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https://doi.org/10.29326/2304-196X-2024-13-1-64-72

Risk factors for African swine fever spread in wild boar in the Russian Federation

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ABSTRACT

The analysis and assessment of risk factors associated with the occurrence, spread and persistence of African swine fever (ASF) virus in wild boar population are an important tool in determining the strategic measures aimed at eradicating epizootics and mitigating their consequences. A thorough examination of foreign and domestic literature revealed that wild boar population management factors, socio-economic and environmental ones, that mainly account for the density and number of animals were the most significant and associated with the risk of ASF outbreak occurrence in wild animals. In order to identify risk factors for the spread of the disease in wild boar in the Russian Federation subjects, a regression model was built to examine the relationship between the annual number of ASF outbreaks in wild boar at the municipal raion level, wild boar population density and some other factors for the period between 2007 and 2022. Based on the subject-level regression modelling results, a positive association between the intensity of the disease outbreaks and wild boar population density was identified in 42.5% of the model regions of the Russian Federation. Other significant factors were the length of roads, the presence of forest cover and outbreaks in domestic pigs. However, on the whole, for all the infected subjects, the regression model demonstrated the failure of the wild boar population density factor to explain the observed ASF outbreak distribution, and this may be indicative of the existence of other epizootic drivers of the disease spread in the wild. One of such mechanisms may be the persistence of infectious potential in the external environment and in the formed stationary local foci of African swine fever, despite the anti-epizootic measures taken, including the measures aimed at regulating the number of susceptible population – depopulation.

Keywords: African swine fever, risk factors, wild boar, population density, regression analysis, Russian Federation

Acknowledgement: The study was supported by the Ministry of Education and Science of the Russian Federation in the framework of the State Assignment of the Federal Research Center for Virology and Microbiology.

For citations: Zakharova O. I., Blokhin A. A., Burova O. A., Yashin I. V., Korennoy F. I. Risk factors for African swine fever spread in wild boar in the Russian Federation. *Veterinary Science Today*. 2024; 13 (1): 64–72. https://doi.org/10.29326/2304-196X-2024-13-1-64-72

Conflict of interests: The authors declare no conflict of interests.

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УДК 619:616.98:578.842.1:639.111.14:616-036.22(470)

Факторы риска распространения африканской чумы свиней среди диких кабанов в Российской Федерации

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РЕЗЮМЕ

Анализ и оценка факторов риска, связанных с возникновением, распространением и персистенцией вируса африканской чумы свиней в популяции диких кабанов, представляет собой важный инструмент в определении стратегических мер, направленных на ликвидацию и смягчение последствий эпизоотий. Детальное изучение зарубежной и отечественной литературы позволило сделать вывод, что факторы управления популяциями диких кабанов, социально-экономические и связанные с внешней средой, в основном определяющие плотность и численность животных, являлись наиболее значимыми и ассоциированными с риском возникновения очагов африканской чумы свиней в дикой фауне. Для выявления факторов риска распространения заболевания среди диких кабанов в субъектах Российской Федерации была построена регрессионная модель, исследующая взаимосвязь между ежегодным количеством вспышек африканской чумы свиней среди кабанов на уровне муниципальных районов, плотностью популяции кабана и рядом других факторов за период с 2007 по 2022 г. По результатам проведенного регрессионного моделирования на уровне субъектов в 42,5% модельных регионов Российской Федерации была выявлена положительная взаимосвязь интенсивности вспышек заболевания и плотности популяции кабана. Другими значимыми факторами явились протяженность автодорог, наличие лесного покрова и вспышек среди домашних свиней. Однако в целом для всех неблагополучных субъектов регрессионная модель показала несостоятельность фактора плотности популяции кабана для объяснения наблюдаемого распределения вспышек африканской чумы свиней, что может указывать на наличие иных эпизоотических драйверов распространения заболевания в дикой природе. Одним из таких механизмов может являться сохранение инфекционного потенциала во внешней среде и в сформированных стационарных локальных очагах африканской чумы свиней, несмотря на принимаемые противоэпизоотические мероприятия, включающие в себя и меры по регулированию численности восприимчивого поголовья – депопуляцию.

Ключевые слова: африканская чума свиней, факторы риска, кабан, плотность популяции, регрессионный анализ, Российская Федерация

Благодарности: Работа выполнена при поддержке Минобрнауки РФ в рамках государственного задания ФГБНУ «Федеральный исследовательский центр вирусологии и микробиологии».

Для цитирования: Захарова О. И., Блохин А. А., Бурова О. А., Яшин И. В., Коренной Ф. И. Факторы риска распространения африканской чумы свиней среди диких кабанов в Российской Федерации. *Ветеринария сегодня*. 2024; 13 (1): 64–72. https://doi.org/10.29326/2304-196X-2024-13-1-64-72

Конфликт интересов: Авторы заявляют об отсутствии конфликта интересов.

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INTRODUCTION

African swine fever (ASF) is a transboundary viral disease that affects both domestic and wild pigs and causes enormous damage to pig farming [1, 2, 3, 4]. African swine fever may demonstrate unique regional patterns associated with a set of risk factors that should be taken into consideration when choosing appropriate surveillance and control strategies [5]. Multiple studies focus on the elucidation of the role of domestic and wild pigs in the occurrence of outbreaks and the spread of the infection.

Of particular interest is the analysis of risk factors contributing to the spread of the disease in wild boar, including its introduction into the ASF free areas [6]. The ecological cycle with the involvement of the wild boar and ASF virus presence in the environment is the main challenge of the present-day ASF epizootiology, since not all mechanisms of the pathogen persistence in the ASF infected areas have yet been revealed [7, 8].

The analysis of the ASF situation in the Russian Federation shows that the disease is widely spread both in wild boar and domestic pig populations almost throughout the entire territory of the country, including the regions where wild boar population density is reportedly very low [9].

Despite numerous attempts undertaken by researchers in many countries to develop a safe and effective vaccine against African swine fever, the disease eradication strategy is at present based on the principles of risk assessment and identification of the main factors contributing to the infection spread, as well as on compliance with strict biosecurity and biocontainment measures. Most ASF eradication and prevention measures are grounded on the classical principles of disease control, including epizootiological surveillance, investigation and killing of infected herds, establishment of protection and surveillance zones. These measures are coupled with a ban on swill feeding to pigs, strict quarantine and biosecurity/biocontainment measures, as well as with control over the movement of animals and pig products [2, 10, 11].

The importance of assessing the current ASF situation and the spread dynamics of this disease, which is devastating for the pig industry, dictates the need to develop methods for model forecasting of ASF outbreak occurrence in the ASF free areas of the Russian Federation and in the areas where the disease persists.

The remoteness of local foci of the infection in wild boar from initial outbreaks highlights the significance of human economic activities as a major, if not the key, factor associated with the spread of the disease [12, 13, 14]. It should be borne in mind that ASF transmission occurs not only through a direct contact between animals, but also indirectly, for example, through infected carcasses of wild boar killed by the disease and through environmental objects contaminated with the virus [12, 15, 16]. The detection of ASF occurrence in the wild boar habitat during the ongoing epizootic in Europe and its association with environmental factors made it possible to identify and describe the pathogen transmission cycle named "wild boar – habitat" [17, 18]. Thus, it seems justified to conclude that wild boar play an important role in the spread and circulation of ASF virus in the European countries. The complex biology of wild boar and environmental factors having impact on their habitat shall be at the core of efforts aimed at ASF control [19].

Discussions are currently underway regarding the dependence of ASF agent spread rate on wild boar population density. Based on the experience of the European countries, such an association prevails, but it is not always observed [5]. Pejsak Z. et al. suggested that sustained circulation of the virus in wild boar in Poland requires the density that exceeds 2 animals per square kilometer [19]. Due to the peculiarities of the ASF epizootic process, such a trend mainly depends on the structure and social relationships within the susceptible wild boar population and between the age-sex groups.

The threshold density theory does not provide any clear-cut answers regarding the patterns of ASF virus

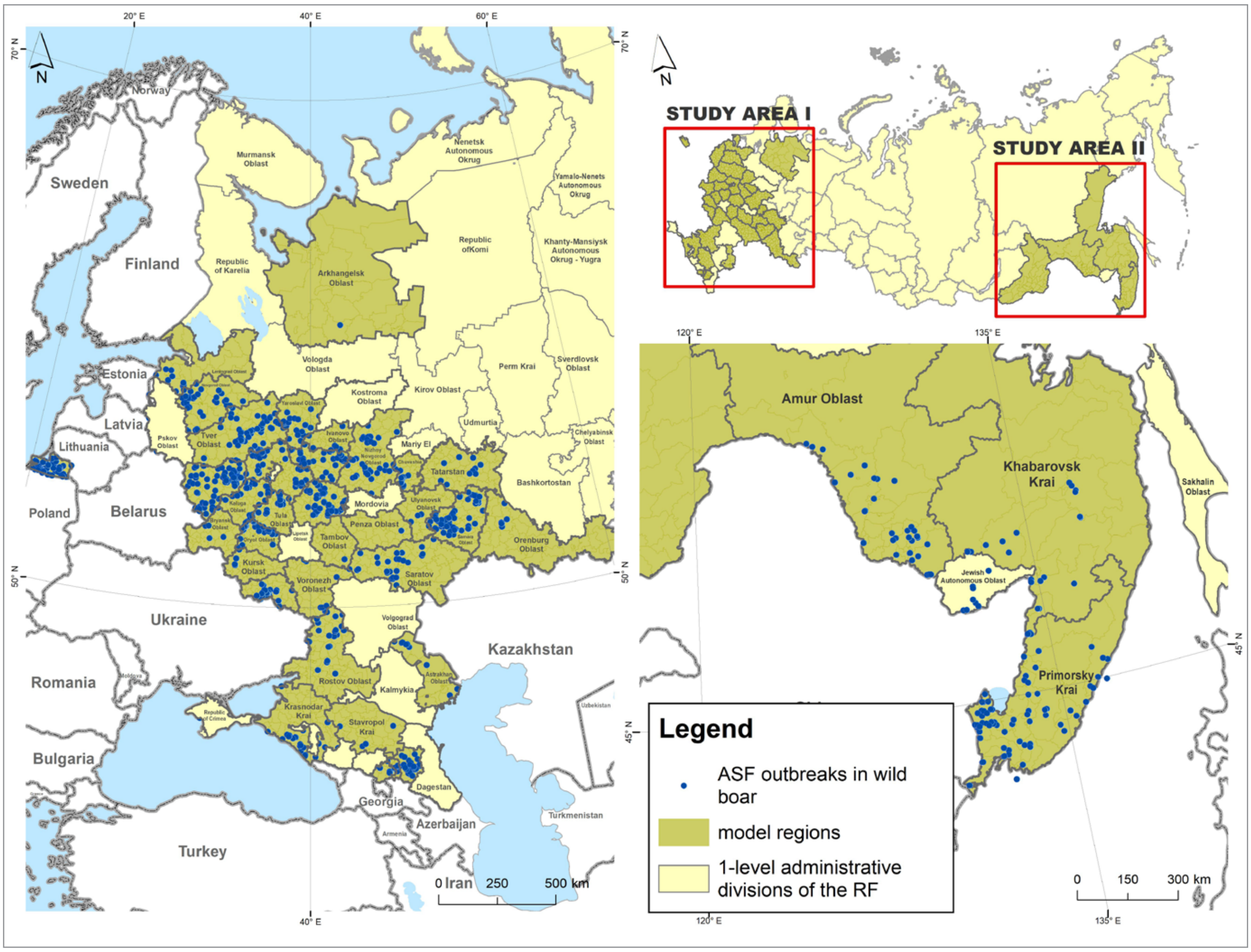

Fig. 1. ASF situation in wild boar population in the Russian Federation subjects (2007–2022)

spread, the persistence of outbreaks in the wild boar population and the disease agent transmission to other susceptible populations, including domestic pigs. Modelling approaches are based on the key assumptions such as homogeneous and random interaction between diseased and healthy animals, which is hardly reproducible in the wild.

The specified urgency of studying the biology of wild boar and ASF virus persistence in the environment highlights ecological, as well as landscape and climatic risk factors for the infection introduction and spread as a special category of predictors that are of priority for consideration [19, 20].

The study was aimed at the identification of the main risk factors for ASF spread in the wild boar population, including the determination of significance of susceptible animal density in the epizootic process in the ASF infected subjects of the Russian Federation.

MATERIALS AND METHODS

Model regions. The subjects of the Russian Federation in which ASF outbreaks were reported in the wild boar population in 2007–2022 and for which the information on the number of wild boar at the raion level was available for the said period were selected for the study. The model regions shown in Figure 1 comprise 40 subjects located in the European (zone I) and Far-Eastern (zone II) parts of Russia. Municipal raions were used as model units for the assessment of the disease occurrence and factors.

African swine fever data. Data on ASF outbreaks reported in the wild boar population in the Russian Federation in 2007–2022 were acquired from the official database of the World Organisation for Animal Health (WOAH)[1]. Annual information on the number and density of the wild boar population for 2007–2022 was acquired through requests submitted to the regional Ministries of Environment and Natural Resources and Committees on Wildlife Protection and Management of the Russian Federation subjects.

Regression analysis. The investigation of dependence between ASF outbreak occurrence and intensity and risk factors, in particular wild boar population density, involved the use of a negative binomial multi-factor regression model for the model subjects with long-term ASF persistence in wildlife. The dependent (response) variable was the number of ASF outbreaks in wild boar in the specified municipal raion in the relevant year, and the explanatory variables were the socio-economic and ecological factors described below.

A negative binomial regression model is a certain type of regression employed for analyzing count data where

[1] WOAH. Disease situation. https://wahis.woah.org/#/dashboards/country-or-disease-dashboard

the variance of the response is greater than its mean (i.e. where overdispersion is observed) [21]. In our case, choosing negative binomial regression was justified by the distribution of the number of outbreaks in wild boar in the municipal raions where the mean value is 0.84, the variance is 38.41.

The significance of the variables was evaluated with Student's *t*-test based on *p*-value ($p \leq 0.05$ is indicative of sufficient statistical significance of the variable as a regression model predictor). The global fit of the models was evaluated using the adjusted coefficient of determination R^2, which is the proportion of the variation in the dependent variable explained by the model.

Modelling was carried out in two stages:

1) for all raions of the model subjects taken as a whole;

2) for the raions of each individual subject.

Selecting potential risk factors for ASF occurrence in wild boar. As a result of literature data analysis, information was collected on potential risk factors for ASF spread in wild boar population, which is presented in Table 1.

The selected factors were the explanatory variables in the regression modelling aimed at the identification of ASF outbreak dependence on population density and other risk factors using negative binomial regression.

Software. The primary processing and evaluation of data were carried using Microsoft Office Excel software (Microsoft Corporation, Redmond, Washington, the USA). The mapping of ASF situation, the number of wild boar and cluster analysis were carried out using ArcMap 10.8.1 software (Esri, Redlands, California, the USA). Regression modelling was performed using R statistically oriented software environment (R Core Team, 2023).

RESULTS

Retrospective assessment of ASF situation in the wild boar population. During the analyzed period (from 2007 to 2022), 1,054 ASF outbreaks were registered in the wild boar population in the model subjects, which accounted for 41.7% of all outbreaks of the disease. The largest numbers of outbreaks in wild boar were reported in 2013 (116 outbreaks), 2016 (118 outbreaks), 2020 (170 outbreaks) and 2021 (104 outbreaks). Geographically, ASF outbreaks were concentrated in the following subjects: the Ryazan, Moscow, Tula, Tver, Vladimir, Smolensk, Samara Oblasts, as well as in the Pskov and Leningrad Oblasts adjacent to the border with Estonia. In the Far East, the long-term persistence and stationary foci of African swine fever were reported in the Primorsky Krai and in the border areas – local territories, in which wild boar population density is currently still rather high.

In some regions, ASF occurrence in the wild boar population is sporadic with a trend towards the virus persistence in the environment, with the disease outbreaks being reported throughout the entire epizootic (for example, in the Nizhny Novgorod Oblast); in other regions, the disease occurs as a mass epizootic and affects a considerable number of animals within a short period. Such an epizootic occurred in the Samara Oblast in 2020, with 60 ASF outbreaks having been reported in wild boar within the year.

The disease occurrence in wild boar was characterized by pronounced seasonality with peaks during summer months (July – August), as well as in November – December and February (Fig. 2).

Identification of dependence of ASF outbreak occurrence in wild boar on population density and other risk factors. Modelling for all the model subjects as a whole showed that wild boar population density is statistically insignificant as an explanatory factor ($p_t = 0.546$) and the coefficient of mutual determination is low ($R^2 = 0.256$). This allows for the conclusion that it is impossible to establish an unequivocal association between wild boar population density and repeated ASF outbreaks for all the model subjects as a whole (Table 2).

At the same time, modelling for individual subjects of the Russian Federation revealed statistically significant ($p_t < 0.05$) positive dependence of ASF outbreak

Table 1
Risk factors for ASF spread in wild boar population (overview)

Risk factors	Measuring units	Information on possible effect	References
Forest cover (proportion of the total area of a raion)	%	The availability of a large forested area, proximity to forest expanses increase the probability of diseased animal detection	[15, 22, 23, 24]
Water bodies (proportion of the total area of a raion)	%	There is an association between the availability of and proximity to surface watercourses and ASF spread	[15, 24]
Fields with shrub vegetation (area)	km^2	There is an association between the availability of meadow and shrub vegetation with a height of more than 1.5 m and infected animal detection	[15]
Height above sea level	m	High probability of infected animal detection under optimal habitat conditions	[25, 26, 27]
Human population density	people/km^2	There is an association between high human population density and infection occurrence	[24]
Concentration of settlements, including rural settlements and villages	settlements/km^2	Changes in the concentration may have an effect on diseased animal detection	[15, 22, 25, 26, 27]
Hunted wild boar	animals	There is an association between the probability of diseased animal detection and the number of hunted animals	[26, 27]
Road length and density	km and km/km^2	An increase in the number of roads may result in increased infected animal detection; it is also an indirect indicator of the economic activity of the human population	[15, 25, 26, 27]
Agriculture, the availability of small pig farms	farms	There is an association between an increase in the number of pig farms, especially small ones, and increased infection occurrence in animals	[26, 27]
ASF outbreaks in domestic pigs	outbreaks	Proximity to outbreaks increases the probability of infection occurrence	[26, 27]
Wild boar population density	animals/km^2	There is an association between high density and the probability of disease occurrence	[22, 25, 26, 27, 28]

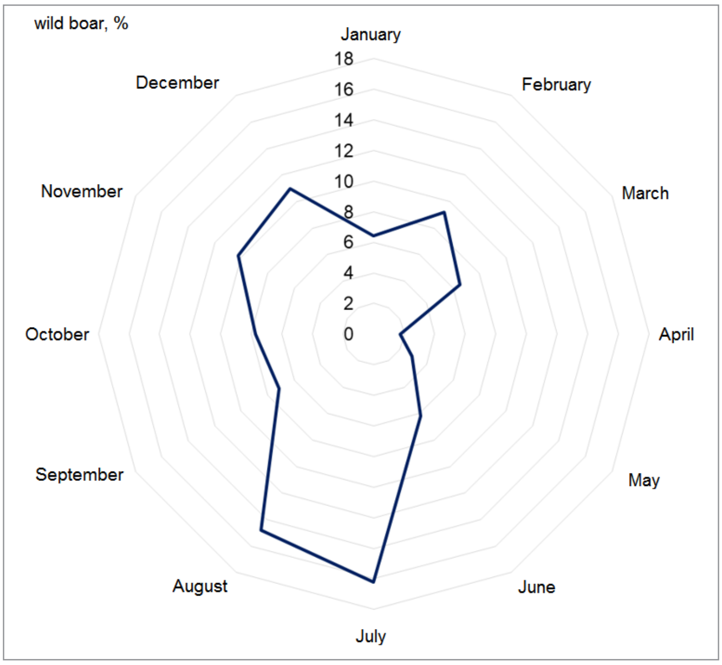

Fig. 2. Seasonality of ASF outbreaks in wild boar in the Russian Federation subjects, 2007–2022

Table 2
Results of regression analysis of ASF outbreak dependence on risk factors in the Russian Federation subjects (2007–2022)

Variables	Regression coefficient	Standard error	*p*-value
Forest cover proportion, %	0.657	0.342	0.0001
Road length, km	0.354	0.235	0.0001
ASF outbreaks in domestic pigs	1.032	0.657	0.003
Wild boar population density, animals/km^2	3.056	3.415	0.546

occurrence on wild boar population density in 17 out of 40 regions (42.5%), which is shown in Table 3.

Despite the revealed dependence of epizootic intensity on wild boar density in certain subjects of the Russian Federation, ASF outbreaks in wild boar in some regions were reported even in those areas where wild boar population density was significantly lower than the recommended value of 0.25 animal per 1,000 ha (0.025 animal/km^2) approved by Order of the Government of the Russian Federation No. 2048-r of 30 September 2016 (as amended on 4 February 2021) on the "Action plan for prevention of African swine fever introduction into and spread in the Russian Federation". This suggests that wild boar population density is not the only risk factor for ASF spread.

Figure 3 shows the results of regression modelling of ASF outbreak occurrence dependence on wild boar population density in the model subjects of the Russian Federation. Also, the distribution of susceptible animal population density in 2022 is shown for the regions in which the reliable dependence of ASF spread on wild boar population density was revealed.

The results of negative binomial regression analysis of reported ASF cases in wild boar taking into account several climatic and socio-demographic factors are presented in Table 2. The proportion of forest cover, the length of roads and outbreaks in domestic pigs were found to be the main predictors of epizootics.

DISCUSSION

Based on the analysis of literature sources describing risk factors for ASF expansion in the countries of the world, human activity is presented as the most significant predictor, especially as regards the movement and import of live pigs and pig products [12, 22, 25]. Many researchers note that wild boar dead of ASF, being a source of the infection spread, act as a no less important factor in the virus transmission both within the wild boar population and to domestic pigs, and this may be indicative of the virus persistence due to the presence of infected wild boar carcasses or their remains [16, 29, 30].

When considering wild boar habitat conditions as part of ASF spread risk analysis, one should take into account both biotic and abiotic factors such as climatic factors (temperature, rainfall amount, humidity, cloud amount, UV radiation level), landscape factors (vegetation type, vegetation cover area, height above sea level, soil type, the presence and accessibility of water bodies), anthropogenic activity and associated changes in the wild boar habitat (human population density, man-made structures, buildings, roads, farm concentration and livestock density), as well as factors related to wild boar population characteristics (wild boar population density, geographical distribution) and the biological properties of ASF virus – the form and stage of the disease (the proportion of seropositive wild boar in the population), viral load, incidence and prevalence levels [31].

Thus, a comprehensive understanding of potential risk factors for ASF spread in wild boar is fundamental and crucial for effective control of the disease. In this respect, it is obvious that in case of single-factor analysis of ASF risk, there is a probability of leaving out essential elements relevant for the infection transmission to wild boar. Therefore, to model the association between ASF occurrence in wild boar and potential predictors, many studies applied multi-factor approaches, thereby emphasizing the significance of the identified risk factors [23, 26, 32, 33].

Environmental factors that directly influence the possibility of the disease occurrence underlie the spatial and temporal patterns of ASF spread. It is known that the condition of forest cover has potential impact on the maintenance of favourable wild boar habitat conditions; another key predictor of ASF occurrence is the presence of water bodies [34].

As regards optimal wild boar habitat conditions, any type of land cover that provides animals with shelter, water and feed should be taken into account as an ecological risk factor for ASF occurrence [28, 35, 36]. It is possible that maintaining the size of wild boar populations at the specified level requires optimal habitat conditions, including forest cover consisting of certain tree species [35]. In accordance with this viewpoint, researchers demonstrated the association between ASF occurrence in wild boar and the area of forest cover in different geographical regions of Europe, including the Baltic countries [25, 26] and Italy [23], which indicates that the probability of detecting the infection agent in this animal species is higher in the regions with large forest expanses [37]. The results of a spatio-temporal study conducted in Czechia in the area affected by ASF in 2017–2018 provided additional

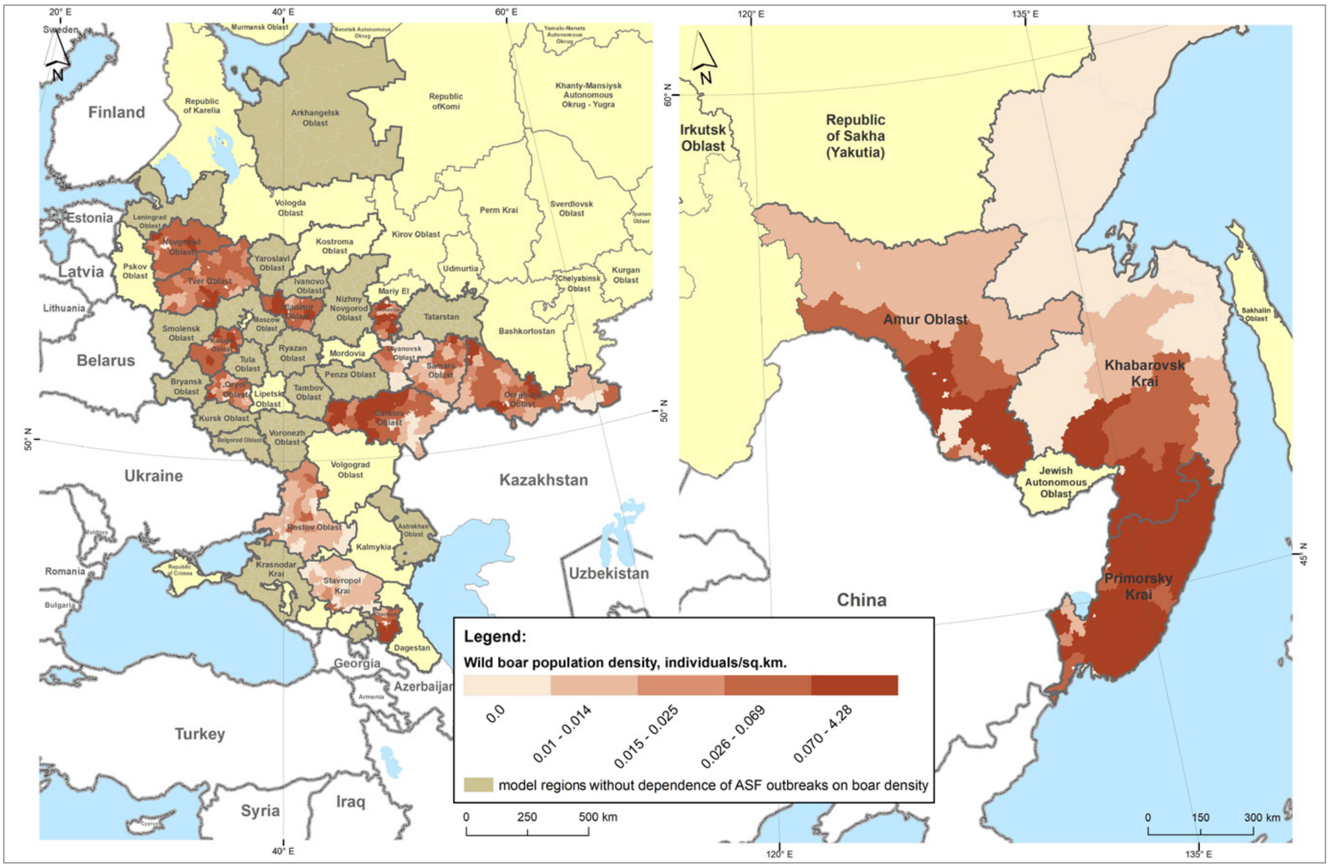

Fig. 3. Dependence of ASF spread in the raions of the Russian Federation subjects on wild boar population density based on regression modelling results. The figure shows the wild boar population density as of 2022

information on the relative effect of forest cover on detection of ASF virus infected wild boar. Though search activities aimed at detecting dead animals were carried out in a relatively small area affected by ASF, more than 70% of all carcasses were found in the forests [15]. The regression modelling of factors underlying the risk of ASF spread in the Russian Federation subjects demonstrated the significance of the forest cover factor, thus confirming the above statement.

Risk factors for ASF occurrence in wild boar associated with the population characteristics of the species include the total number or density, spatial and temporal distribution of animals. The concentration of ASF susceptible animals (domestic pigs, wild boar) plays an important role in the infection transmission chain. Despite the potential significance of the wild boar population density factor for ASF spread [38], it is very difficult, practically impossible, to determine the actual number of these animals and to conduct continuous monitoring due to their constant migrations. Therefore, in many countries, the population density is estimated based on the number of hunted wild boar per size of the area [35, 39] or using other methods such as camera traps [40]. It is important to understand that actual estimates of wild boar density are likely to be rough approximations of the true absolute value and are probably biased depending on the availability of initial data on the number of hunted animals.

The revealed spatio-temporal patterns of ASF outbreak spread in the Russian Federation subjects suggest that even with low wild boar population density (less than 0.25 animal per 1,000 ha of hunting areas), there is still

Table 3
Characteristics of regression indicators of dependence of ASF outbreaks in wild boar on wild boar population density in the Russian Federation subjects (2007–2022)

Russian Federation subject	Regression coefficient	Standard error	95% CI (confidence interval)	*p*-value
Kaluga Oblast	5.565	1.811	1.421–15.634	0.002
Novgorod Oblast	8.834	3.869	0.679–19.679	0.022
Orenburg Oblast	34.163	15.493	5.325–25.456	0.027
Oryol Oblast	13.296	5.807	3.911–28.044	0.022
Chechen Republic	4.345	3.211	1.658–2.213	0.032
Chuvash Republic	39.070	12.047	7.579–91.482	0.001
Rostov Oblast	33.495	0.785	31.944–135.024	0.000
Samara Oblast	27.656	8.844	10.487–50.677	0.001
Saratov Oblast	7.278	2.167	2.269–15.414	0.000
Stavropol Krai	87.722	11.827	64.026–110.587	0.000
Ulyanovsk Oblast	96.345	35.817	12.109–260.338	0.000
Vladimir Oblast	13.059	3.137	1.244–25.423	0.000
Volgograd Oblast	18.234	5.342	5.341–21.231	0.000
Tver Oblast	8.274	1.539	3.661–14.281	0.000
Amur Oblast	21.052	9.438	9.438–34.887	0.000
Primorsky Krai	1.051	0.713	0.123–4.063	0.014
Khabarovsk Krai	6.870	3.398	0.01–10.456	0.043

a possibility of the pathogen transmission from infected objects to susceptible animals and the virus spread in the environment [41, 42]. The overall regression model of ASF outbreak occurrence dependence on wild boar population density in the ASF infected subjects of the Russian Federation in 2007–2022 showed that the intensity of ASF outbreaks generally does not depend on the population density, and this may be attributed to uneven raion-level spatial distribution of this animal species. Despite the said fact, such dependence still exists in some subjects; this confirms the assumption that in some regions, there are raion-level geographical sites with increased susceptible animal densities, and migrations lead to ASF virus spread to new, previously ASF free areas. At the same time, it is important to pay attention to the nature of the revealed dependence: the positive values of regression coefficients confirm that a higher population density contributes to a more intensive spread of the disease.

Our study demonstrated the significance of the road length factor, which is associated with the possibility of people movement during ASF monitoring, especially in summer and autumn; it is also an indirect indicator of the intensity of transport and economic links contributing to the dissemination of products contaminated with the agent throughout the territory. A similar conclusion was made in the studies conducted in Estonia between 2014 and 2017. It was proved that the length of roads in the region is a factor that enhances the chances of detecting infected animals [25].

Hunting is repeatedly mentioned in the literature as a risk factor for ASF spread due to potential wild boar migrations as a result of hunting activities of humans. Therefore, when an ASF virus infected wild boar is detected and quarantine is imposed in the hunting area, it is recommended to stop any kind of hunting within the surveillance zone, except for activities aimed at regulating the number of wild boar to be carried out by specially trained people, while maintaining necessary measures to prevent the movement of animals outside this zone [43, 44].

The analysis of data obtained in Estonia in 2018 and 2019 showed that pig population density on small farms where a maximum of 10 pigs are kept is a risk factor for ASF occurrence in wild boar [6, 27]. This may be due to potential contacts between domestic and wild pigs that are typical for small farms without any biosecurity/biocontainment measures in place. The results of our study also demonstrate that ASF outbreaks in domestic pigs are an important risk factor for the infection spread in wild boar.

CONCLUSION

The literature analysis results allow for the conclusion that main factors for ASF spread in wild boar are environmental factors and human activities, which determine the major directions of the strategy for the infection control in wildlife. Regression modelling was aimed at the identification of main risk factors for ASF spread in the wild boar population in the ASF infected subjects of the Russian Federation. For Russia as a whole, the overall regression model demonstrated the failure of the wild boar population density factor to explain the observed ASF outbreak distribution, and this may be indicative of the persistence of infectious potential in the external environment and in the formed stationary local foci of African swine fever. However, it should be noted that results are heavily dependent on the reliability of available data on the size of the wild boar population. Modelling of an epizootic allowed for the identification of factors for ASF outbreak spread in wild boar such as forest cover percentage, road length and ASF outbreaks in domestic pigs, which confirm the significance of both natural and socio-demographic predictors. The wild boar, being a participant of the ASF transmission chain, may act as a risk factor only in case of high susceptible animal density at the initial stage of an epizootic. Selection of an ASF control strategy should take account of every link in the virus transmission chain and every opportunity for the infection elimination in the area where eradication measures are implemented.

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Received 28.12.2023
Revised 19.01.2024
Accepted 20.02.2024

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Вклад авторов: Захарова О. И. – концепция исследования, анализ и интерпретация данных, подготовка текста; Блохин А. А. – подготовка текста; Бурова О. А. – анализ научной литературы по заявленной проблеме; Яшин И. В. – подготовка текста; Коренной Ф. И. – концепция представления материалов, подготовка текста, интерпретация данных.