yahoo.com; sherasiyaanjum@gmail.com

Summary

Estimating the occurrence and distribution of infection and identification of risk factors remain key components in understanding the epizootiology and monitoring of peste des petits ruminants (PPR). This study was performed from 1997 to 2017, and it included details of flocks with emergent infections, within-flock prevalence and risk association between PPR incidence and various flock management factors worldwide. In assessing the impact of PPR on livestock, outbreak incidence per country was used as an effective indicator of the intensity of the infection process. To decode the spatial and temporal dynamics of PPR outbreaks and clarify their relationship with geographical factors, systematic review and logistic regression analyses were conducted. The impact of climatic and socioeconomic conditions on PPR was moderate and high, respectively. In the PPR risk analysis, infected PPR zones were 1.68 times more likely to spread the infection to goat farms than to sheep farms (relative risk: 1.69; odds ratio: 3.26). Moreover, during PPR occurrence, goats are more susceptible to infection than sheep. Through a regression model of outbreaks, a value of 960.67 outbreaks was calculated as the expected mean in 2018. The polynomial regression of PPR cases was followed by extrapolation (medium-sized smoothing of the three following points) to define the expected value in 2018. The probability of PPR could be effectively reduced by coordinating the work in disadvantaged countries with low-income farmers, and disease control must be prioritised to support alleviation of poverty, which has a negative impact on livestock production.

Keywords

Epidemiology – Flock – Outbreak incidence – Peste des petits ruminants – Risk.

Introduction

Peste des petits ruminants (PPR) is a highly contagious transboundary infection with serious socioeconomic consequences. It is an important infectious disease of small ruminants that threatens the food security and sustainable livelihood of farmers across Africa, the Middle East and Asia (1, 2, 3). Peste des petits ruminants virus (PPRV) was first reported in sheep and goats in West Africa (Cote d'Ivoire, 1942) (4, 5). The PPRV is a member of the genus *Morbillivirus* in the family Paramyxoviridae (5, 6). This genus comprises a group of close-antigenicity viruses including measles virus, cattle plague (rinderpest) virus and canine distemper virus (4, 5, 7).

The disease was classified as a particularly dangerous disease because of colossal economic damage to goat and sheep breeding. Small ruminant production has been widely affected; when PPR is first brought to a previously uninfected territory, it can infect up to 100% of the small ruminants. Mortality in the primary focus of infection may reach 100%, and up to 50% or even more in permanently infected territories (3, 8, 9). Moreover, the evolutionary dynamics (rate) of PPRV during an epidemic was approximately 2.61×10^{6} nucleotide substitutions/site/day in a recent study (2).

To understand how the occurrence of PPR has become wide-ranging, it is necessary to investigate the circumstances of flocks in different geographical areas. In fact, the identification of risk factors for PPR has become increasingly challenging and has gained research interest globally. Hence, this study aimed to investigate the PPR occurrence worldwide and to identify particular factors enhancing its emergence.

To overcome the disease worldwide by 2030, in 2015 the Food and Agriculture Organization of the United Nations (FAO) and the World Organisation for Animal Health (OIE) launched a global programme to eradicate PPR, based on a broad international consensus reached in Abidjan, Cote d'Ivoire. The first phase of this programme covers the period from 2017 to 2021, with a budget of around US$ 996 million (10, 11).

Aside from goats and sheep, clinical cases have been reported in wild small ruminants such as the Laristan mouflon, dorcas gazelle, gemsbok, antelopes, other gazelles and the Nubian ibex, and antibody formation against PPRV has been serologically diagnosed in these animals; however, according to other reports, no circulation of PPRV exists among wildlife (12, 13, 14, 15). Although some wildlife species are clearly susceptible to infection, the role of this population in the epidemiology of PPR remains controversial. The available information about the occurrence of the disease in free-ranging wildlife is mainly derived from surveys based on serological evidence (16, 17).

This study aimed to identify different components in understanding the epidemiology and management of PPR. Data obtained from 1997 to 2017 were analysed to help study various PPR-infected flocks and herds, and to investigate the risk factors. With the aim of displaying the spatiotemporal features of PPR outbreaks and investigating its relationship to meteorological factors, a systematic review and logistic regression analysis were conducted.

Materials and methods

Ethical approval

This study did not require ethical approval because it was based on data retrieved from published studies already available in the public domain.

Study area and data collections

A systematic and analytical review was conducted on PPR disease among susceptible animals worldwide, taking into account the special reporting items for the meta-analysis criteria (18, 19, 20, 21). Relevant studies were indexed by different scientific databases (22, 23, 24, 25, 26, 27).

The data presented to the OIE from different local veterinary services had an imposed time limitation from 1997 to 2017, and they were last updated on 31 December 2017 (28).

Veterinary departments of each country worldwide confirmed and reported outbreaks officially to the OIE; samples were collected from animals with suspected PPR in infected areas. Enzyme-linked immunosorbent assay (ELISA) and polymerase chain reaction (PCR) were mainly used in laboratory diagnosis of PPR, with the inclusion of the number of susceptible, infected and dead animals and outbreaks from 1997 to 2017. Google was used as an addition to the online databases where it had sufficiently wide coverage to be used as a search engine; data were collected using similar keywords and criteria to those used for the literature search.

Statistical analysis

Data were encoded in a Microsoft Excel (2013; IBM Corp., NY, United States of America [USA]) spreadsheet for analysis. In all statistical analyses used, the significance level was set at 5%

($p < 0.05$). Moreover, a cluster analysis of cases and outbreak incidence (number of cases/outbreaks in one focus of PPR infection) with mapping was processed.

Socioeconomic and geographical conditions may encourage the emergence and spread of different infections. Hence, to analyse the structure of the PPR range, hypothesis-testing methods were used, such as the χ^2 criterion for multivalued populations. Such methods aid in identifying significant prerequisites of the disease and provide an impact information indicator (III) of the degree of influence of each factor on the level of tension of the epizootic situation, through the following formula (29, 30) (results in Table I):

$$\text{III} = \sqrt{\frac{\Sigma H\ (A) - \frac{\Sigma\left(nk \Sigma\ \mathrm{H}\ (\mathrm{A/bk})\right)}{n}}{\Sigma H\ (A)}}$$

where (n_kH (A/$\mathrm{b_k}$))/n is the entropy of accidental diversity and *ΣH(A)* is the general entropy. The variables are defined in the footnote to Table I.

Table I

Influence of geographical–climatic conditions on the tension of the peste des petits ruminants situation in the period from 1997 to 2017

Regions	Outbreak incidence					Σ F	P_1	ΣE	ΣE*Σ f
	[0–12]	[>12–33]	[>33–98]	[>98–311]	[>311]				
	1		2			3	0.056		
South Asia	0.33		0.67					0.93	
	0.528		0.402						2.79
	1	4	3	1		9	0.167		
Middle East	0.11	0.44	0.33	0.11				1.75	
	0.35	0.52	0.528	0.35					15.75
	3	1		1		5	0.092		
Sub-Saharan (Sahel)	0.6	0.2		0.2				1.37	
	0.444	0.464		0.464					5.85
Eastern Europe		1		1		02	0.037		
		0.5		0.5				1	2
		0.5		0.5					

Central Asia			1		1	2	0.037		
			0.5		0.5			1	2
			0.5		0.5				
East Asia		1	2	1		4	0.074		
		0.25	0.5	0.25				1.5	
		0.5	0.5	0.5					6
Mediterranean		4	1			5	0.092		
		0.8	0.2					0.82	4.1
		0.256	0.464						
Central Africa (Equatorial)	9	4	3	3	5	24	0.444		
	0.375	0.167	0.125	0.125	0.21			2.17	52.08
	0.52	0.43	0.375	0.375	0.472				
Σ F	14	15	12	7	6	54			
P_2	0.259	0.278	0.222	0.129	0.111				
H(A)	0.504	0.5013	0.481	0.38	0.351				

Regions
F Frequency; number of infected objects (countries) in each class
P P = f /n frequency fractions, n is the total in each class
E = H = $p \log_2 p$; particular entropies by class, found for each fraction (with error probability = 0.05)
N Total number of objects (or regions)

Class intervals were suggested based on incidence criteria. Homogeneity was tested. Regions were categorised according to climate similarities.

The risk analysis was conducted based on the calculated relative risk (RR) and, logically, its components. The RR may also be called the risk ratio, which differs from the odds ratio (OR). The suggested null hypothesis (H_0) was that the arranged data in every section were not random but linked to one another. If the calculated χ^2 value falls into the critical region of the χ^2 curve there is a hidden tie in the data between PPR occurrence and potential risk factors.

Trend analysis was also used in this study. The curves produced had a low approximation foreseen factor, the proportion of the variance in the dependent variable that is predicted from the independent variable(s) (R^2 less than 0.3), which required extrapolation of two and three values in order to obtain a credible forecast.

Results and discussion

This study focused on the spatial dynamics associated with the spread of PPR in the last two decades (from 1997 to 2017), in which the disease had threatened more than 21.6 million animals, with an overall prevalence of 7.2% and mortality rate of 17.54%. The results suggested that PPR-infected goat herds were as severely affected as sheep flocks, with 6.7% and 7% morbidity, respectively, but losses were greater among sheep than among goats (case fatality rate 20.6% and 13.7%, respectively). Such results are consistent with other studies in different circumstances and areas, despite variations in the sheep and goat farming models in different geographical regions and in the socioeconomic status of individual farmers (24, 31, 32, 33).

The disease has been spreading especially in developing countries in Africa and Asia, among which India and Nepal were the top endemic countries (2,263 and 2,146 foci of infection, respectively). Furthermore, losses were severe in Nigeria, where PPR was reported in 750,000 animals (with 13% mortality, i.e. fewer than 100,000 individuals); in Iran, over 250,000 animals were infected, while more than 127,000 and 106,000 animals were infected (with 20.4% and 28.5% mortality) in India and Nepal, respectively (28).

Figure 1 illustrates those losses and indicates the locations at high risk of infection.

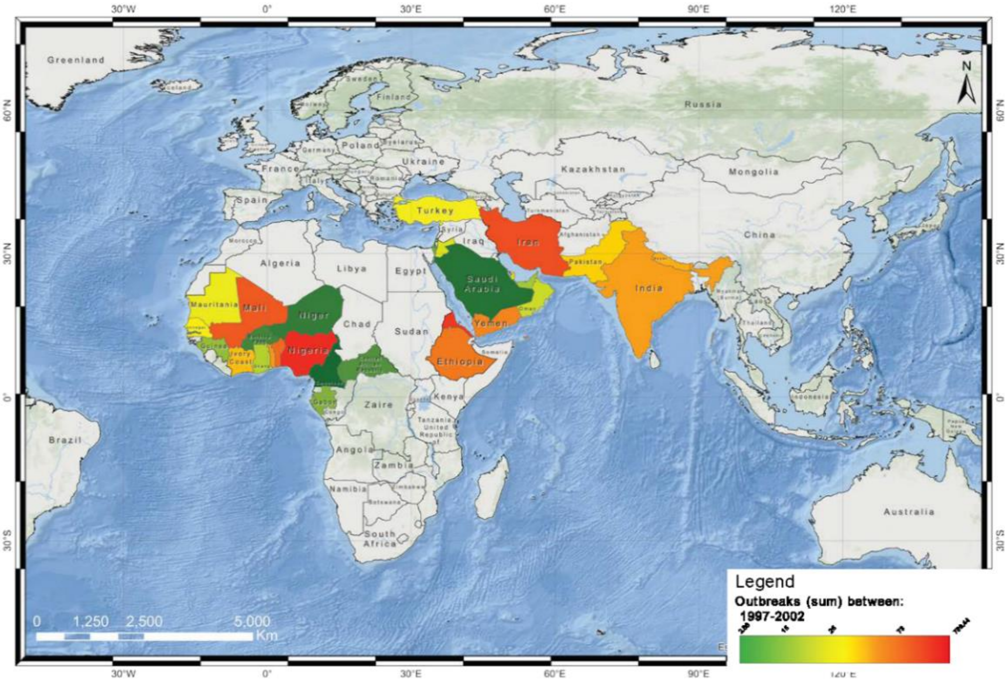

Fig. 1a
Incidence of clusters of outbreaks of peste des petits ruminants in the period 1997–2002

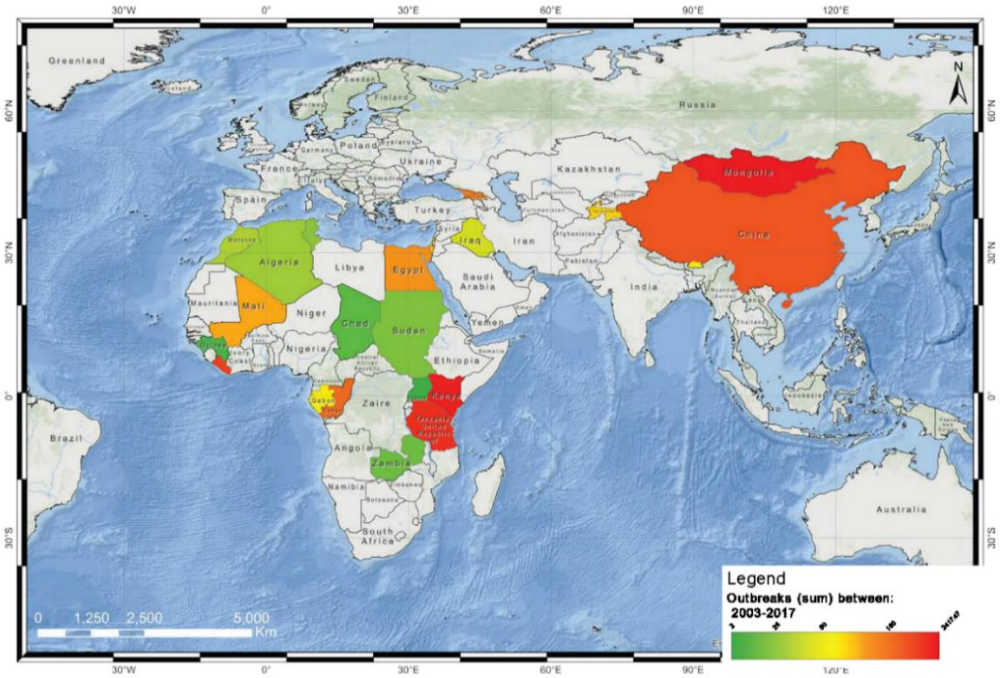

Fig. 1b
Development of the incidence of peste des petits ruminants outbreaks, 2003–2017

Moreover, in general, two periods of disease dissemination were observed visually (based on Fig. 2), which overlapped in 2002. In African equatorial countries and South Asia, PPR infection occurred until 2002; throughout this period, more than 20 million animals were under the risk of PPR infection (Fig. 1). In these countries, where a high percentage of the human population depends on small ruminant production, losses were severe. Around 1.5 million animals were infected, with an overall prevalence of 6.92% and mortality of approximately 15.42%. The prevalence and mortality rate reached 100% on several occasions in various regions, such as Gabon in 2002–2003 (mortality in sheep) and Palestine in 2000 (mortality in goats).

Another critical index that can explain the intensity of PPR spread is the size of the focus of infection; this showed an average of 126 animals, indicating how PPR quickly disseminated within each infected location. In 1997, the peak occurred in Nigeria, which experienced a huge PPR outbreak, involving 5,629 goats and 3,501 sheep, in one focus of infection.

In the second phase, PPR showed further propagation globally, with new areas of infection. The disease had resulted in immense fear. Its prevalence and mortality increased by two and three times (14.75% and 44.27%), respectively. The average index of the focus of infection did not decrease; instead, it showed more infected animals (160 on average). The worst situation was registered in Kenya in 2007, with 3,020 affected animals per infected location; in Mongolia, approximately 2,858 animals were affected by PPR in 2016 (Fig. 1).

The prevalence and mortality rate reached 100% several times in different regions, such as Palestine in 2016 and 2017 (mortality in goats), Bhutan in 2010 (mortality in sheep) and Democratic Republic of Congo in 2005–2006 (morbidity and mortality).

The disease emergence rate was assessed by estimating the incidence of outbreaks (the average number of infected animals per focus of infection) (Fig. 1). This has been used in mapping global PPR risk zones in the last 20 years.

In the visual analysis of the cartogram shown in Figure 1a, the highest risk of registering PPR affected flocks is exhibited in Western Africa, as well as in the Indian subcontinent and its surrounding regions (especially Iran), where the incidence of registered outbreaks was higher than the global average (85 animals/outbreak). Moreover, a maximum of 789 animals per outbreak was registered in Nigeria. The normal distribution of these values showed that the first quartile (Q_1) is at 14.53 and the third quartile (Q_3) is at 63.42; hence, the majority of PPR foci were below the global average bar in this period, including Saudi Arabia, Mauritania, Nepal, Niger and Gambia.

The second period is illustrated in Figure 1b. The highest PPR risk belonged to the regions of central Africa and Asia, with a remarkable value of over 2,299.8 cases in Kenya and 2,417.4 in Mongolia. The disease at this time was becoming more endemic in several geographical areas.

The average was estimated at 235 animals per PPR affected flock or herd. Moreover, Q_1–Q_3 reached 10.7–110.33. The spatial occurrence of PPR increased initially and, subsequently, severe losses hit the livestock industry.

Analysis of the impact of socioeconomic and geographical conditions on the intensity of peste des petits ruminants

As shown in the visual analysis in Figure 1, the spatial dynamics of PPR is relatively linked to geographical and economic conditions. Risk factors influencing PPR may be different from one area to another and merely demonstrate a coaction, which defines the final map. To estimate how PPR occurrence depends on climatic conditions, all similar infected regions were classified together to investigate how the occurrence of PPR varied. The geographical data for all regions were collected from the FAO. Table I clarifies how PPR occurrence may vary, depending on geographical conditions.

The minimum, Q_1, mean, Q_3 and maximum values were used to identify the given intervals.

With the variables defined in Table I, the III was obtained as follows:

$n = \Sigma F = 54$

$(nk * H (A/bk)) = \Sigma (\Sigma F * \Sigma E) = 90.57$

$Ey = \Sigma H (A) = 2.217, Ez = 1.677$

$Ex = Ey – Ez = 0.54$

$III = 0.493$

In obtaining this value, the epidemiological analysis considered a range of indicators for socioeconomic factors that reflect the level of socioeconomic development of different regions (29).

The results of the PPR analysis of structural area, derived from assessing the impact of socioeconomic background on the epizootic situation, were obtained using a similar approach, and to avoid repetition, the final result is reported. The III for socioeconomic conditions is up to 0.59.

Thus, a statistically significant proportional effect of geographical and climatic conditions was found on the outbreak incidence index, with a less strong bond than for socioeconomic conditions, suggesting conditionality. This dependence is caused by an increase in their coexistence.

According to the distribution of the statistical results, the gravest situation of PPR had been developing in the Middle East, Central Africa and East Asia, driven by the entropy of accidental diversity. In other serious situations shown in Table I, the general entropy decreased, whereas the outbreak incidence increased; this finding may be possibly related to the impact of socioeconomic conditions in the regions concerned (sub-Saharan and Equatorial Africa) where the livestock farms are traditional and not very large. Findings showed that the dissemination of PPR had a significant multidirectional occurrence ($p < 0.05$).

According to other recent studies, geographical factors may be important variables that affect PPR transmission and should be considered in future monitoring programmes for PPR (16, 34). Thus, considering that small ruminants are highly important for low-income and landless farmers, disease control should be the first step of poverty alleviation.

Peste des petits ruminants risk analysis

To simplify the processing approach, all registered outbreaks were selected and classified strictly according to the type of farm (i.e. sheep or goat). Only goat and sheep infected points (farms) were considered in order to calculate their individual risks and odds ratios. All results are presented in Table II.

Table II

Analysis of the risk distribution for peste des petits ruminants (PPR) outbreaks, cases and losses on different farms during the period from 1997 to 2017

Criteria	Infected	Total	Risk/Odds ratio	
Caprine outbreaks	270	431	R_1 = 0.626	
Ovine outbreaks	161	431	R_0 = 0.373	RR = 1.677
Caprine cases	235,043	348,146	R_1 = 0.675	
Ovine cases	113,103	348,146	R_0 = 0.324	RR = 2.078
Caprine deaths	12,634	21,121	R_1 = 0.598	
Ovine deaths	8,487	21,121	R_0 = 0.401	RR = 1.488
Goats	235,043	2,804,775	C_1 = 0.083	
Sheep	113,103	414,105	C_2 = 0.273	OR = 3.259

OR: odds ratio
R_1 is the possible risk of an event/factor occurring in a studied group (PPR infected farms, outbreak/cases/death) relative to the total number in the study
R_0 is the risk probability of the considered control/reference group relative to the whole group studied
RR (relative risk) is the ratio of R_1 to R_0
C1 is the incidence of PPR infection in goats relative to the total number of animals in the study over a period of time
C2 is the incidence of PPR infection in sheep on all farms

The H_0 (null hypothesis) testing procedure had been verified for all data by the chi-square test: $\chi^2_{crit} = 3.84$ (χ^2_{obs}: all results > 3.84). The χ^2_{obs} value fell into the critical region: $\chi^2 > \chi^2_{crit}$, so the H_0 was rejected with an error probability of $\alpha = 5\%$; thus, both indicators are considered dependent.

According to the interpretation of the data shown in Table II, in a PPR-infected area, the disease has 1.68 times more chance of spreading in goat farming as opposed to sheep farming. Therefore, the RR of PPR increased by 67.7% in this case (in one-species farming).

The RR of PPR in goats compared with that in sheep was over 1, which should be considered to indicate a high-level risk of diffusion of infection in this species. Furthermore, the excess risk of emergence was approximately 0.59 (excess risk is equal to R_0/R_1). This observation is consistent with similar research conducted by Al-Majali *et al.* in a particular geographical region in Jordan (35). Differences among studied regions and grazing systems were not statistically important, but the univariate analysis of a flock or herd's direct contact with others as a risk factor for the spread of PPR has been noted by many authors (32, 33, 36, 37, 38).

In other studies, the risk of PPR was found to be associated not only with species but also with the sex of the animals and the husbandry practices. Similarly, the seasonal movement of animals towards autumn green pastures has an impact on the infectious process (3, 16, 33, 37).

To conclude the analysis, a forecast for the expected situation with regard to PPR was made. Trends in outbreaks, cases and dead animals were analysed (Fig. 2).

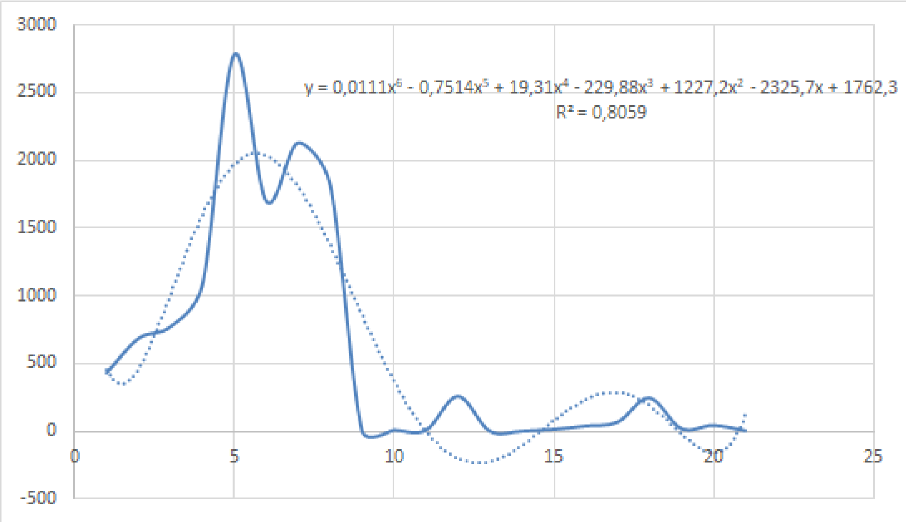

Fig. 2a

Dynamics (blue dotted line) and its regression model for peste des petits ruminants outbreaks in the period 1997–2017 worldwide

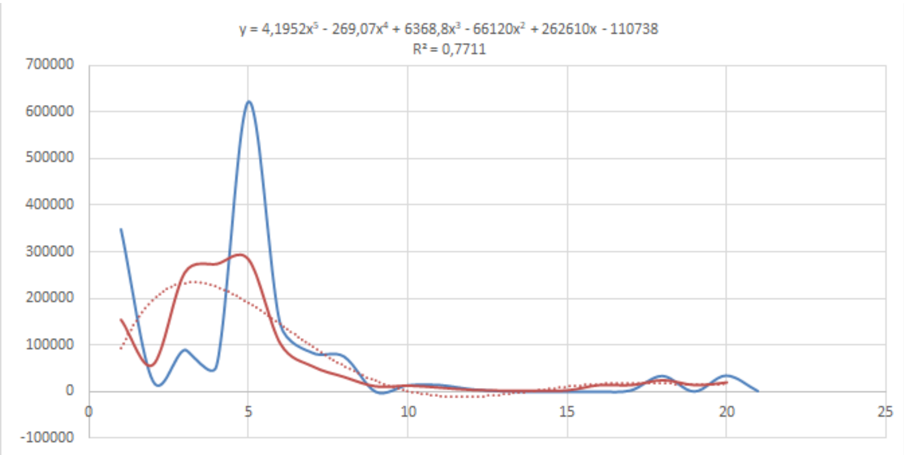

Fig. 2b

Dynamics (full brown line), average smoothing (brown dotted line) and its regression model for peste des petits ruminants cases in the period 1997–2017 worldwide

As illustrated in Figure 2a, the studied indicator in small ruminants was intermittently expressed in a different freestyle period (the period within a peak on the graph); the PPR cases dropped before 2003 but continued to spread in the subsequent years.

Trends and forecast

For estimating the expected situation with a high R^2 approximation (Fig. 2a), a regression model was developed. Through this model, a value of 960.67 outbreaks was calculated as the expected mean in 2018.

The trend of cases followed that of outbreaks logically. Polynomial regression does not work in this situation because of the low R^2 value, and improving it with extrapolation is required. To decrease the large standard deviation, a medium-sized smoothing of three following points (values) was built. The resulting model is shown in Figure 2b:

$$y = 4.1952x^5 – 269.07x^4 + 6368.8x^3 – 66120x^2 + 262610x – 110738.$$

Where Y_t is the value of the dynamics models of the epizootic situation and x is the serial number of the year; $R^2 = 0.77$ denotes a good approximation. The model of theoretical values was supported in 2001 when the peak value of 620,000 infected individuals was clearly demonstrated.

According to this model, the expected incidence of cases would rise to 31,226.64 in 2018, with a forecasted mortality rate of approximately 7.83%.

In a previous study, the authors analysed disease data in a limited period, from 2007 to 2017, in Russia as an example of a special limited territory (3). In Russia, the risk of PPR spread, based on the 10-year period, was not negligible, but it has revealed a tendency to decline according to the contrived forecast. As opposed to the current study, in which PPR spread geographically and over the years, the time interval used in the previous approach allowed an overview of the spatiotemporal dynamics and how the risk factors assessed were changing.

The point at which the forecast was exaggerated is more pronounced in the recent study and may not be unrealistic, considering the number of countries and the number of animals at risk worldwide. Furthermore, the risk factors demonstrated similarities with, unsurprisingly, a gap in values and this could be understood within the context of the tremendous variety of social and economic circumstances that have accompanied PPR affected flocks. The spread of infection may be reduced in the next few years, according to the predictions obtained in both studies.

Recommendations

The results of this study provide evidence of the organised work conducted by the OIE and other organisations in decreasing global economic losses due to PPR. Linking local factors in each homogenised area (economically or geographically) to every micro-plan and collaborating with these areas even if they are not PPR-endemic may yield further improvement.

Conclusion

The entropy model used to identify geographical and socioeconomic factors has a potential influence on the outbreak incidence of PPR. Goat farming is more susceptible to PPR than sheep farming.

The probability of PPR could be effectively reduced by coordinating with disadvantaged countries; considering the high importance of small ruminants to farmers in such countries, disease control should be aimed at first to support poverty alleviation.

According to the forecast obtained by the model, the incidence of infection was estimated at 960 flocks or herds in the following year (2018), affecting 31,000 animals.

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