Mapping the risks of the spread of Peste des Petits Ruminants in the Republic of Kazakhstan

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Abstract

Peste des petits ruminants (PPR) is a viral transboundary disease of small ruminants that causes significant damage to agriculture. This disease has not been previously registered in the Republic of Kazakhstan (RK). This paper presents an assessment of the susceptibility of the RK's territory to the spread of the disease in the event of its importation from infected countries. The Generalized Linear Negative Binomial regression model that was trained on the PPR outbreaks in China was used to rank municipal districts in the RK in terms of PPR spread risk. The outbreaks count per administrative district was used as a risk indicator, while a number of socio-economic, landscape and climatic factors were considered as explanatory variables. Summary road length, altitude, the density of small ruminants, the maximum green vegetation fraction, cattle density and the Engel coefficient were the most significant factors. The model demonstrated a good performance in training data ($R^2 = 0.69$) and was transferred to the RK, suggesting a significantly lower susceptibility of this country to the spread of PPR. Hot Spot analysis identified three clusters of districts at the highest risk, located in the western, eastern and southern parts of Kazakhstan. As part of the study, a countrywide survey was conducted to collect data on the distribution of livestock populations, which resulted in the compilation of a complete geo-database of small ruminant holdings in the RK. The research results may be used to formulate a national strategy for preventing the importation and spread of PPR in Kazakhstan through targeted monitoring in high-risk areas.

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Running title: PPR risk Kazakhstan

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Abstract

Peste des petits ruminants (PPR) is a viral transboundary disease of small ruminants that causes significant damage to agriculture. This disease has not been previously registered in the Republic of Kazakhstan (RK). This paper presents an assessment of the susceptibility of the RK's territory to the spread of the disease in the event of its importation from infected countries. The Generalized Linear Negative Binomial regression model that was trained on the PPR outbreaks in China was used to rank municipal districts in the RK in terms of PPR spread risk. The outbreaks count per administrative district was used as a risk indicator, while a number of socio-economic, landscape and climatic factors were considered as explanatory variables. Summary road length, altitude, the density of small ruminants, the maximum green vegetation fraction, cattle density and the Engel coefficient were the most significant factors. The model demonstrated a good performance in training data ($R^2 = 0.69$) and was transferred to the RK, suggesting a significantly lower susceptibility of this country to the spread of PPR. Hot Spot analysis identified three clusters of districts at the highest risk, located in the western, eastern and southern parts of Kazakhstan. As part of the study, a countrywide survey was conducted to collect data on the distribution of livestock populations, which resulted in the compilation of a complete geo-database of small ruminant holdings in the RK. The research results may be used to formulate a national strategy for preventing the importation and spread of PPR in Kazakhstan through targeted monitoring in high-risk areas.

Keywords : Peste des Petits Ruminants, Republic of Kazakhstan, People's Republic of China, Generalized Linear Negative Binomial Regression, Risk Factors, ArcGIS.

Introduction

The preservation of the sustainable epizootic welfare of the country's livestock in relation to threats from especially dangerous diseases, such as Peste des petits ruminants (PPR), is the most important task of veterinary science and practice, which is of paramount importance in protecting the health and lives of people, providing the population with high-grade and safe food products, and providing industry with high-quality raw materials.

PPR is a highly contagious viral disease that affects small ruminants with a 10% to 90% mortality rate among infected animals (EFSA AHAW Panel, 2015; Peste des petits ruminants, 2021). Due to the significant socio-economic damage and negative impact on food security in many countries around the world, PPR is included on the list of priority diseases of the Five-Year Plan of Action of the FAO / OIE World Framework Program for the progressive control of transboundary animal diseases which aims to eliminate PPR by 2030 (Global Strategy for the Control and Eradication of PPR, 2015). The proliferation of this disease in countries close to Kazakhstan makes it necessary to analyze the threat of the importation and subsequent spread of PPR in this country (Ahaduzzaman, 2020).

PPR is a typical transboundary disease: first reported in West Africa in 1942, this disease has steadily extended its range over the years. Thus, during the period 2001 to 2011, this disease spread in 56 countries: 35 in Africa and 21 in Asia (Munir, 2015), and by 2016 it had been registered in more than 70 countries and had become endemic in parts of North, East, and West Africa, the Near and Middle East, South and Central Asia, and Western Eurasia (Balamurugan et al., 2014; Bouchemla et al., 2018; Zhuravlyova et al., 2020). The above African and Asian regions are home to more than 80% of the world's sheep and goats; products such as goat's milk, lamb, and wool play a huge role in the welfare of many families (Robinson et al., 2011; Gilbert et al., 2018). The FAO estimates that about 300 million small farming families worldwide depend on small ruminants, as sheep and goats are critical assets for poor rural households, providing them with protein, milk, fertilizer, and wool, and often representing substantial social capital and access to financial loans (Global Strategy for the Control and Eradication of PPR, 2015).

According to official information provided by the OIE, the epizootic situation with regard to PPR in the world remains tense (OIE WAHIS, 2021). Despite intense international, regional, and national efforts to combat this disease, most developing countries around the world are not free of PPR, thus constituting a constraint to free and liberal global trade in animals and livestock products (Peste des petits ruminants, 2021).

The epizootic situation with regard to PPR in the Central Asian countries neighboring Kazakhstan is ambiguous. Thus, in Armenia, Azerbaijan, and Turkmenistan, outbreaks of PPR have not been previously registered, although monitoring studies and preventive vaccinations of 33-70% of animals susceptible to PPR in risk zones are being carried out (Koshemetov et al., 2014; Amirbekov et al., 2020). In Uzbekistan and Kyrgyzstan, isolated outbreaks of this disease have been previously recorded, and active monitoring and preventive vaccination are currently being carried out (Yapici et al., 2014; Fine et al., 2020).

This disease leads to large economic losses annually. For example, a series of epidemics in Kenya in 2006-2008 caused the deaths of 1.2 million small ruminants, resulting in losses of more than US $23.5 million, and milk production declining by 2.1 million liters. In general, the annual damage from PPR is estimated at US $1.4-2.1 billion (Kihu et al., 2015; Jones et al., 2016; Bardhan et al., 2017).

For the successful prevention of PPR, regional studies of the epizootic process are important, which will allow the features of its manifestation within a specific territory to be studied in specific natural-geographical and socio-economic conditions, with subsequent forecasting as a reliable foundation for managing the epizootic process through the development and implementation of effective counter-epizootic measures.

According to the official data of the State Veterinary Service of the RK, PPR has never been registered in this country before, although some publications indicated the isolation of the PPR pathogen from sick sheep and goats in the RK in 2003 and 2014 (Lundervold et al., 2004; Kock et al., 2015). The socio-economic, organizational, structural, and geopolitical changes in Kazakhstan during the post-Soviet era, as well as the expansion of international trade and economic and cultural ties have led to greater risks of dangerous infectious disease pathogens being imported onto its territory, including via cross-border areas. The Republic of Kazakhstan has been historically characterized by unique natural conditions that preserve the activity of many known disease natural foci that can cause a sudden aggravation of the epizootic situation in this region.

The purpose of this research is to assess the susceptibility of the RK's territory to the spread of PPR, also treated as the risk of PPR spreading in the event of the pathogen being imported into this country.

Materials and methods

Study area

The area of interest for modeling the risk of the spread of PPR was the entire territory of the Republic of Kazakhstan (RK, Kazakhstan). The RK is a land-locked state in Central Asia, occupying an area of 2,725,000 km^2 with a population of 18.28 million. Administratively, the RK is divided into 14 units on the first level – regions ("oblasts"). Each of these regions is sub-divided into second-level administrative units – districts, whose area ranges from 283 to 138,663 km^2 (mean 15,780 km^2). In total, there are 173 districts in the RK (Fig. 1).

Figure 1. Republic of Kazakhstan: first- and second-level administrative divisions, small ruminants' population density and location of small ruminants' farms

PPR outbreaks in the People's Republic of China (PRC, China) were used to train a regression model. The total area of China is 9,598,962 km^2, while the population exceeds 1,404.328 million. The second (prefectural) level of administrative divisions comprises 333 units with an area between 490 and 473,671 km^2 (mean 27,670 km^2).

In terms of area, China is the third largest country in the world, while Kazakhstan is the ninth largest. Both countries share a land border of more than 1,600 km.

We excluded from the model the two smallest Kazakhstan districts (Almaty and Shymkent), which represent urban areas with a high population density and no populations of small ruminants. For the sake of consistency between the ranges of the explanatory variables for both countries, we removed from the model Chinese prefectures with geographical areas outside the range of Kazakhstan's district areas. Thus, the total number of analyzed administrative units was 311 in China and 171 in Kazakhstan (Fig. 2).

Figure 2. The study region (Republic of Kazakhstan and People's Republic of China) and distribution of Peste des petits ruminants (PPR) outbreaks in China, 2007 – 2020. Data source: FAO EMPRES-i.

Modeling method

Since the RK is currently free from PPR, no outbreaks were available to validate an internally built model. Thus, to rank Kazakhstan's districts in terms of the risk of PPR spreading, a regression model trained on outbreaks in China was applied. Second level administrative units (districts in Kazakhstan, counties or prefectures in China) were chosen as the units of analysis for building a regression model. For each unit, the number of PPR outbreaks and explanatory factors were extracted (see below). We considered the number of outbreaks' per administrative district throughout the entire study period to be a response variable. As this count variable demonstrates significant overdispersion (a variance of 2.60 and a mean of 0.87), we chose a Generalized Linear Negative Binomial (GLNB) model to reveal the relationships between the number of outbreaks per district and a set of predictors (Venables & Ripley, 2002).

The following geographically distributed landscape, climate, and socio-economic characteristics for each administrative unit were selected as potential explanatory factors based on an analysis of scientific publications on the spatial and temporal modeling of PPR (Lembo et al., 2013; Ma et al., 2017, 2019; Mokhtari et al., 2017; Cao et al., 2018; Gao et al., 2019; Ruget et al., 2019): 1) variables that serve as a proxy of an intensity of regional economic activity that may influence the disease spread by transport links - total road length; road density; average population density and the Engel coefficient11The Engel coefficient, known also as Engel's network density ratio, presents a density of the road network adjusted for population density and is calculated as a total road length of a region divided by the square root of its area and population number. This parameter is used to evaluate the development of the transportation network and its availability to population thus providing an indirect metric for peoples' movements intensity (Mesjasz-Lech and Nowicka-Skowron, 2013; Golskay, 2019; Plotnikov et al., 2019).; 2) average density of small ruminants and average cattle density as indicators of susceptible population's and other potential host's density; 3) most general landscape and climatic factors that may shape suitable habitat for small ruminants and provide favorable conditions for the virus spread - average elevation; annual mean temperature; annual precipitation and maximum green vegetation fraction. To provide environmental and socio-economic similarity between the study regions in China and Kazakhstan, we ensured that each variable's range overlapped for both countries. The measurement units, data sources, and range of variables are shown in Table 1. The distribution of variables within the study area as well as their density plots for both countries are presented in the Supplementary material (Figs. S1-S10). The only variable that was significantly higher for all the Chinese prefectures than for the Kazakhstan districts was population density, so we removed this variable from the further analysis. To avoid the multicollinearity of the model, we checked all the variables for correlation using a Pearson test with a threshold of $r_s = 0.7$.

<Table 1 about here>

The GLNB model was fitted to the China data by the backward stepwise removal of the insignificant explanatory variables as evaluated by the significance p-value (p[?]0.05). The overall model significance was judged based on Akaike's Information Criterion (AIC) and a pseudo R^2, indicating a proportion of the response variables' variance could be explained by regression.

The performance of the obtained model was tested by predicting for the Chinese study region and comparing the observed and predicted number of PPR outbreaks. The regression residuals were tested for spatial autocorrelation using Moran's I test (Mitchell, 2005). Moran's Index close to zero with a high p-value indicates that the observed residuals' distribution is likely produced by a random spatial process and no clustering patterns are detected.

Further, the successful model was used to predict the expected number of outbreaks for the model region of Kazakhstan. To visualize spatial clusters of districts that were most susceptible to the spread of PPR, Hot Spot Analysis using Getis-Ord Gi* statistics was performed on the predicted values to find aggregations of districts with statistically significantly high predicted numbers of outbreaks at 90%, 95%, and 99% confidence levels (Getis and Ord, 1992; Mitchel, 2005).

Data sources

The data on the PPR outbreaks in China for the period 2007 to 2020 (as of 30.08.2020) were obtained from the FAO EMPRES-I database (*http://empres-i.fao.org/eipws3g/*). During this period, 289 PPR outbreaks were registered in China, of which 273 fell within the prefectures chosen for the analysis (Fig. 2). For 231 (85%) of these outbreaks, the OIE is indicated as a source of data, while the remaining 15% are attributed to "national authorities". Of these outbreaks, the vast majority (245; 90%) were recorded in 2014. Within each outbreak, a number of infected animals ranged between one and 3290 with a mean of 152. According to the data available, a mean prevalence was 0.49±0.31 (defined as the proportion of infected animals in the total number of susceptible within each outbreak). In terms of small ruminants' population, China holds a leading place in the world having more than 372 million head (FAOSTAT, 2021) that provides an average density of 0 to 611 (mean 62) head/km^2.

Detailed data on the distribution of small ruminants in Kazakhstan were obtained during a nationwide livestock survey undertaken by the research team members from 2018 to 2019 (Schettino & Abdrakhmanov, 2021). This survey included a series of expeditionary trips coordinated with regional veterinary authorities. During this survey, complete information was collected about livestock farms in the RK, including geographical coordinates and the population, which allowed the livestock population at any required level of spatial resolution to be mapped. A total of 2,478 small ruminant holdings (farms) were georeferenced with 18 to 167,918 (mean 8,988) animals. The total population of small ruminants in the RK thus adds up to 22,271,628 head, providing a district-level density of between zero and 81 (mean 7) head/km^2. The density of the small ruminant population at the district level along with the locations of the farms are presented in Figure 1.

Software

The spatial data processing and visualization were conducted using ArcMap Desktop 10.8.1 geographical information system with Spatial Analyst (Esri, USA) extension. The regression was fitted in an R software environment (R Core Team, 2020) with MASS package (Venables and Ripley, 2002), while the correlation analysis and some of the data processing were conducted using Microsoft Office Excel (Redmonds, WA, USA).

Results and discussion

Variables selection and fitting the regression model

Independent variable correlation analysis demonstrated a significant correlation between only two variables: temperature and precipitation ($r = 0.81$, $p < 0.05$). Both variables, which were further independently tested in the model, showed no significance and were thus excluded. Fitting the Generalized Linear Negative Binomial regression revealed the best combination of six independent variables that demonstrated significance at $p < 0.05$ and provided the lowest AIC: road length, altitude, density of small ruminants, MGVF, density of cattle, and the Engel coefficient. The prediction for the Chinese study region using the obtained model returned a satisfactory fit with R^2 of 0.69 (Fig. 3).

Figure 3. Observed vs. Predicted PPR outbreaks number as per the model fit to the training prefectures in China

Testing the residuals using Moran's I global autocorrelation tool returned a Moran's Index of 0.038 (p-value>0.1), which suggests the absence of residual spatial clustering and thus allowing a fairly good fit of the model.

Table 2 shows the regression model metrics. For each coefficient, a standardized value is indicated, which allows a direct comparison between the relative contribution of each variable on the same scale.

<Table 2 about here>

Analysis of the obtained coefficients allows conclusions to be made about the largest contribution of the Engel coefficient that demonstrated a negative relation with the dependent variable, so that districts with less dense road networks per area and population were found to be more vulnerable to the spread of PPR, which can obviously be explained by the higher proportion of pastoral land in these districts. The second important predictor was the maximum green vegetation fraction to be positively associated with the number of PPR outbreaks. This variable may be also related to the availability of pasturing lands and greenery, thus providing food resources for small ruminants. The density of small ruminants was also among those contributory factors that demonstrated a positive relation with PPR, which may naturally be thought of as an indicator of the contact rate between herds. The road length showed a positive influence on the number of outbreaks, which may be seen as a proxy of the regional geographic area. A positive association of high altitudes with increased PPR numbers may be related to poorer biosecurity in remote mountainous pastures. The least important but still statistically significant predictor was cattle density, which is negatively associated with the number of PPR outbreaks. According to data in the literature, cattle may demonstrate seropositivity to PPR, thus presenting a potential disease transmission link (Lembo et al., 2013). Additionally, cattle density in China was found to be low but positively correlated with the density of small ruminants ($r = 0.43$), thus providing a natural idea of a similarly positive effect on PPR outbreaks. A possible hypothesis explaining the observed contradictory dependency comprises better surveillance and biosecurity practices in those regions with a high density of cattle, as cattle are a more resource-demanding species than small ruminants. Thus, the presence of cattle in an agricultural area may suggest better organization of livestock maintenance, thus providing a better defense against potential diseases spread.

Extrapolation of the model to Kazakhstan districts

Using the obtained coefficients (Table 2), the GLNB model was applied to the entire study area of Kazakhstan. Though the explanatory variables demonstrate different density distributions (Fig. S1, S3, S5, S9, S10, Supplementary material), their ranges for Kazakhstan fall within the ranges for China thus allowing to avoid extrapolation. The resulting predicted distribution of PPR outbreaks is shown in Fig. 4. In general, the model suggests overall lower suitability to the spread of PPR in Kazakhstan and demonstrates a heterogenous distribution of predicted PPR outbreaks within the country. Hot Spot analysis allowed three clusters of districts with increased predicted PPR outbreaks in the southern part of Kazakhstan to be isolated (Turkistan oblast and parts of Zhambyl oblast), the north-east part (eastern districts of East Kazakhstan oblast), and the north-west part (western districts of West Kazakhstan oblast) (Fig. 5).

These areas are characterized by a higher density of small ruminants (Fig. 1). In particular, Turkistan and Zhambyl oblasts are historically leading areas in terms of small ruminant breeding. In these areas, there is also a high probability that the disease is being imported from the border regions of Turkmenistan, Kyrgyzstan, Uzbekistan, and China, which feature high density of small ruminants and demonstrated sporadic outbreaks in the past (Yapici et al., 2014; Fine et al., 2020).

Figure 4. Predicted PPR outbreaks' distribution in RK

Figure 5. Clusters of high-risk districts with regard to the PPR spread in Kazakhstan

Model limitations

The constructed model demonstrates a satisfactory ability to explain the variations in the input data, which can be partly explained by the need to extrapolate the dependencies obtained for another country to the territory of Kazakhstan, which was determined by the absence of PPR outbreaks in the RK. The geographical and socio-economic risk factors used in the model are the most general indicators and, perhaps, not exhaustive for explaining the observed patterns of the epizootic situation in China. Since the PPR spread is to lesser extent influenced by environmental factors, the registration of outbreaks mainly depends on the virus transmission on transport links, as well as interstage and interfarm contacts, herd management practices, social and cultural practices (Ruget et al., 2020), which could only be introduced into the model indirectly through the geographical factors used. Other important factors that may contribute into the observed spread of PPR in China include animal movements data and detailed information of farms' distribution, which were both not available to authors. Another model limitation is a potential incompleteness of data on PPR outbreaks in China due to the possible underreporting of PPR from less populated prefectures in central and western parts of the country.

It should also be noted that the information on the small ruminant population distribution used for modeling is the most accurate and relevant for the Republic of Kazakhstan, as it was obtained by the direct collection of the georeferenced data from 2018 to 2019, while for China we used modelled data obtained by the dasymetric mapping based on the 2010 national survey results.

In general, it can be noted that the created model demonstrates a reasonable distribution of PPR spread risks across the RK districts, which would be expected based on the information on the density of small ruminant populations and the intensity of economic links, and can thus be used by the national veterinary authorities as scientific support for the national strategy for PPR prevention. The development of a more accurate risk assessment study, as well as assessing the ways the disease is possibly being imported, requires a more comprehensive model to be built and more factors to be taken into account, both landscape and socio-economic (in particular, building a network of animal movements requires movement data that are not currently collected in the RK on a regular basis), as well as knowledge of the current epizootic situation and the results of monitoring studies on PPR in the countries bordering the Republic of Kazakhstan.

Conclusion

Our study presents a first ever attempt to assess the risks of the spread of Peste des petits ruminants in the Republic of Kazakhstan based on some of the most general socio-economic and landscape indicators. The analysis that was performed by transferring a regression model trained on PPR outbreaks in China demonstrated a greater vulnerability of the Kazakhstan districts along the north-western, north-eastern, and southern borders to the spread of PPR in the event of its introduction, which corresponds to logical expectations based on the greater density of small ruminant and of socio-economic links. This study also introduced the newly created nationwide database of small ruminant population distributions, which may also be used in veterinary risk assessment studies.

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Conflict of interests

The authors declare no conflicts of interests with regard to this study.

Ethics statement

The authors confirm that the ethical policies of the journal, as noted on the journal's author guidelines page, have been adhered to. No ethical approval was required as this article does not include any research on live animals or biological samples.

Data Availability Statement

The data on the small ruminant population in Kazakhstan that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or commercial restrictions.

Authors' contribution

SKA – study conceptualization and design, project management, writing, and reviewing; YYM, GNY, SNB, AN, AAA – data collection and analysis; AAS – grant acquisition; AP – data analysis, reviewing; FIK – data analysis, visualization, writing, and editing. All the authors have read and agreed to the published version of the manuscript.

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List of tables

Table 1. Candidate explanatory variables, their ranges and data sources

Variable	**Measurement units**	**Data sources**	**Range for Kazakhstan**	**Range for China**
Road length	km	Esri Data and Maps: *https://www.arcgis.com/home/item.html?id=83535020ce154bd5a498957c159e*	0 - 642	0 – 2667
Road density	km^{-1}	Esri Data and Maps: *https://www.arcgis.com/home/item.html?id=83535020ce154bd5a498957c159e*	0 – 0.06	0 – 0.255
Small ruminants density	head/km^2	For China: FAO Gridded Livestock of the World (Robinson et al., 2010) *http://www.fao.org/geonetwork/srv/en/main.home* For Kazakhstan: national survey data described below	0 - 81	0 – 611
Cattle density	head/km^2	FAO Gridded Livestock of the World (Robinson et al., 2010) *http://www.fao.org/geonetwork/srv/en/main.home*	0.08 – 21.8	0 – 337
Population density	person/km^2	Gridded Population of the World (GPW), v4 (Center for International Earth Science Information Network, 2018) *https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-count-rev11/data-download*	0.34 - 247	5.05 – 6492

Variable	Measurement units	Data sources	Range for Kazakhstan	Range for China
Elevation	m	USGS Earth Resources Observation and Science (EROS) Center (Danielson and Gesch, 2011): *https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-global-multi-resolution-terrain-elevation?qt-science_center_-objects=0#qt-science_center_-objects*	-28 - 2260	0 – 2197
Annual mean temperature	°C	WorldClim 2 (Fick and Hijmans, 2017) *https://worldclim.org/*	-1.4 – 15.6	-4.3 – 25.0
Annual precipitation	mm	WorldClim 2 (Fick and Hijmans, 2017) *https://worldclim.org/*	117 - 701	40 – 2055
Maximum green vegetation fraction (MGVF)	proportion	Broxton et al., 2014; *https://archive.usgs.gov/archive/sites/landcover.usgs.gov/green_-veg.html*	14 - 100	0 – 100
Engel coefficient	person^{-2}	Calculated from other data	0 – 0.38	0.25

Table 2. Generalized Linear Negative Binomial model metrics

Variable	Coefficient	Standardized Coefficient	Standard Error	z value	Significance p-val
Intercept	-1.895e+00		7.205e-01	-2.630	0.00854
Road length	6.153e-04	0.144	1.197e-04	5.139	2.77e-07
Altitude	5.513e-04	0.198	9.527e-05	5.787	7.15e-09
Small ruminants density	4.345e-03	0.255	7.700e-04	5.643	1.67e-08
MGVF	2.331e-02	0.270	7.309e-03	3.189	0.00143
Cattle density	-5.861e-03	-0.118	2.842e-03	-2.062	0.03917
Engel coefficient	-1.377e+02	-3.265	2.686e+01	-5.128	2.93e-07

Z value indicates a ratio of the model coefficient to its standard error. Significance p-value presents a probability that a particular z value statistic is as extreme as, or more so, than what has been observed under the null hypothesis of the coefficient equal to zero**List of figures****Fig. 1.** Republic of Kazakhstan: first- and second-level administrative divisions, small ruminants' population density and location of small ruminants' farms**Fig. 2.** The study region (Republic of Kazakhstan and People's Republic of China) and distribution of Peste des petits ruminants (PPR) outbreaks in China, 2007 – 2020. Data source: FAO EMPRES-i.**Fig. 3.** Observed vs. Predicted PPR outbreaks number as per the model fit to the training prefectures in China**Fig. 4.** Predicted PPR outbreaks' distribution in RK**Fig. 5.** Clusters of high-risk districts with regard to the PPR spread in Kazakhstan

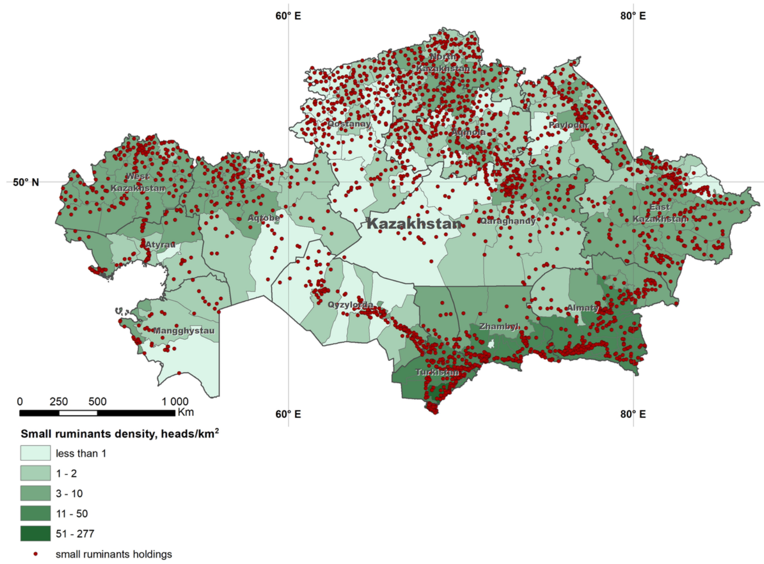


Fig. 1

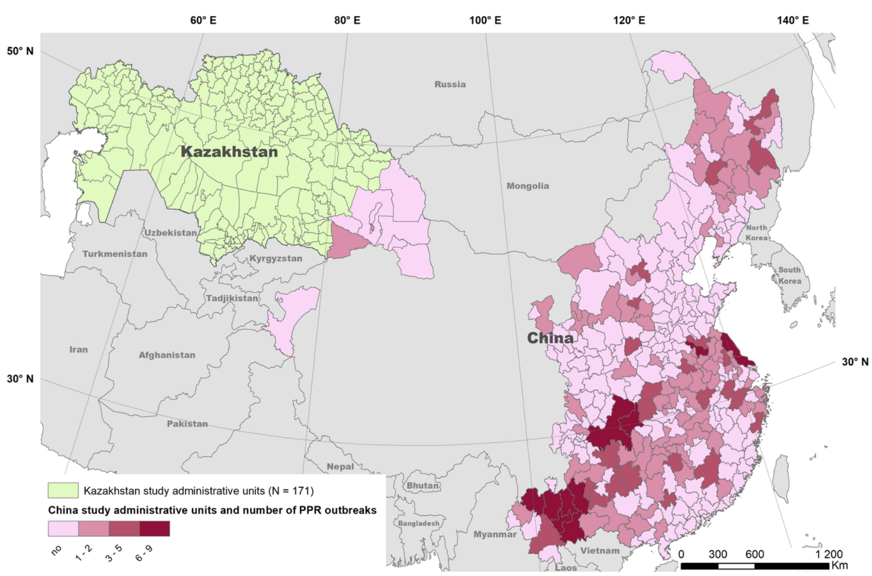


Fig. 2

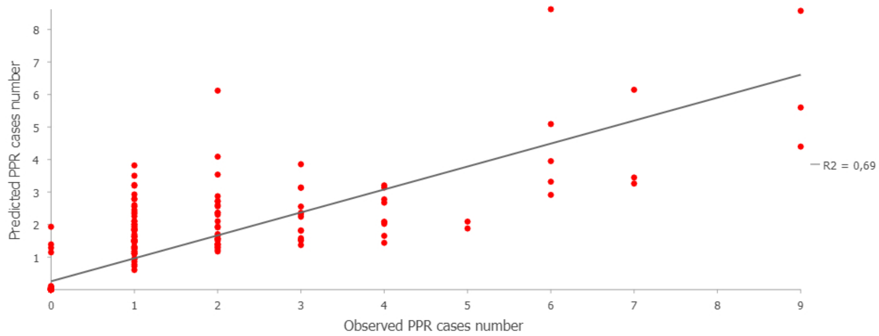

Predicted PPR cases number
Observed PPR cases number
R2 = 0,69

Fig. 3

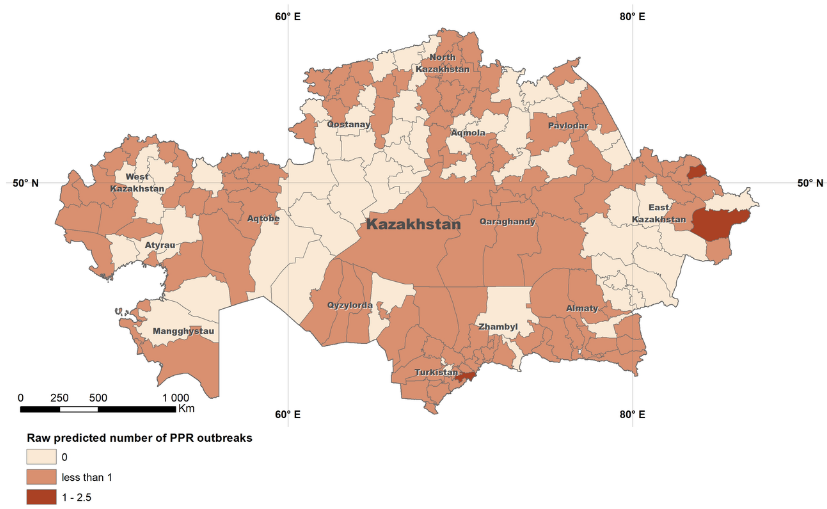

60° E
80° E
50° N
North Kazakhstan
Qostanay
Aqmola
Pavlodar
West Kazakhstan
Aqtobe
Kazakhstan
Qaraghandy
East Kazakhstan
Atyrau
Qyzylorda
Almaty
Zhambyl
Mangghystau
Turkistan
0 250 500 1 000 Km
Raw predicted number of PPR outbreaks
0
less than 1
1 - 2.5

Fig. 4

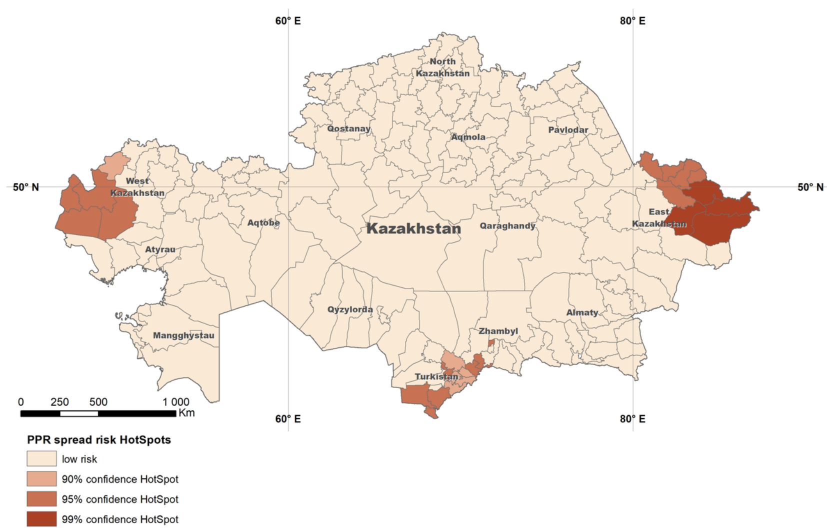
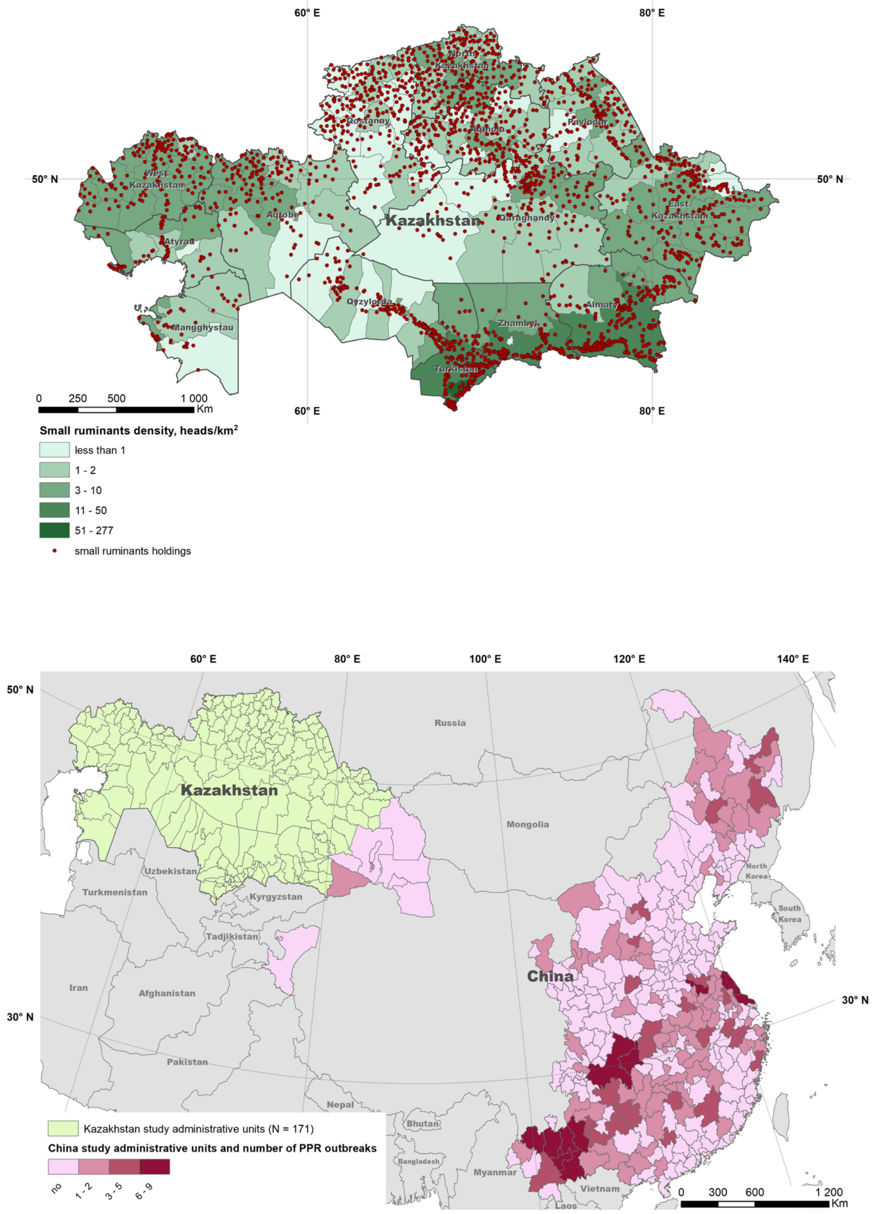
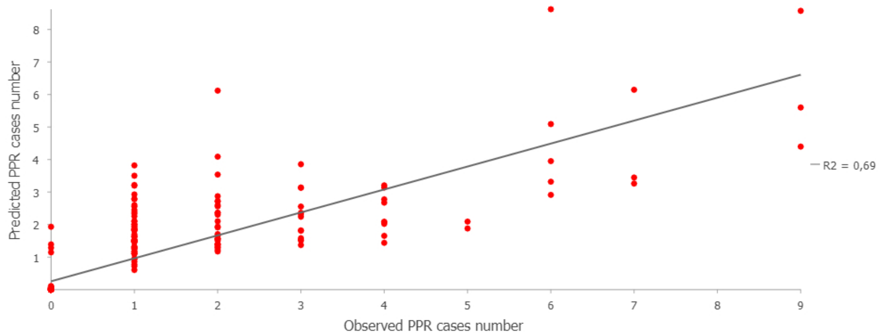

60° E
80° E
50° N
North Kazakhstan
Qostanay
Aqmola
Pavlodar
West Kazakhstan
Aqtobe
Kazakhstan
Qaraghandy
East Kazakhstan
Atyrau
Qyzylorda
Almaty
Zhambyl
Mangghystau
Turkistan
0 250 500 1 000 Km
PPR spread risk HotSpots
low risk
90% confidence HotSpot
95% confidence HotSpot
99% confidence HotSpot

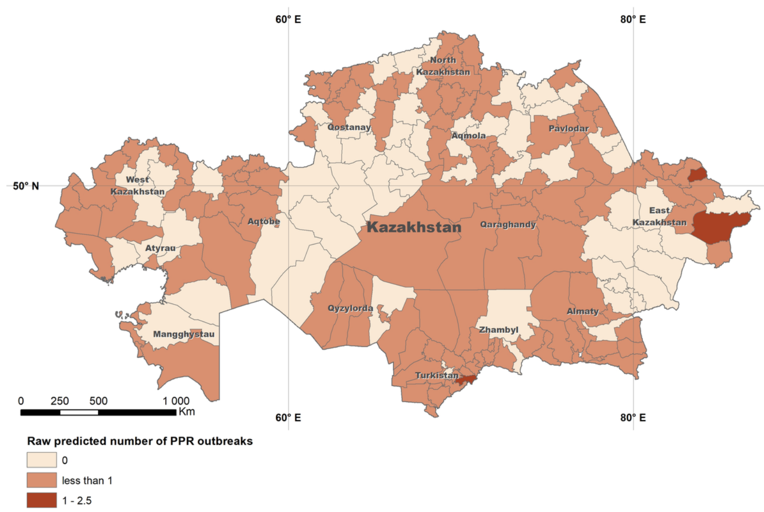
Fig.5



60° E
80° E
50° N
50° N
West Kazakhstan
Aqtobe
Atyrau
Mangghystau
Qostanay
Pavlodar
Kazakhstan
Qaraghandy
East Kazakhstan
Qyzylorda
Almaty
Zhambyl
Turkistan
0 250 500 1 000 Km
Small ruminants density, heads/km²
less than 1
1 - 2
3 - 10
11 - 50
51 - 277
small ruminants holdings
60° E
80° E
100° E
120° E
140° E
50° N
30° N
30° N
Russia
Kazakhstan
Mongolia
Uzbekistan
Turkmenistan
Kyrgyzstan
Tadjikistan
Iran
Afghanistan
Pakistan
Nepal
Bhutan
Bangladesh
Myanmar
Vietnam
Laos
China
North Korea
South Korea
0 300 600 1 200 Km
Kazakhstan study administrative units (N = 171)
China study administrative units and number of PPR outbreaks
no
1 - 2
3 - 5
6 - 9



Predicted PPR cases number
Observed PPR cases number
R2 = 0,69



60° E
80° E
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North Kazakhstan
Qostanay
Aqmola
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Kazakhstan
Qaraghandy
East Kazakhstan
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Zhambyl
Mangghystau
Turkistan
0 250 500 1 000 Km
Raw predicted number of PPR outbreaks
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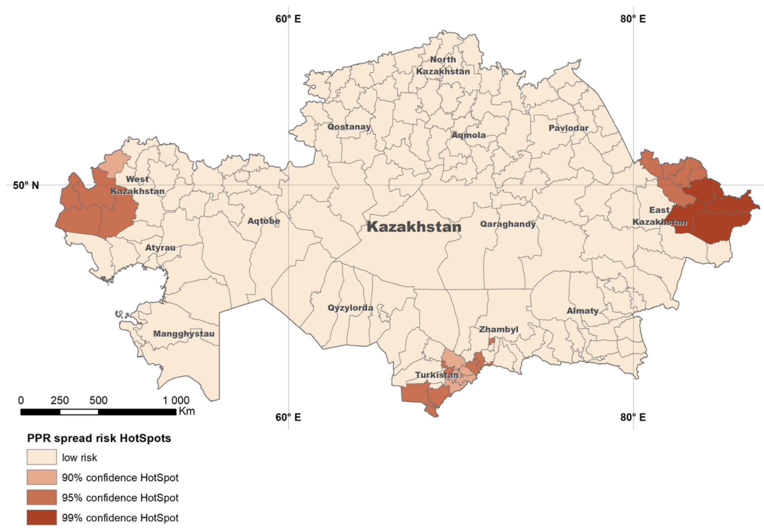

60° E
80° E
50° N
North Kazakhstan
Qostanay
Aqmola
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West Kazakhstan
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Kazakhstan
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East Kazakhstan
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Qyzylorda
Almaty
Zhambyl
Mangghystau
Turkistan
0 250 500 1 000 Km
PPR spread risk HotSpots
low risk
90% confidence HotSpot
95% confidence HotSpot
99% confidence HotSpot