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EPIZOOTIC SITUATION AND MODELING OF POTENTIAL NOSOAREALS OF PESTE DES PETITS RUMINANTS, SHEEP AND GOAT POX AND RIFT VALLEY FEVER UP TO 2030

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Abstract

The current global epizootic situation is characterized by a pronounced increase in the tension for a number of special danger viral infections of livestock including sheep and goat diseases. The above diseases include peste des petits ruminants (PPR), sheep and goat pox (SGP) and Rift Valley fever (RVF), the probability of their entering the Russian Federation being rather high. In this report we have pioneered determination of PPR, SGP and/or RVF potential nosoareas varying in the above infections emergence danger levels, both in the Russian Federation and the neighboring countries, based on the monitoring of the global epizootic situation using mathematical extrapolation of regressive models. Also, the natural ecological factor was shown to have the most serious impact on the intensity of an epizootic process. Our work was aimed at evaluation of the spatial-dynamic features and regularities of the global spreading of peste des petits ruminants, sheep & goat pox, and Rift Valley fever, as well as evaluation of the risks of these infections emerging and spread in the Russian Federation and the neighboring countries in the period of 2020 to 2030. We used the statistical data of Food and Agriculture Organization (FAO) and Office International des Epizooties (OIE) reflecting the global epizootic situation for PPR, SGP and RVF in 1984 to 2018, the data on the economic status of sheep and goat husbandry worldwide, and also some information on a range of special danger animal infections from the Federal Service for Veterinary and Phytosanitary Surveillance, and The Veterinary Center of Russia. The epizootological method of the research applied here included calculation of indices of the intensity of an epizootic situation, namely the stationarity index and the incidence index. Also, statistical verification of a relation of the epizootic situation intensity with some natural and socio-economic factors was performed, and the informational impact indicator (III) was calculated. To model and predict the dynamics and the structures of PPR, SGP and/or RVF nosoareas, the calculation of regression & information models was used. The probability of a disease emergence was calculated through spatially dynamic modeling of its incidence in the nosoarea-involved countries in 1984-2018, taking into account the factors of the natural and/or socio-economic background on the stationarity index values within the global nosoarea. According to the summarized data, the largest numbers of PPR- or RVF-affected countries were registered in the African continent in 1984 to 2018. A few more countries affected with SGP were found in Asia. Nevertheless, the numbers of PPR (more than 38 thousand) and SGP (more than 39 thousand) outbreaks recorded in Asia significantly exceeded the respective values as observed in African countries. The autocorrelation analyses revealed 13- to 15-year cyclicity for PPR, 12- to 13-year or 21- to 22-year one for SGP, and 25- to 27-year or 8- to 10-year for RVF infections. In Russia, as many as three potential nozoreas for PPR and/or SGP and two potential nozoareas for RVF were identified which varied in the quantitative indicators of their incidence. Also, natural environment and climatic factors were found to have the greatest influence on the intensity of an epizootic situation. In the period up to 2030, the emergence and spread of SGP and/or PPR is possible throughout the territory of the Russian Federation, the highest probability being predicted in the North Caucasus Federal District (the Republic of Dagestan, the Republic of Ingushetia, Kabardino-Balkaria, the Republic of North Ossetia, Chechnya or Stavropol Territory) and the South Federal District (Krasnodar Territory, the Republic of Adygeya, and the Republic of Crimea). Furthermore, there is a low likelihood of RVF introduction and emergence in the above regions. Among the neighboring countries, Tajikistan, Kyrgyzstan, Kazakhstan, Uzbekistan, Afghanistan, Turkmenistan, Armenia, Georgia, Azerbaijan, Turkey, Iran, Mongolia and China pose the greatest danger for PPR and/or SGP while countries of the African continent, Arabian Peninsula, and the southern region of Asia for RVF. The data obtained indicate the requirement for carrying out a comprehensive monitoring of the epizootic situation for PPR, SGP and RVF worldwide combined with the development of forecasts for these infections and the implementation of a set of preventive antiepizootic measures to ensure sanitary and epizootic welfare of animal husbandry in the Russian Federation.

Keywords: stationarity index, incidence index of outbreaks, Rift Valley fever, epizootic monitoring, intensity of epizootic situation, sheep and goat pox, potential nosoarea, epizootological prediction, spatial-dynamic model, peste des petits ruminants

According to FAO (Food and Agriculture Organization, FAO) and OIE (Office International des Epizooties, OIE) information, in recent years the epizootic situation for some transboundary special danger viral diseases of small ruminants like peste des petits ruminants (PPR), sheep and goat pox (SGP), Rift Valley fever (RVF) in the world remains difficult [1, 2]. The causative agents of these special danger infections can be used for bioterrorism. While PPR and SGP affect mainly sheep, goats and wild artiodactyls, which can be carriers of the infections, Rift Valley fever belongs to zooanthroponoses. Not only the mentioned animals but also cattle, horses, camels, antelopes, monkeys, some other mammals, as well as humans are susceptible to RVF [3, 4; FAO/OIE/WHO. Animal health yearbook 1985-1995 FAO, Rome, 1986-1996] which poses a special threat.

Over the past decade, a marked tendency towards international spread and an increase in the number of epizootic outbreaks has begun to appear on these diseases, which causes significant economic damage to the affected countries, both directly due to the increase in the numbers of diseased animals and their death rates and in connection with the necessary quarantine and other restrictive measures [5].

The causative agents of SGP, PPR and RVF are not identical in their taxonomic affiliations and biological characteristics, their high contagiousness for small ruminants being the common feature. The mortality rates in the primary foci of infection can reach 50-90% [10]. Along with the high virulence of the pathogens, this is explained by the method of sheep and goat breeding when large groups of animals are located in limited area.

The peste des petits ruminants has been known since 1942, and is currently not registered in the Russian Federation. The modern nosoareal of the disease covers the countries of Africa and Eurasia, of which the states bordering the Russian Federation or having close economic ties with it, in particular China [6, 7], Mongolia [8], Kazakhstan [7], Georgia [8], Tajikistan [7], Turkey [7, 9], and Iran [7] are the most dangerous for Russia. China is recognized as a country endemic for PPR, with the infection foci having been determined in Manchuria bordering the Far Eastern Federal District [6, 7]. In total, as many as 57 countries of Africa and Eurasia were recognized as the disease-affected from 1985 to 2014 [8].

In 1984 to 2014, sheep and goat pox was registered in 34 countries of the African continent and in 42 countries of Eurasia. In the second half of the 20th century, SGP outbreaks among small ruminants in ex-USSR countries occurred mainly in the republics of Central Asia, Transcaucasia, Kazakhstan and Kyrgyzstan [10, 11]. In the Russian Federation, the epizootic situation for sheep and goat pox aggravated in 1994-1998, when the disease was detected in 12 regions of the country. In 2010-2015, SGP was detected in Primorsky [12-14] and Trans-Baikal [12-14] regions, in the Amur [12-14] and Chita [13] regions, in Dagestan [12, 13, 15] and

Kalmykia [12, 14, 16].

Rift Valley fever is a vector-borne infection, the virus vectors being mosquitoes of the genera *Culex*, *Aedes* and *Erenmopodites* spread throughout Russia, which poses a threat of the pathogen entering this country [3, 13]. At the end of the 20th century, RVF was most common in southeastern Africa [17-20]. In 2006, RVF caused major epizootics in Kenya, Tanzania, and Somalia, where the number of diseased animals (i.e., small ruminants and cattle) exceeded 36 thousand, and more than 4 thousand animals died [21]. In Asia, RVF was first described in Saudi Arabia in 2000 [22-24], then in Turkey in 2010 [13] and in China in 2016 [25, 26]. New outbreaks of RVF in Yemen and Saudi Arabia, as well as the case of the disease introduction to the Iberian Peninsula, indicate its spread beyond the African continent and the possibility of its spreading to countries of Asia and/or Europe [13, 27, 28].

To substantiate and work out antiepizootic action plans against PPR, SGP or RVF, constant monitoring of the global epizootic situation for the above infections is required which comprises identification of possible pathways of the pathogens invasion and spread, as well as considering probable livestock population losses.

In the presented work, with the use of regression models for mathematical extrapolation of global epizootic monitoring data, we first determined potential nosoareas for PPR, SGP and RVF in the Russian Federation and neighboring countries during the next decade, which differ in the disease emergence risk levels. Furthermore, some environmental factors were found have the most serious effect upon epizootic tension.

Our goal was to assess the spatial and dynamic characteristics and patterns of the global spread of peste des petits ruminants, sheep and goat pox and Rift Valley fever and to assess the risk of these infections emergence and spread both in the Russian Federation and its neighboring countries in 2020-2030.

Materials and methods. We used the OIE and FAO statistics on the world epizootic situation for PPR, SGP and RVF for 1984-2018, the data on the economic status of the world sheep and goat breeding, as well as the information obtained from the Federal Service for Veterinary and Phytosanitary Surveillance and the Center for Veterinary for special danger animal diseases [12, 13, 16, 29]. The epizootological research method included calculation of the indicators of an epizootic situation: the stationarity index (SI) as the ratio of the number of years during which the disease was recorded in the country/region to the number of years of observation, and the incidence index (II) as the ratio of the number of susceptible livestock in the country to the number of new epizootic outbreaks within 12 months [30-32].

The estimates of the influence of various systems of factors (namely, natural and socio -economic) on the epizootic situation (through the of stationarity and incidence indexes) for the infections was calculated according to the formula of the informational impact indicator (III):

$$\sqrt{\frac{\sum H(A) - \frac{\sum(n_k \cdot \sum H(A/b_k))}{n}}{\sum H(A)}},$$

where $\sum H(A)$ is total entropy of the complex, and

$\frac{\sum(n_k \cdot \sum H(A/b_k))}{n}$ is entropy of random diversity.

For the III calculation, tables of communication channels were used reflecting the calculations and relationships of specific values of risk factors with certain values of indicators characterizing epizootic situation.

The statistical significance characterizing the relationship of epizootic tension with natural and socio-economic factors was evaluated in accordance with the methods adopted [30]. Calculation of regression and information models [30] was used to simulate and predict the dynamics of PPR, SGP, RVF and the structure of their nosoareas.

The probability of a disease incidence was calculated through spatial-dynamic modeling of the frequency of its occurrence in nozoarea countries in 1984-2018 with regard to the influence of natural and socio-economic factors on the stationarity index within the global nozoarea. In constructing diagrams, a method of aligning empirical series was used, in particular, a regression analysis and periodic functions [33].

Results. The current nozoarea of PPR covers 38 African countries, 23 Asian countries, Georgia and Bulgaria [8, 12, 34]. According to the OIE information, the number of PPR outbreaks in the world over a 30-year period has exceeded 54 thousand, of which over 15.8 thousand took place in Africa, over 38.2 thousand in Asia, and in Georgia and Bulgaria were 10 outbreaks (namely in 2016 and 2018, 3 and 7 foci of the disease, respectively).

In the Russian Federation, PPR cases have not been registered. Statistically significant rises of SGP incidence in the world occurred in 1985-1989, 1996-1997, and 2012-2013. In 2016-2017, as many as 116 PPR outbreaks were identified in Turkey, and 295 and 998 in Afghanistan and Iran, respectively. Currently, Mongolia and China are endemic for PPR. The infection foci have been determined in Manchuria and in other China regions bordering the Far Eastern Federal District of Russia, Kazakhstan and Mongolia. In Kazakhstan, PPR outbreaks were diagnosed in 2003, 2005, 2006. In Mongolia, PPR was first reported in August 2016, and in 2017 several foci of the disease were detected among saigas (the number of infected and dead animals was more than 5,000). Thus, saigas can become an intermediate link when the infection enters susceptible livestock population (i.e., sheep and goats) in the unaffected regions.

In 1984-2018, SGP were recorded in 77 countries (34 countries of Africa, 38 countries of Asia and 5 countries of Europe with more than 20,960, 39,131 and 509 outbreaks detected, respectively). The incidence of SGP among sheep and goats markedly increased in 1989-1993, 1999-2005 and 2010-2012. The countries of Africa (Algeria, Nigeria, Cameroon, Libya, Ethiopia, Mali, Mauritania, Morocco, Niger, Senegal, Tanzania, Uganda) and Asia (China, Pakistan, India, Iran, Qatar, Kuwait, Tajikistan, Turkey, Israel, Kazakhstan, Mongolia, Kyrgyzstan, Kazakhstan, Vietnam) are permanently affected with SGP. In Europe, sheep pox has been registered in Greece, Russia and Bulgaria. In Central and South America (Costa Rica, Bolivia), SGP outbreaks were registered in 1990. In the ex-USSR, the disease outbreaks occurred mainly in the republics of Central Asia, Transcaucasia, Kazakhstan, and Kyrgyzstan in the second half of the 20th century [10, 11]. In 2000-2002, SGP outbreaks characterized by high morbidity and mortality levels occurred in Angora goats in the Republic of Tajikistan on the border with Afghanistan.

In the Russian Federation, the SGP outbreaks of 1994-1998, when the disease was first registered in Dagestan (5 affected points) and then in the Stavropol Territory and 10 more regions, caused significant economic damage to sheep breeding. In 2008, there was a pox outbreak among goats in the Khabarovsk Territory, in 2010-2015 sheep and goat pox was registered in four Russian regions bordering China, as well as in Dagestan and Kalmykia, in 2016, pox was diagnosed in sheep in seven districts of the Yaroslavl region, and in 2018 in the Moscow and Tula regions, and the Republic of Kalmykia [13, 16]

In 1984-2015, RVF was registered in 30 countries on the African continent, in 4 countries of Asia, and in one country in Europe [13, 35]. In total, more than 1.6 thousand outbreaks of the disease occurred during this period including 1.2 thousand in Africa (the highest numbers of 0.7 and 0.16 thousand having been observed in South Africa and Kenya, respectively), more than 200 in Asia (in Yemen, Saudi Arabia, Turkey and China), and one in Europe (in Portugal). The disease spread mainly among sheep, goats and cattle and to a lesser extent among other artiodactyls. The epizootic situation for RVF was characterized by a pronounced increase in tension in 1984-2018 with periods of 8-10 and 25-27 years. Within the 10-year cycles, the highest RVF incidence values were seen in 1988, 1998, 2006, and 2016. The seasonality of the increase in the number of RVF outbreaks in the tropical and subtropical zones of Africa and Asia was associated with the heat and moisture regime of the nosoareal. The disease incidence rates were higher in the countries of eastern, southern and western parts of Africa (SI of 0.4-0.6 and higher), the highest II levels being characteristic of the countries of the southeast and west of the African continent, and the Arabian Peninsula.

As per the data summarized in Table 1, the largest amounts of PPR- and/or RVF-affected countries fell on the African continent. A few more SGP-affected countries were found in Asia. At the same time, the numbers of outbreaks of PPR (more than 38 thousand) and SGP (more than 39 thousand) in Asia significantly exceeded the corresponding figure for African countries.

1. World incidence of peste des petits ruminants (PPR), sheep and goat pox (SGP) and Rift Valley fever (RVF) in 1984-2018

Continent/subcontinent	Number of countries			Number of outbreaks		
	PPR	SGP	RVF	PPR	SGP	RVF
Africa	38	34	30	15824	20960	1200
Eurasia:						
total	25	43	5	38281	39640	< 200
in Asia	23	38	4	38271	39131	< 200
in Europe	2	5	1	10	509	1
Total in the world	63	77	35	54105	60600	< 1400

An autocorrelation analysis of the data characterizing the dynamics of the epizootic situation revealed a 13-15-year disease cycle for PPR, 12-13-year and 21-22-year cycles for SGP, and 25-27-year and 8-10-year cycles for LDR.

To perform a multidimensional informational cartographic analysis of the structure of PPR, SGP and RVF nosoareas, we used nosogeographic maps that reflect the spatial distribution of the SI and II values in the affected countries for the period of 1984-2018 [30-32]. The natural background maps reflected the spatial distribution of geographical types of landscapes and the small ruminant population zoogeographic distribution. The socio-economic maps reflected regionalization of agricultural production worldwide, in particular, the economic growth indices for sheep and goat husbandry and the provision of veterinary services.

2. Information analysis of the worldwide structure of nosoareas for peste des petits ruminants (PPR), sheep and goat pox (SGP) and Rift Valley fever (RVF) based on epizootic development intensity and impact factors (1984-2018)

Factors	Stationarity index			Incidence index		
	PPR	SGP	RVF	PPR	SGP	RVF
Environmental	0.603	0.580	0.416	0.600	0.420	0.317
Socio-economic	0.514	0.450	0.320	0.516	0.530	0.387
Complex of environmental and socio-economic factors	0.730	0.650	0.610	0.700	0.650	0.490
Statistical significance, α-value	0.05	0.05	0.05	0.05	0.05	0.05

The III values for environmental (natural) and socio-economic factors (as per the indicators of epizootic intensity) for PPR, SGP and RVF ranged from 0.317

to 0.730 (Table 2). The greatest impact on the epizootic situation for these diseases was, as a rule, characteristic of environmental factors (SI from 0.416 to 0.603, II from 0.317 to 0.600), the values for the socio-economic complex were slightly lower (SI and AI from 0.320 to 0.516) (the example of the III calculation for PPR in Excel see the website http: //www.agrobiology/ru). The distribution of data by gradations of epizootic intensity was close to lognormal indicating the possibility of using regression analysis for epizootic forecasting.

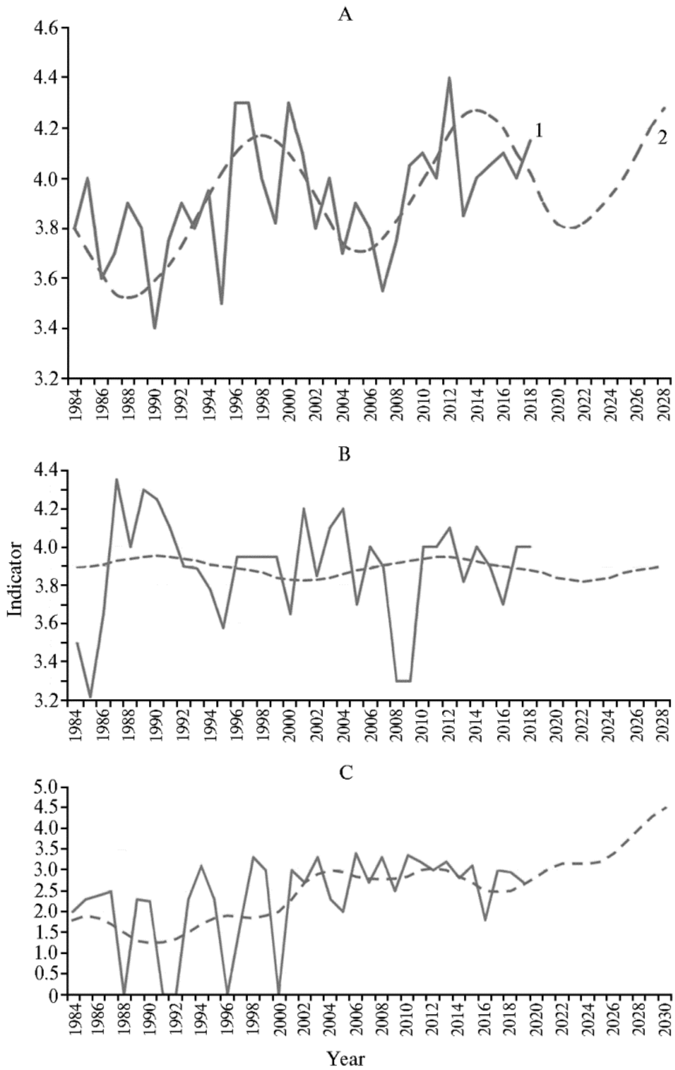

Fig. 1. Actual incidence index (1) **and incidence index model up to 2030** (2) **for peste des petits ruminants** (A)**, sheep and goat pox** (B) **and Rift Valley fever** (C) **outbreaks in potentially affected regions worldwide.**

Math extrapolation of the regression models allowed us to make a forecast for the period until 2030 for PPR, SGP and RVF epizootic situation in potentially affected regions worldwide (Fig. 1). In 2019-2023, the downward trend for PPR and SGP showed a decrease in the epizootic tension, and the upward trend for RVF predicted its increase due to cyclical fluctuations in the epizootic situation.

A potential nosoarea within Africa and Eurasia, including the territory of the Russian Federation, is differentiated into 5 regions depending on the probability (P) of the disease emergence: P ranging from 0 to 0.2 corresponds to a minor risk level, from 0.2 to 0.4 to low, from 0.4 to 0.6 to medium, from 0.6 to 0.8 to significant, and from 0.8 to 1.0 to high risk of the infection entry.

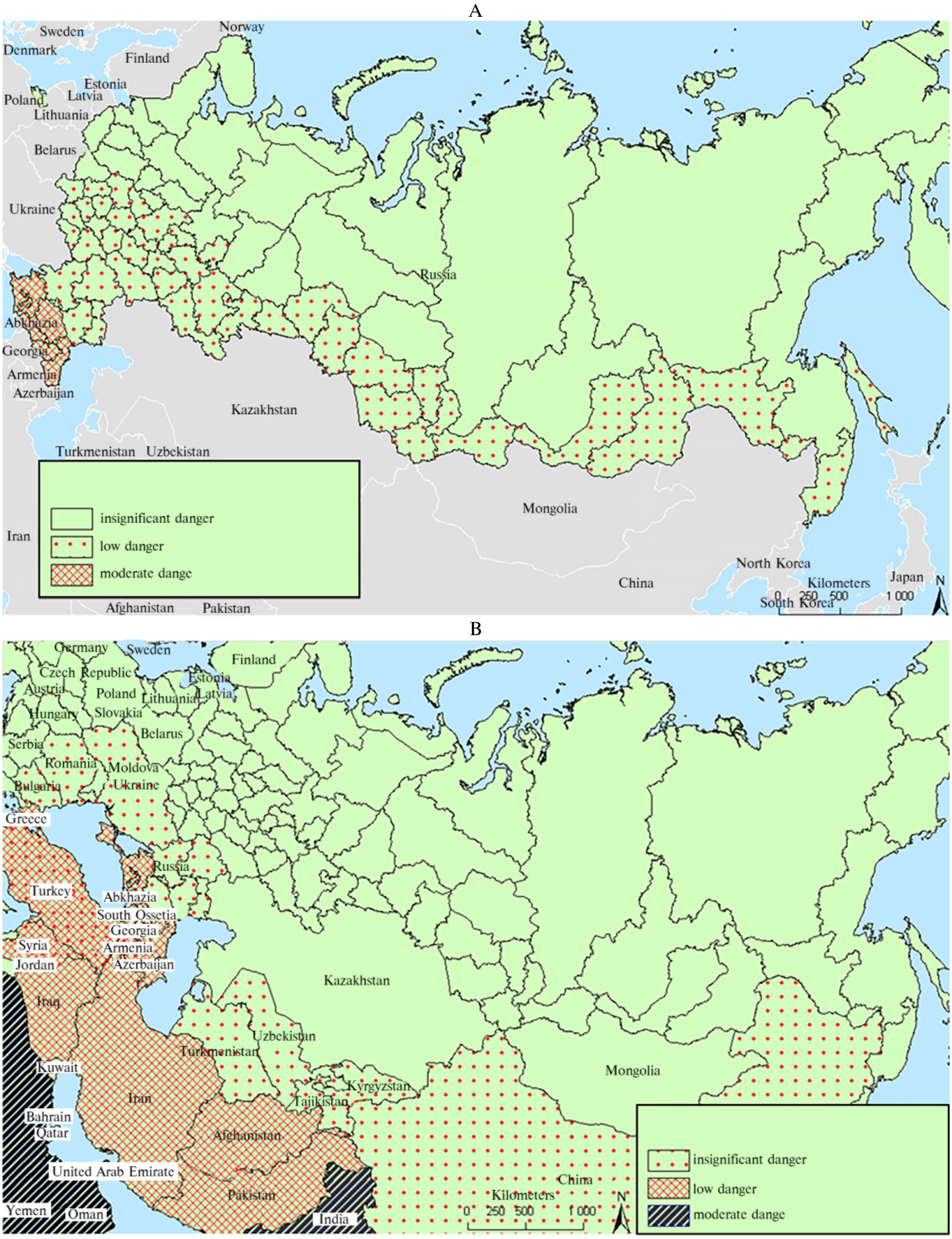

Fig. 2. The level of danger of emergence and spread of special danger viral diseases of sheep and goats in the Russian Federation given the epizootic situation in the surrounding territories (2020-2030): A — peste des petits ruminants, B — Rift Valley fever. Detailed data on the subjects of the Russian Federation are presented in tables (see the website http://www.agrobiology/ru).

In Russia, zones in 2020-2030 with an average, low, and negligible risk levels for the above infections' emergence are distinguished. Zones with an average risk level (with an outbreak probability of 0.4 to 0.6) include the Republic of Dagestan, the Republic of Ingushetia, the Kabardino-Balkarian Republic, the Republic of North Ossetia, the Chechen Republic, the Stavropol Territory (North Caucasus Federal District), the Krasnodar Territory, the Republic of Adygea, the

Republic of Kalmykiya, the Republic of Crimea (Southern Federal District), as well as areas bordering Mongolia and China. Regions with a low and negligible risk levels for SGP and PPR (with a probability of less than 0.4) are the subjects of the Central, the Volga, the Siberian, the Far Eastern and the North-Western federal districts (Fig. 2, A). At the same time, a significant risk of SGP and/or PPR outbreaks is predicted for the countries of South-West Asia and Southern Europe

A potential RVF nosoarea worldwide is differentiated into the following zones of the disease probable emergence: high risk level (P from 0.6 to 1.0; agroecosystems of the African continent, Arabian Peninsula, and southern region of Asia), moderate risk (from 0.4 up to 0.6; countries of the northern region of Africa and southwestern Asia covering Afghanistan, Iraq, Iran and Pakistan), low risk level (from 0.2 to 0.4; countries of southern Europe, Transcaucasia and Central Asia), an negligible risk level (from 0 to 0.2; agroecosystems of the temperate climatic zone of Europe in which RVF has not been registered earlier). For the Russian Federation, the spatial prognosis of the potential RVF nosoarea for 2020-2030 indicates the possibility of the disease emergence in two zones. The first zone with a probability of the diseases incidence below the average value includes the territories of the North Caucasus and Southern Federal Districts (the Krasnodar Territory, the Republic of Adygea, the Republic of Dagestan and the Crimea). The second zone with a low probability of RVF emergence includes some subjects of the Southern Federal District (Astrakhan, Rostov and Volgograd regions, the Republic of Kalmykia and the Stavropol Territory) (Fig. 2, B).

The most important task of epizootological forecasting is to determine the risk of an infectious disease emergence associated with the interaction of a pathogen with a population of susceptible animals in specific environmental and socio-economic conditions to ground taking effective anti-epizootic measures [35, 36]. In the present work, the study was carried out in accordance with the "Methodological recommendations for epizootological monitoring of exotic highly dangerous and/or exotic animal diseases" developed with our participation [30]. We confirmed the effectiveness and reliability of this method earlier when monitoring and predicting other infections like nodular dermatitis of cattle [37], Newcastle disease [38], African swine fever (ASF) [39].

It should be noted that a significant number of publications has been devoted to the development of epizootics and methods for their prediction. For example, the results of studies using the cluster analysis method show that the intensity of ASF outbreaks spread in a certain area is associated with the denseness indices of pig-breeding complexes and/or private farms, the road network density, and anthropogenic activities [40, 41]. In the epizootological forecasting of special danger diseases of humans and animals, the basic methods of statistical analysis, analytical epidemiology and system modeling with the Pausson model are used [42]. Also, some modern geographic information systems based on computer technologies for automated processing, storage and analysis of epidemiological information with its visualization on maps have been developed in recent years [43-45].

Thus, a long-term (2020—2030) prognosis of the spread of peste des petits ruminants (PPR), sheep and goat pox (SGP) and Rift Valley fever (RVF) among sheep and goats indicates a trend towards an aggravation of the world's epizootic situation for these diseases. Of the countries with which Russia is bordering and/or has close trade and economic ties, Tajikistan, Kyrgyzstan, Kazakhstan, Uzbekistan, Afghanistan, Turkmenistan, Armenia, Georgia, Azerbaijan, Turkey, Iran, Mongolia and China pose the greatest danger for PPR and SGP, and the countries of the African continent, the Arabian Peninsula and the south of Asia for RVF.

In the period until 2030, the emergence and spread of PPR and SGP is possible throughout the territory of the Russian Federation, with the North Caucasus and the Southern Federal Districts exhibiting the highest predicted probability of the above infections emergence. Also, there is a low probability of RVF entry in these regions. Our data indicate the requirement of systemic monitoring and forecasting of the epizootic situation for PPR, SGP and RVF and carrying out antiepizootic and preventing campaigns to ensure sanitary and epizootic safety.

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