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ZONING OF THE REPUBLIC OF KAZAKHSTAN AS TO THE RISK OF NATURAL FOCAL DISEASES IN ANIMALS: THE CASE OF RABIES AND ANTHRAX

ABSTRACT. Rabies and anthrax, being natural focal diseases, are characterized by the ability to persist in areas with a certain combination of environmental factors without human intervention. These infections annually cause sporadic outbreaks in domestic, livestock and wild animals in the Republic of Kazakhstan (RK) receiving close attention of the veterinary service. In particular, targeted mass vaccination and surveillance are conducted, which requires zoning of the country according to the exposure to the diseases.

This paper presents a zoning approach based on the estimation of suitability to the study diseases using the Environmental Niche Modelling method. Retrospective data on animal rabies outbreaks in the RK for 2003-2014, as well as data on anthrax burial sites for 1933-2014 were used. The following environmental factors were treated as potential explanatory variables: 1) a set of climate data derived variables BIOCLIM; 2) altitude above the sea level; 3) land cover type; 4) the maximum green vegetation fraction and 5) soil type.

The modelling outcomes for both diseases indicate elevated risks along the northern and southeastern borders of the RK that not only follows the distribution of historic disease cases, but also accounts for potentially suitable environmental conditions. To comply with the requirements of the veterinary service, gridded risk maps were converted into categorical maps by averaging risk values within municipal districts and ranking according to four categories: low, medium, high, and very high.

The maps obtained may be used as recommendations to the veterinary service as a basis for developing region-specific anti-epizootic measures.

KEY WORDS: Anthrax, rabies, zoning, Kazakhstan, suitability modelling, Maxent

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INTRODUCTION

The prevention and elimination of zoonotic infections remains a priority and responsibility of veterinary science and practice. Rabies and anthrax are among the most significant zoonoses that form the epizootic and epidemic status of many countries and regions of the world, including the Republic of Kazakhstan (RK). The epidemic and epizootic status of these infections is specified according to the level of epidemic danger and the degree of activity of foci in the territory of the RK (Sanzybaev 2003; Antyuganov 2012).

Rabies is a highly dangerous zoonotic disease. This is a viral disease that affects all warm-blooded animals and humans. This disease is characterized by an acute course, signs of polyencephalomyelitis and absolute mortality in the absence of timely treatment, and causes deaths of more than 55 thousand people and more than 1 million animals annually. Today, rabies is registered in 113 countries of the world (Zavodskih 2007; Makarov et al. 2008; Smreczak et al. 2009, 2012; Orłowska et al. 2011; Youla et al. 2014). Direct economic losses from rabies are about 4 billion Euro per year (Nouvellet et al. 2013; Robardet

et al. 2013). Over the recent years, the epizootic situation on rabies in the RK remains tense: the rabies incidence in animals (foxes, raccoon dogs, wolves, cats and cattle) tends to increase by an average of 7 % annually. Up to 700 head of farm animals die annually from rabies in the RK; more than 50% of them are cattle and up to 25% are sheep and goats (Abdrakhmanov et al. 2010).

In most regions of the RK, the epizootic status for rabies is extremely difficult: the incidence among various animal species has increased over the last decade; the disease also causes fatalities in humans (Bersagurov 2002; Zholshorinov 2004). Ongoing measures have failed to limit the spread of the rabies infection and completely eliminate the disease in the RK. This fact is associated with many factors and, in particular, the presence of natural foci of infection (Domskey 2002; Chubirko 2003; Dudnikov 2003). The main measures to control the rabies situation in the RK include: 1) oral vaccination of wild animals in epizootic outbreaks and in areas of potential infection spread; 2) forced and prophylactic vaccination of susceptible productive and domestic preying animals, the latter as a necessary measure of urban control of the rabies spread

among people. Moreover, strict registration and control of the number of domestic and stray preying animals and outreach activities among the population have been implemented.

Anthrax may be considered “old” and well-studied disease, but the problems associated with its prevention in animals and humans are still unresolved. This is due both to epidemiological characteristics of the disease and to the ecology of the pathogen itself. Every year, from 2 000 to 20 000 cases of anthrax are registered in the world. The disease is widespread in many countries in Africa, Asia, South and Central America, the Middle East and the Caribbean (Adamovich and Nikonov 1970; Aikembayev et al. 2010).

Kazakhstan historically belongs to the category of anthrax endemic countries. The system of anti-anthrax measures presently used in the veterinary medicine of the RK has enabled reducing the intensity of the epizootic situation. However, the risk of new livestock animals becoming infected with anthrax in historically affected areas has been maintained for decades.

Maintaining the epizootological and epidemiological danger in the country is related to the presence of a large number of persistent anthrax locations, which comprises numerous burials of animal corpses fallen from anthrax (Lukhnova et al. 2013; Abdrakhmanov et al. 2014).

As of December 31, 2014, there are 4 058 historic anthrax foci in the republic since 1933, of which 1 800 sites have been registered and certified as permanent anthrax locations.

Against the background of geographically distributed epidemiological risk factors, the sporadic outbreaks in both humans and animals are still registered. As such, eight anthrax cases in livestock animals have been reported 2015–2019 in different regions of the country (FAO EMPRES-i 2019).

The wide spread of animal anthrax and rabies with the formation of favorable prerequisites for new epizootic complications drives the need to improve the measures of epizootological supervision while preventing these zoonoses in the RK.

Research and applied developments provide tools that are both relevant and required for ensuring the country's biological safety regarding the study infections. These tools allow the visualization, zoning, mathematical modelling, and predicting the risk of re-emerging outbreaks of the diseases. Among the geography-based methods, the most informative is zoning, i.e. categorizing of the country in accordance with the intensity of the epizootic situation and the risk of re-occurrence of the disease. Zoning is of great practical importance and allows focused attention of regional veterinary services to the territories (regions, districts, settlements), which have the highest level of zoonotic occurrence and the greatest potential for recurrent outbreaks, based on a combination of favorable landscape-climatic factors coupled with the presence of historically registered foci of diseases (Norström 2001).

This paper was initiated to generalize the methodology of zoning of the RK according to the degree of risk of rabies and anthrax outbreaks (Abdrakhmanov et al. 2016, 2017). Given the natural focal nature of both studied diseases, the zoning was carried out using the mathematical-geographic method for modelling environmental niches (ENM) with optimization by the principle of maximum entropy (MaxEnt). Databases on historic outbreaks of rabies and anthrax in the RK were used as input presence data, while the set of ecological and climatic variables BIOCLIM along with some geographical parameters was used as explanatory factors.

MATERIALS AND METHODS

Rabies data

Data on rabies outbreaks in the RK for 2003–2014 were provided by the veterinary service of the administrative

territories (region, district) and collected during field visits. The database consists of 762 rabies cases among various animals: cats, dogs, cows, foxes, camels, sheep, horses and wolves.

For the purposes of modelling, all animal species are divided into three categories: domestic, wild and farm (livestock) animals. Cats and dogs are classified as domestic animals; wolves and foxes are wild animals; horses, cows, sheep and camels are farm animals.

For each outbreak of rabies, the following data are available that are relevant for further modelling: geographical coordinates (latitude, longitude); date of the outbreak; the number and species of infected animals; the name of the settlement, district and region. Fig. 1 shows a map of the RK with mapped cases of rabies in three categories of animals.

Anthrax data

Data on anthrax outbreaks in the RK for 1933–2014 were provided by the veterinary service of administrative territories (regions, districts) and collected during field visits. The database includes anthrax outbreaks in farm animals. For each outbreak, the following attributes are indicated: geographical coordinates, diseased species, number of infected animals, and date of the outbreak registration. After exclusion of unreliable data (in particular, with no geographical coordinates or with erroneously indicated coordinates), the database has 4058 anthrax outbreaks, each of which reports from 1 to 851 infected animals. Humans were also infected in a number of outbreaks. The outbreak map is shown in Fig. 2.

It should be noted that in some cases several outbreaks were associated with the same location (settlement), i.e. identified by the same geographic coordinates. This resulted in 1798 unique locations, a lower number than the total number of outbreaks.

All data on outbreaks were provided for the cartographic presentation in the form of shape files. For modelling with MaxEnt data were converted into .csv files.

Climate and landscape data

The following geospatial variables were used:

1. A set of 19 bioclimatic variables BIO1 – BIO19 (hereinafter – BIOCLIM), which are derived from monthly averages of air temperature and precipitation obtained from meteorological stations worldwide (Hijmans et al. 2005). Data are available for download at <http://worldclim.org/version1>. The “current” data set for 1950–2000 was used. The variables are presented in Table 1;
2. Altitude above the sea level (ALT) (USGS 2019);
3. Maximum green vegetation fraction (MGVF), reflecting the presence and intensity of vegetation cover. Annual average data for 2001–2012 are used (Broxton et al. 2019a);
4. Land cover type presented by 17 categories dataset based on IGBP classification (Table 2) (Broxton et al. 2019b);
5. Soil type (SOIL) (Digital Soil Map of the World 2019). This variable was included in the model for anthrax only, since the influence of soil type on the survival of the anthrax pathogen is known, and, therefore, a correlation may be expected between the type of soil in a given area and the presence of anthrax outbreaks (Cherkassky 1999, Hugh-Jones and Blackburn 2009; Mullins et al. 2011). Table 3 summarizes the soil units presented in the RK.

All geospatial variables presented in raster format were corrected to a common resolution of 1x1 km, clipped by the shape of the RK, and converted to ASCII format as required for modelling by the MaxEnt software.

Method of risk identification: a description of the maximum entropy principle

To identify the prevailing tendency of the rabies and anthrax outbreaks in animals in areas with a certain combination of landscape-climatic conditions, the maximum

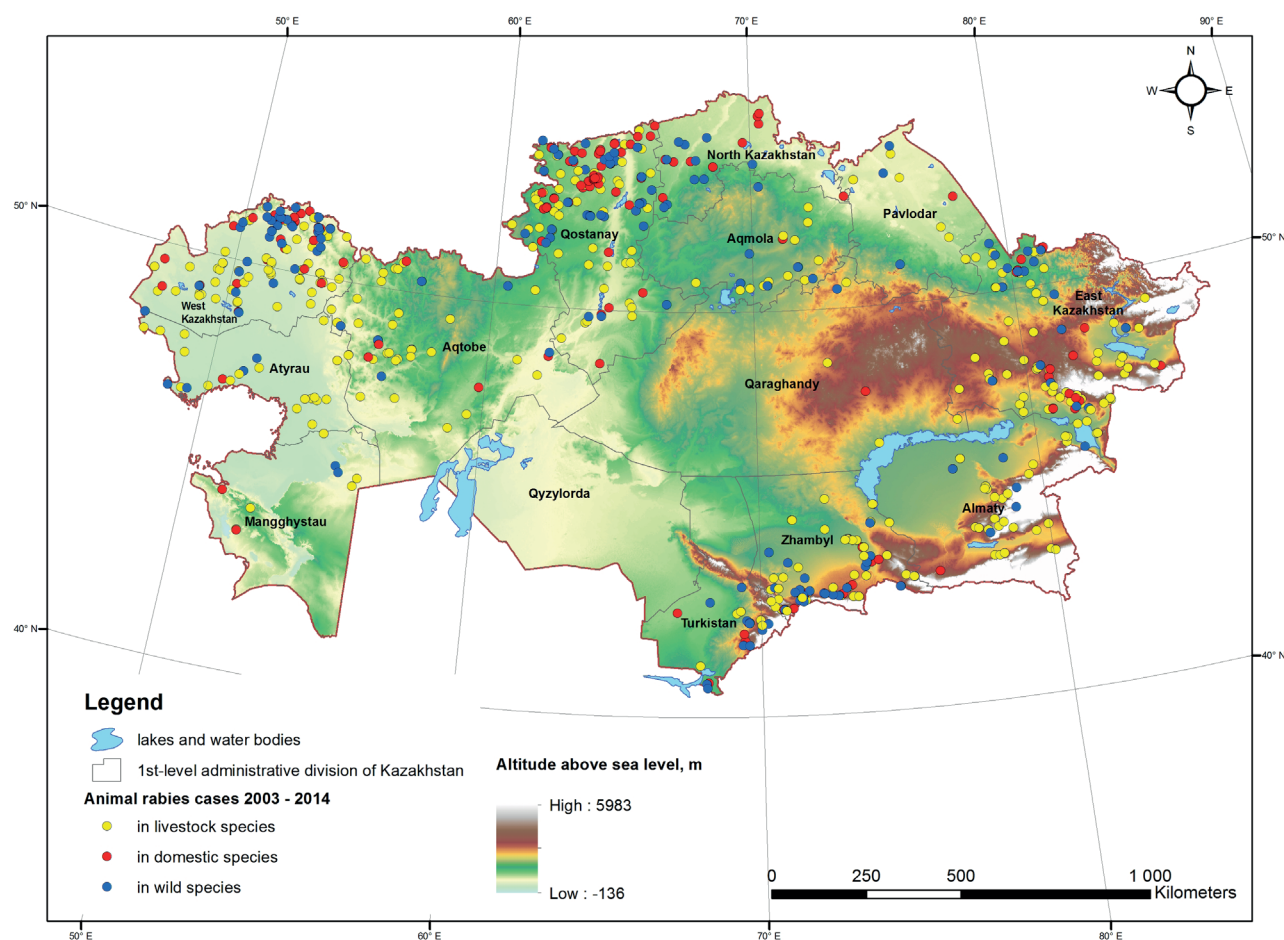


Fig. 1. Physical map of the Republic of Kazakhstan and rabies cases in three categories of animals, 2003-2014

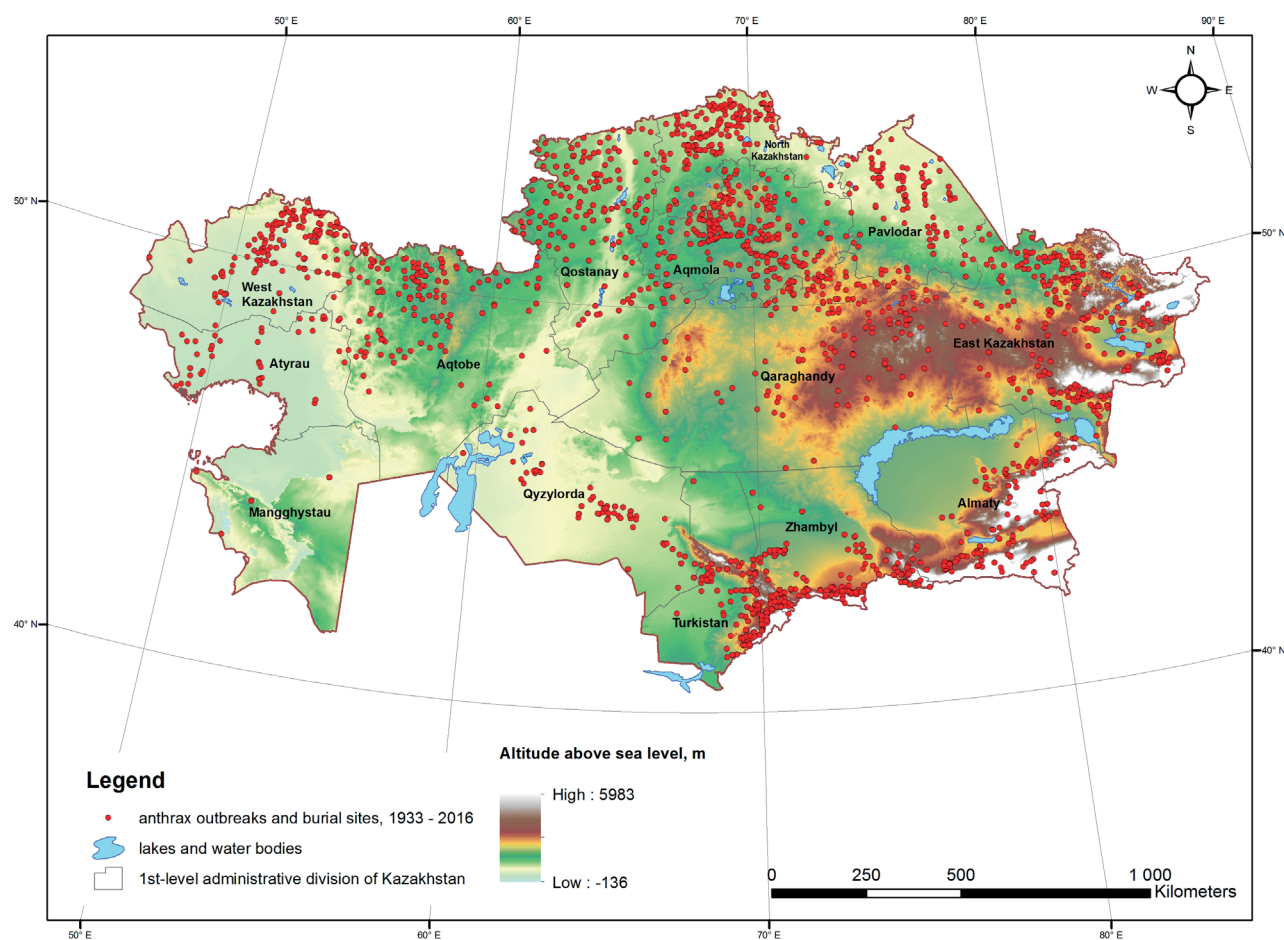


Fig. 2. Physical map of the Republic of Kazakhstan and anthrax burial sites, 1933-2014

Table 1. BIOCLIM variables description

Variable	Description
BIO1	the annual average temperature
BIO2	the average daily temperature
BIO3	isothermal (BIO2/BIO7 * 100)
BIO4	seasonal temperatures (standard deviation * 100)
BIO5	the maximum temperature of the warmest month
BIO6	the minimum temperature of the coldest month
BIO7	the annual temperature range (BIO5 – BIO6)
BIO8	the average temperature of the wettest quarter
BIO9	the average temperature of the driest quarter
BIO10	the average temperature of the warmest quarter
BIO11	the average temperature of the coldest quarter
BIO12	the annual average of precipitation
BIO13	precipitation in the wettest month
BIO14	precipitation of the driest month
BIO15	seasonal rainfall (coefficient of variation)
BIO16	precipitation of the wettest quarter
BIO17	precipitation of the driest quarter
BIO18	precipitation of the warmest quarter
BIO19	precipitation of the coldest quarter

Table 2. Categories of LAND COVER

Category of land cover	Land cover description
0	water
1	evergreen coniferous forests
2	evergreen broad-leaved forests
3	deciduous coniferous forests
4	deciduous broad-leaved forests
5	mixed forests
6	thick bushes
7	rare bushes
8	the wooded savannah
9	savannah
10	meadows
11	permanent wetlands
12	arable land
13	urban and built-up areas
14	mixed arable land and natural vegetation
15	the snow and ice
16	barren lands and wastelands

entropy method was used for modelling (MaxEnt) (Phillips et al. 2004). This method belongs to the class of Environmental Niche Modelling methods that require only “presence data”, i.e. those locations where the studied phenomenon (in our case – outbreaks of diseases) are reliably registered. The method is widely used to model 1) the habitat of a particular species,

as well as 2) potential range of infectious diseases caused by a specific pathogen. In the latter case, the application of the method is based on the assumption that the disease range is determined by the range of the causative pathogen. As explanatory variables, geospatial factors are normally used that describe the distribution of environmental and (sometimes)

Table 3. Soil units presented in the Republic of Kazakhstan

Category key	Name
Bc	Chromic Cambisols
Bk	Calcic Cambisols
Ch	Haplic Chernozems
Ck	Calcic Chernozems
Cl	Luvic Chernozems
Gc	Calcaric Gleysols
Ge	Eutric Gleysols
Gm	Mollic Gleysols
I	Lithosols
Jc	Calcaric Fluvisols
Je	Eutric Fluvisols
Kh	Haplic Kastanozems
Kk	Calcic Kastanozems
Kl	Luvic Kastanozems
Mo	Orthic Greyzems
Oe	Eutric Histosols
Qc	Cambic Arenosols
Sg	Gleyic Solonetz
Sm	Mollic Solonetz
So	Orthic Solonetz
Xh	Haplic Xerosols
Xk	Calcic Xerosols
Xl	Luvic Xerosols
Yh	Haplic Yermosols
Yk	Calcic Yermosols
Yt	Takyric Yermosols
Zg	Gleyic Solonchaks
Zo	Orthic Solonchaks
Zt	Takyric Solonchaks
RK	Rock debris
GL	Glaciers
DS	Dunes/Shifting sand
ST	Salt flats

socio-economic characteristics in the study area. The factors used can presumably contribute to the formation of conditions favorable for the existence of the studied pathogen and the spread of the disease it causes. The essence of the modelling is to select a probability distribution of the pathogen (or disease) presence in the study area, which is the most uniform (i.e., has the maximum information entropy) of all possible distributions, taking into account the observed actual data distribution. The resulting distribution indicates the suitability of each location for the presence of a pathogen (disease) in terms of the combination of environmental factors used.

The Maxent modelling is performed for rabies and anthrax. In rabies, the modelling was carried out separately for three categories of animals: domestic, wild and farm.

The modelling was carried out in 10 replications, and in each replication, the model worked up to 500 iterations to select the most optimal distribution. In each iteration, 75% of all outbreaks were randomly selected for the training of the model (i.e., to identify the desired distribution), and the remaining 25% used for validation and testing of the resulting distribution.

In each iteration, the contribution of each variable to the total distribution was determined by the Jack-knife method. This procedure allows identification of the variables that are most significant in terms of their impact on the probability of outbreaks.

When modelling rabies, to compensate for the possible data bias caused by uneven diagnostics near settlements, the

density grid of the main roads in the RK was used. It follows the assumption that cases of the disease were more likely recorded in close proximity to settlements and roads. To build the road density grid, we used road data available in the dataset Esri Data & Maps (<https://www.esri.com/arcgis-blog/products/product/mapping/esri-data-maps/>). The density grid has been made using the procedure Kernel Density from the software toolkit Spatial Analyst, ArcGIS.

The predictive ability of a MaxEnt model is usually estimated by the area under the ROC curve (AUC value), which indicates the probability that a randomly selected point of presence will be evaluated by the model as "suitable" rather than "unsuitable". It is usually considered that the value $AUC = 0.5$ indicates the absence of predictive ability of the model; $AUC > 0.7$ is considered a good indicator, and $AUC > 0.8$ is an excellent indicator (Araújo and Pearson 2005).

Generalization of risk levels within administrative areas

Upon obtaining risk maps, which are regular grid-based distribution of the probability of the rabies and anthrax outbreaks in the RK, the maps were summarized for zoning at municipal level in accordance with the practice of the veterinary service of the RK. For this end, the risk levels were integrated by municipal districts by determining the average value within each district (the maximum of three values was taken for rabies). Thereafter, the obtained values were ranked in accordance with Table 4 (Abdrakhmanov et al. 2016, 2017). The zoning results are presented the form of risk maps for each disease.

Software

Data geoprocessing and visualization were made using geographic information system ArcGIS version 10.6 (ESRI, USA) with custom add-in for Environmental Niche Modelling related data processing SDM Toolbox (Brown 2014). Maximum entropy modelling was performed using Maxent software (Maxent software... 2019). Additional statistical data processing and file conversion was done using Microsoft Office Excel (Microsoft, USA).

RESULTS

Rabies zoning of the Republic of Kazakhstan

The distribution of the average "suitability" of the RK territory was obtained for each of the categories "farm animals", "domestic animals" and "wild animals", and shown in Fig. 3 (a, b, c respectively).

The final generalized representation of zoning by municipal districts is shown in Fig. 4.

The predictive ability of the model (AUC value) is 0.782 ± 0.031 for the category "farm animals"; 0.859 ± 0.042 for the category "domestic animals" and 0.809 ± 0.045 for the category "wild animals". Thus, the obtained probability distributions demonstrate sufficiently high degree of reliability in description of the distribution of existing rabies cases in the RK, depending on the combination of the chosen environmental factors.

The variables that make the most contribution to the model were defined as those for which the relative importance of the modelling results is not less than 10%. For the category

of "farm animals", the variables BIO19 (precipitation level of the coldest quarter), LANDCOV (land cover type) and BIO1 (average annual temperature) have the most contribution.

For the category of "domestic animals", the variables LANDCOV, ALT (altitude above sea level), BIO12 (annual average precipitation) and BIO19 have the most contribution.

For the category of "wild animals", the variables LANDCOV, BIO19, ALT and BIO12 have the most contribution.

Anthrax zoning of the Republic of Kazakhstan

Upon Maxent modelling, the AUC value is 0.834 ± 0.005 , which can be considered a good indicator of the predictive ability of the model.

The probability distribution of anthrax outbreaks, taking into account the geospatial factors analyzed, is shown as grid-based probability surface constructed in modelling using all variables (Fig. 5).

When processing geospatial variables, the following factors were found to most explain the distribution of anthrax outbreaks: MGVF (maximum green vegetation fraction), BIO12 (average annual precipitation), BIO13 (precipitation of the wettest month), BIO16 (precipitation of the wettest quarter) and SOILS (soil type). The result obtained allows us to confirm the strong dependence of the locations of anthrax outbreaks on climatic factors, in particular on humidity and precipitation (as demonstrated collectively by the variables BIO12, 13 and 16), on the presence and intensity of vegetation (MGVF) and on the type of soil. In the case of moisture and vegetation, an increase in the corresponding factor entails a corresponding increase in the outbreak probability. The most favorable soil types for the occurrence of anthrax are Bc – Chromic Cambisols, Ch – Haplic Chernozems, Ck – Calcic Chernozems, Je – Eutric Fluvisols and Xk – Calcic Xerosols.

Summarizing and ranking of risk levels by area in accordance with Table 4 gives the following pattern of RK zoning by the degree of biological safety regarding anthrax (Fig. 6).

The obtained probability distribution is in good agreement with the results of other authors that have used similar modelling methods (Mullins et al. 2013).

DISCUSSION

The current system of epizootic surveillance needs automation and the use of modern information technologies to improve its main function – deterrence, prevention and elimination of the infectious threat (Anderson and May 1992). Due to this condition, there is a need to perform zoning in order to assign a certain status to the regions of the RK by categories of biological safety with regard to rabies and anthrax.

In this paper, we perform zoning based on modern mathematical-cartographic methods that take into account not only the presence or absence of outbreaks in a particular territory, as it applies normally, but also the exposure of the territory to their occurrence based on a set of ecological and geographic features.

The maximum entropy method is often used to model the habitats of particular species based on 1) exactly known places where their presence was detected and 2) aggregates of explanatory environmental variables within a study area.

Table 4. The ranking of risks

Risk level (suitability)	Risk category
< 10%	Low risk
10 – 25 %	Average risk
25 – 50%	High risk
>50%	Very high risk

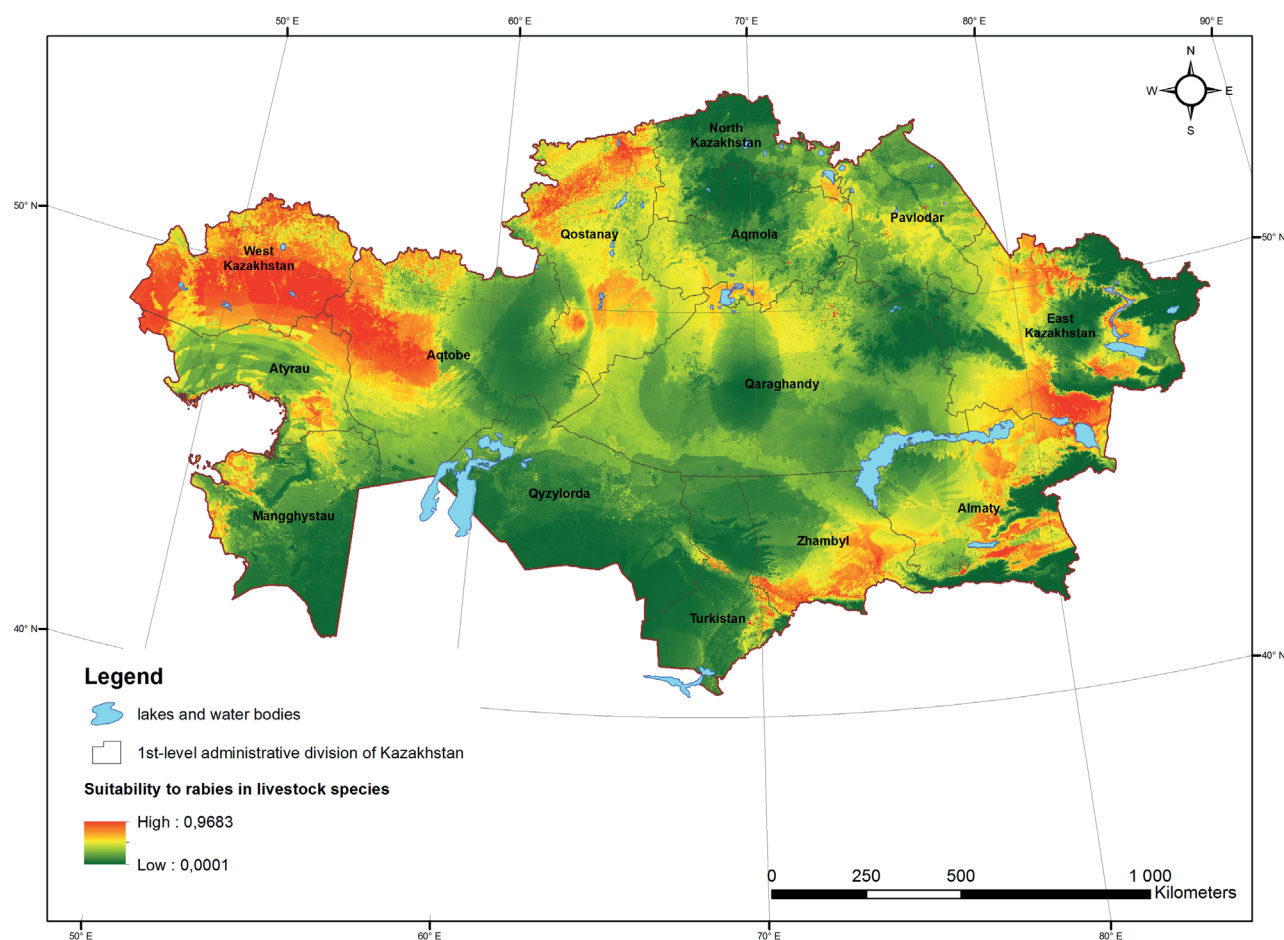


Fig. 3a. Gridded suitability of the RK territory to rabies in farm species

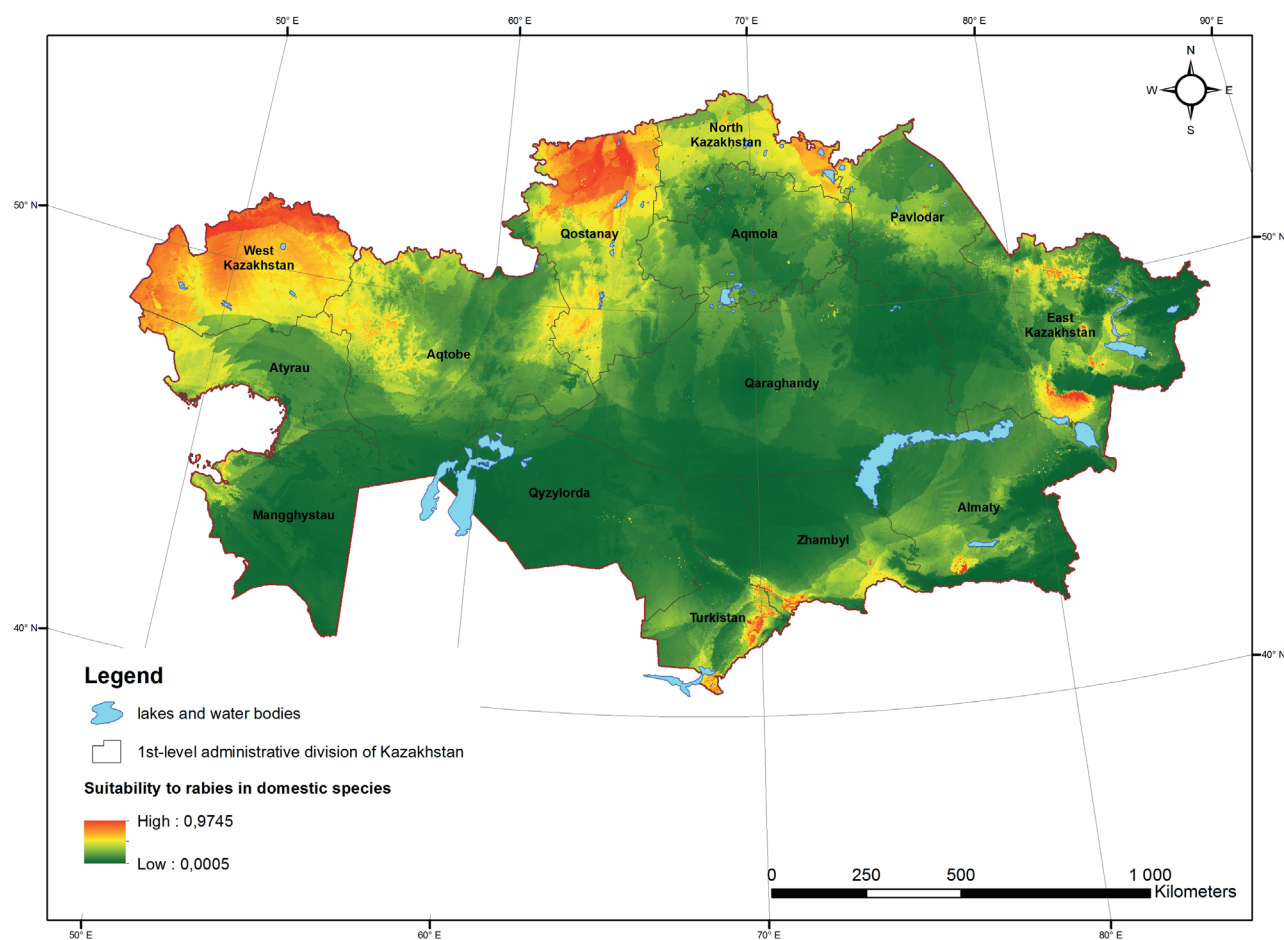


Fig. 3b. Gridded suitability of the RK territory to rabies in domestic species

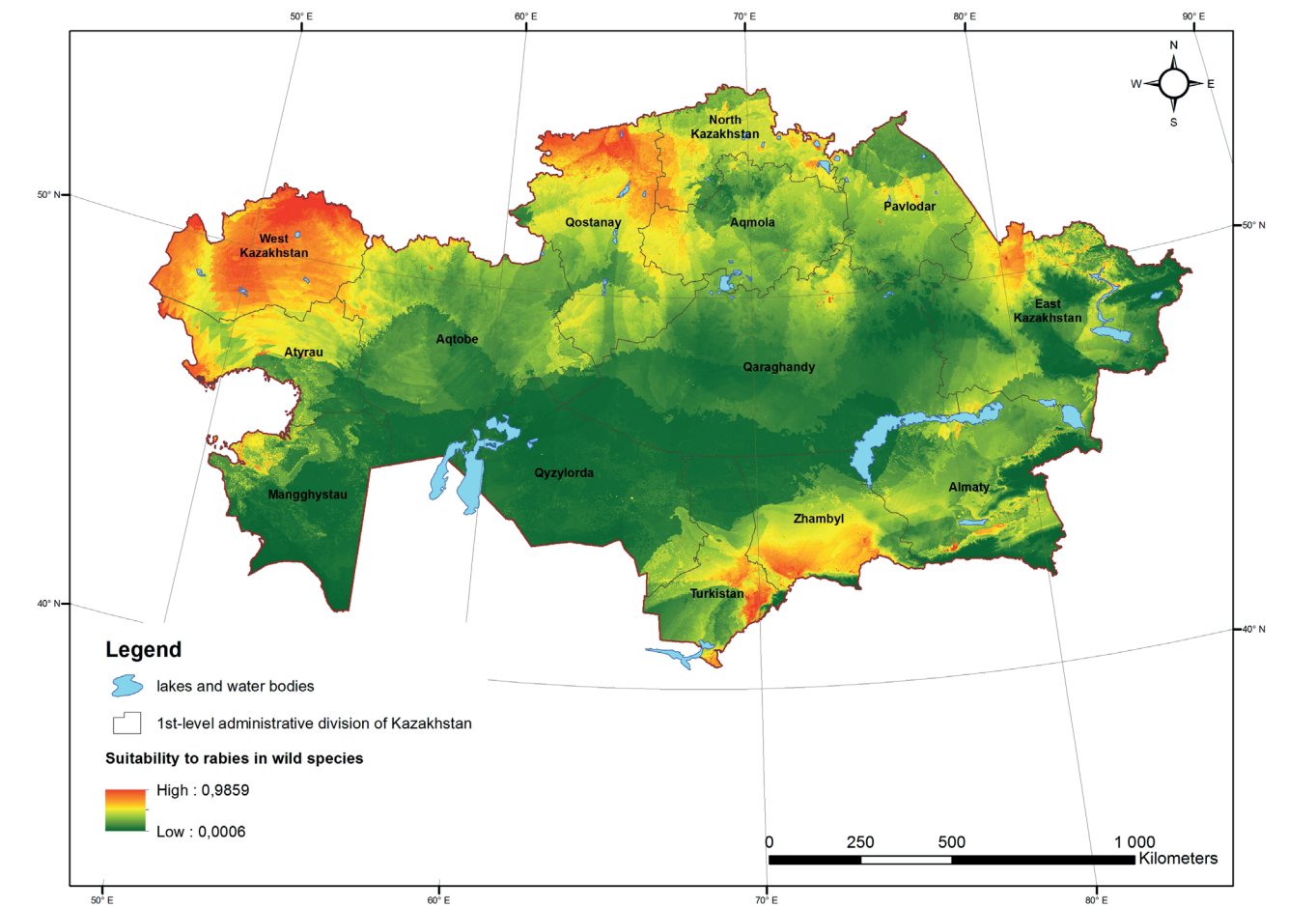


Fig. 3c. Gridded suitability of the RK territory to rabies in wild species

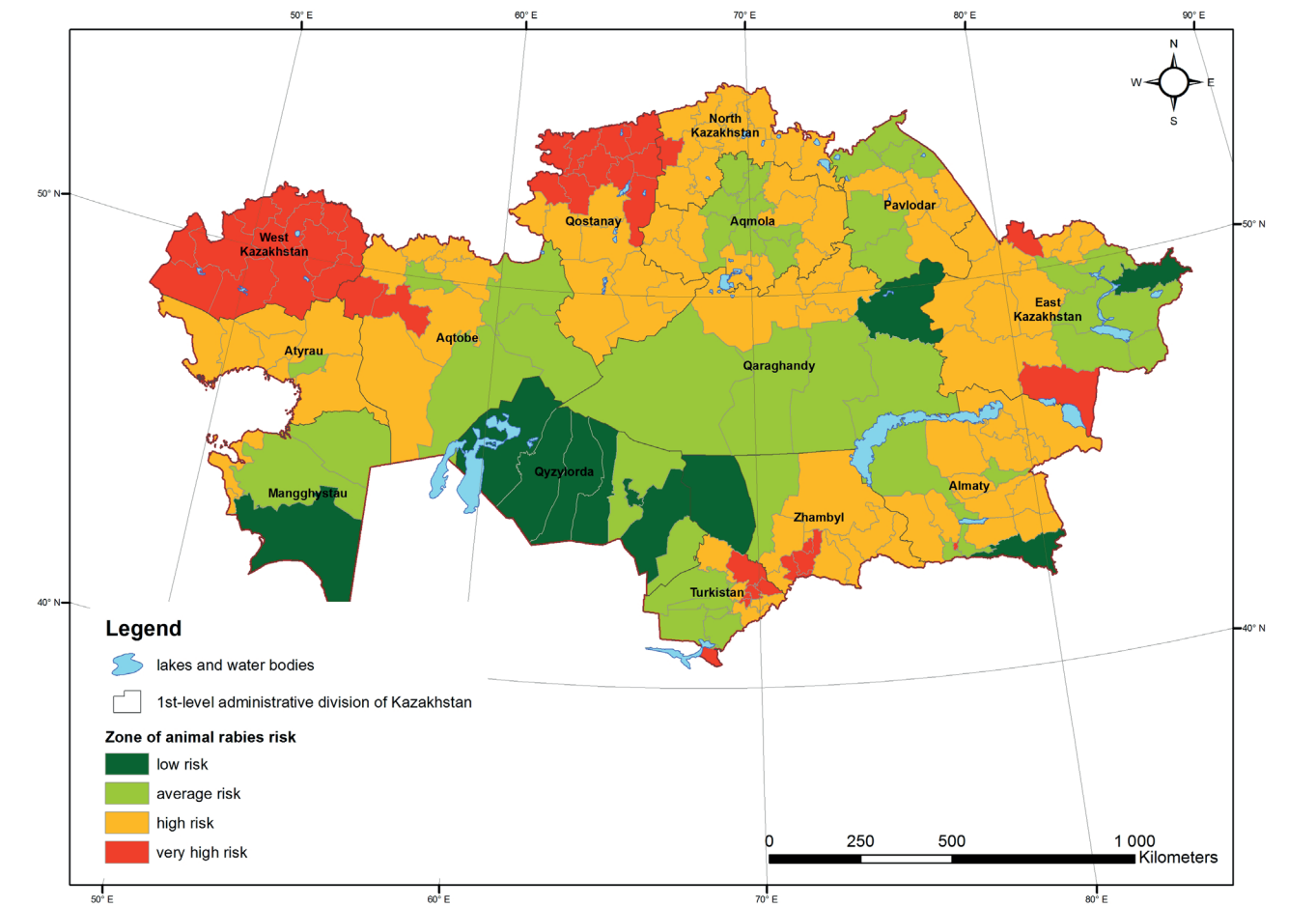


Fig. 4. Integral zoning map of the Republic of Kazakhstan as for risk of rabies in various species

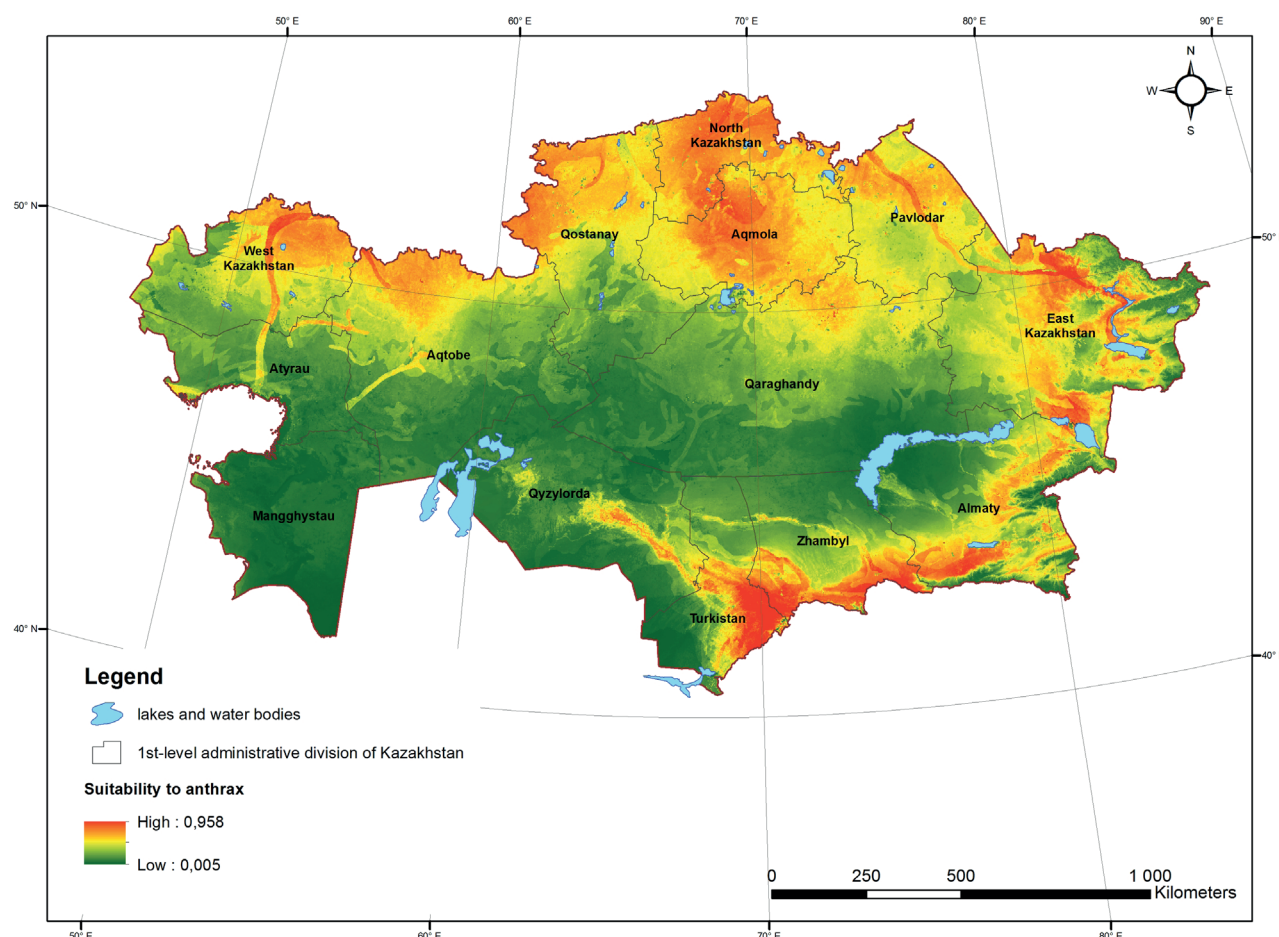


Fig. 5. Gridded distribution of suitability to anthrax in the Republic of Kazakhstan

However, in some studies, the maximum entropy method has been applied to simulate a risk area, in which the occurrence of some disease cases is possible, basing on the previously recorded cases (Stevens and Pfeiffer 2011; Abdrakhmanov et al. 2016).

In our paper, this method is also used to identify areas most at risk of outbreaks of particularly dangerous infectious diseases among animals. Places of registered disease cases are used as "presence locations".

This zoning method is based on the territorial location of the disease and implies the stability of its natural foci, as evidenced by the nature of the diseases, as well as numerous studies. A number of authors used Environmental Niche Modelling methods (Mullins et al. 2011, 2013; Kracalik et al. 2012), which gave similar results with respect to the probability distribution of anthrax outbreaks in the territory of the RK. The method of maximum entropy as used is essentially equivalent to the Poisson regression model, while providing a convenient and illustrative form of presenting the results and evaluating their statistical significance (Renner and Warton 2013).

Different to the studies of other authors, we applied an aggregation of a gridded pattern of the probability distribution by averaging the risk over the second-level administrative units. Such a generalization better fits the traditional practice of the country's veterinary service and gives more visible results in terms of their practical application. That is, the distribution of risk levels by administrative areas allows the country's veterinary service to use its administrative resources more efficiently within each territorial unit, and to make appropriate decisions depending on the current epizootic situation. In the meantime, such a generalization of the risk pattern leads to the loss of more detailed information about the local distribution of risk and specific locations with elevated values. Such information, however, remains available and can be easily displayed.

The key step in the application of the maximum entropy method is the selection of geospatial variables that presumably affect the probability of the disease outbreak being studied. As a rule, the factors under consideration are divided into several main groups depending on the epidemiology of the disease. We identified three main groups of factors: 1) landscape factors; 2) socio-economic factors; 3) climatic factors.

Since rabies and anthrax belong to natural focal diseases, we can assume a strong dependence of the disease cases on a combination of climatic and landscape factors. Moreover, due to the very rapid course of the infection process in infected animals, neither infection tends to spread over long distances but instead remains localized at the site of infection.

The obtained risk maps demonstrate that risks of both studied diseases distributed very similarly to the distribution of population in Kazakhstan. This could have been expected because of predominate tendency of disease diagnostics in close proximity to populated places or other easily accessible locations. In general, districts with medium to high risk can be identified along north, east and south-east borders of the RK. For rabies, very high risk is presented in the most districts of West Kazakhstan region, in Aqtobe and Qostanay regions. These areas do not demonstrate high population density, but provide suitable conditions for livestock breeding, specifically allowing transboundary migration of wild animals that facilitates contacts between livestock and wild species. For anthrax, very high risk is concentrated in high populated districts of Aqmola, North Kazakhstan and Turkistan regions as well as in some other districts providing suitable combination of soils, vegetation cover and amount of precipitation.

As a potential disadvantage of this method, we can mention a possible underestimation of the risk level in certain areas due of its significant variation, which occurs because of the data averaging. Thus, some areas with risk values close to

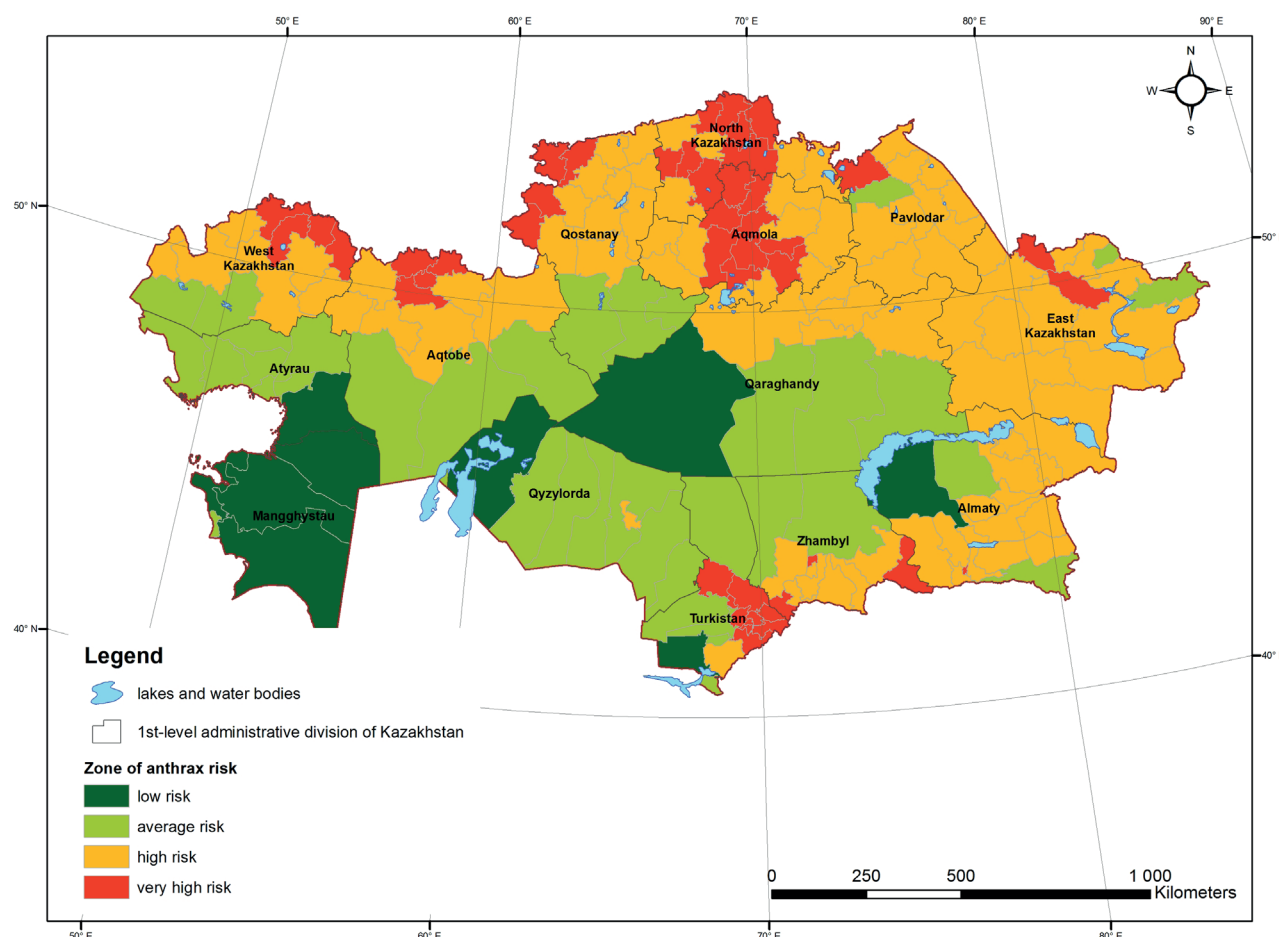


Fig. 6. Integral zoning map of the Republic of Kazakhstan as for risk of anthrax

categories separation may be assigned to a lower risk category. Therefore, for a more detailed epizootological analysis of the territory, it is required to assess the gridded distribution of risk within each administrative unit), also presented in our study.

CONCLUSIONS

The presented study summarizes an approach to veterinary zoning of the country as to the risk of two dangerous zoonotic diseases that is based on the application of Environmental

Niche Modelling method with subsequent averaging risk values within administrative divisions. Such an approach allows not only considering presence or absence of historic disease cases throughout the study area but also accounts for potentially suitable areas, where the disease pathogen may survive based on the specific set of environmental factors. ■

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