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Spatiotemporal analysis of African swine fever spread in wild boar population in Russian Federation, 2007–2022

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SUMMARY

African swine fever is a transboundary disease of all members of *Suidae* family and it causes economic damage to the pig industry and ecology of wild boar as a species. The ASF epidemiology is complex and it is specified by the mechanisms of the agent's transmission in susceptible animal populations. Choice of measures aimed to control and prevent the disease spread in the wild boar population depends mainly on the routes of the disease introduction and stage or phase of the epizootic process. Prevention of the ASFV introduction from an infected region to a free one is the backbone in the infection prevention. Therefore, the research was aimed at the spatiotemporal analysis of African swine fever outbreaks in the wild boar population in the Russian Federation in 2007–2022 and identification of geographical areas that pose risk of new disease epidemics. The analysis was performed using retrospective space-time scan statistics, which does not require data on the wild boar population and which can be used for the assessment of the possibility of new ASF outbreak occurrence upon availability of just data on the reported disease cases and outbreaks. As a result of spatiotemporal cluster analysis, 24 clusters of ASF outbreaks were identified based on the laboratory-confirmed data on the infection in boars found dead, and 22 clusters in hunted wild boars. The analysis results demonstrated spatial heterogeneity of the outbreak cluster distribution in population of wild boars died of the disease and a significant expansion of the passive surveillance geography. Importance and necessity of the enhanced passive surveillance of African swine fever in susceptible animals is demonstrated. The proposed method can be used for regular scanning of a geographic region for the presence of developing zones and areas at risk of re-emerging ASF outbreaks in the wild boar population at different spatial scales.

Keywords: African swine fever, cluster analysis, confidence, wild boar, surveillance, relative risk

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Пространственно-временной анализ распространения африканской чумы свиней в популяции диких кабанов на территории Российской Федерации в 2007–2022 гг.

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РЕЗЮМЕ

Африканская чума свиней является трансграничной болезнью всех представителей семейства *Suidae*, приносящей экономический ущерб свиноводческой отрасли и экологии кабана как вида. Эпизоотология африканской чумы свиней сложна и определяется механизмами передачи возбудителя в популяциях восприимчивых животных. Выбор мер борьбы и предупреждения распространения заболевания в популяции кабанов зависит в основном от путей заноса, стадии или фазы эпизоотического процесса. Предотвращение заноса вируса африканской чумы свиней из неблагополучного региона в благополучный является основой профилактики инфекции. В связи с этим целью исследований явился пространственно-временной анализ очагов африканской чумы

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свиней в популяции кабанов в Российской Федерации в 2007–2022 гг. и обозначение географических территорий, представляющих риск возникновения новых эпизоотий. Анализ проведен с помощью ретроспективной статистики пространственно-временного сканирования, которая не требует данных о численности популяции кабана и которую можно использовать для оценки возможного возникновения новых очагов африканской чумы свиней, когда доступны только данные о зарегистрированных случаях или очагах болезни. При выполнении пространственно-временного кластерного анализа было выявлено 24 кластера очагов африканской чумы свиней, зарегистрированных на основании лабораторно подтвержденных данных об инфицировании кабанов, найденных мертвыми, и 22 кластера – кабанов, добытых на охоте. Результаты проведенного анализа продемонстрировали пространственную неоднородность распределения кластеров очагов инфекции в популяции кабанов, павших от болезни, а также существенное расширение географического охвата территории вследствие применения пассивного мониторинга. Показана важность и необходимость проведения усиленного пассивного мониторинга африканской чумы свиней среди восприимчивых животных. Предлагаемый метод можно использовать для регулярного сканирования географического региона на вероятность формирования зон и территорий риска новых вспышек африканской чумы свиней в популяции дикого кабана на территориях различного пространственного масштаба.

Ключевые слова: африканская чума свиней, кластерный анализ, достоверность, кабан, мониторинг, относительный риск

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INTRODUCTION

African swine fever (ASF) is a viral, contagious disease infecting domestic pigs and wild boars and causing significant damage to the pig industry and ecology of the species at large. The ASF epidemiology is complicated and is determined by the mechanisms of the pathogen transmission in susceptible populations [1–3]. Unlike successful ASF control in domestic pigs, which entails stamping out of the on-farm population, cleaning and disinfection of the contaminated facilities, the disease eradication in wild boars is a challenge [4]. Due to geographical and regional features of wild boar habitats, there is no standard control strategy of the epidemic process, which can be applied for all ASF affected areas [5, 6]. Standard prophylaxis preferably includes measures required to prevent the virus spillover from the affected regions to the disease-free ones [7, 8].

The role of wild boars and density of their population is a disputable factor of ASFV transmission and is still under discussion. However, many scientists and world experts agree that a reduction of the wild boar abundance mitigates the risk of ASFV spillover and transmission both in the hot spots and in the observation zone [7, 9].

Studies on ASF spread in wild boars in the Eastern European countries show that the disease can persist even at a very low level of prevalence and low population density, unless the infected dead animals and their remains are timely eliminated [10–12].

Measures taken to control and prevent ASF spread in wild boars are chosen, mainly, based on the routes of introduction and the stage of the epizootic process. In addition, the territory status is an important factor to be considered when choosing ASF preventive measures. The territory status refers to the situation recorded at the moment of the outbreak registration: disease-free, previously disease-affected, not adjacent to a hot spot – the observation zone. Early detection of the infected wild boars is an important link in the disease control strategy [13].

Methods chosen to detect an increased concentration of the disease outbreaks (clusters) play a significant role in modern epidemiological studies, in public health and preventive veterinary medicine. Their use makes it possible to identify possible etiological and pathogenic reasons behind the epidemics, as well as to choose optimal solutions to eliminate the infections [14].

Time, space and space-time scan statistics [15–21] are widely used now to identify and evaluate clusters of various diseases, including both human and animal infections and non-infectious pathology [18, 19].

Most analytical methods in epidemiology used for early detection of animal diseases are purely time-based. These methods are useful to report outbreaks that simultaneously cover all the areas of the monitored region, but may lag behind in case of local epizooties, which are confined to a certain geographical area. However, purely time-based methods can be used simultaneously for all overlapping parts of the region that differ in size, in order to include all possible disease cases and occurring outbreaks. Nevertheless, this approach causes serious problems, since it includes multiple laboratory tests, which give much more false results than the nominal significance level can show [22, 23].

This work represents retrospective space-time scan statistics, which do not require data on the number of wild boars in areas at ASF risk, and which can be used, if there

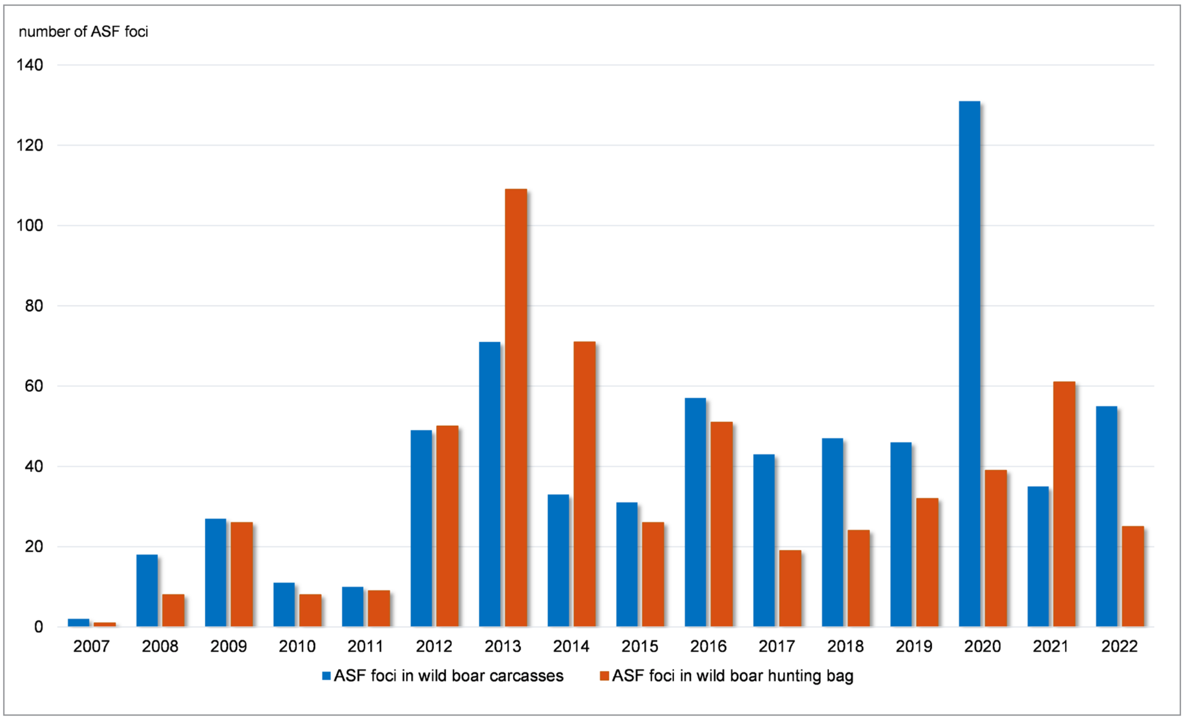

Fig. 1. History of ASF outbreaks reported in the wild boar population (dead animals and remnants thereof – N = 592; hunted animals – N = 562)

is only information on registered dead animals (or their remains) or hunted animals, detected after biomaterial tests. This method can be used to regularly scan geographical regions of various size in order to determine ASF risk zones and territories inhabited by wild boars. For each region, this method considers both potential one-day outbreaks and sporadic outbreaks, so that to spot a rapidly spreading epizooty [20–23]. Therefore, the purpose of the research was to conduct a spatiotemporal analysis of ASF outbreaks and to determine the infection trend in wild boars in the affected subjects of the Russian Federation with the possible identification of geographical territories that pose a risk of local epizooties.

MATERIALS AND METHODS

Our research focused on a retrospective data analysis of ASF outbreaks registered in wild boars. The data were taken from the official reports of the FGBI "Center for Veterinary Medicine" (Moscow)[1]. The term "outbreak" refers to a territory officially notified by the veterinary services of the RF Subject, with given geographical coordinates, where ASFV-infected wild boars are detected. In turn, an individual animal (or a carcass) is considered as a case[2]. Information on the ASF outbreaks registered in wild boars, detected both within passive monitoring and hunting, included the period from 2007 to 2022.

The spatiotemporal analysis was based on the total number of ASF outbreaks in wild boars in the affected Subjects of the Russian Federation. The cluster analysis is based on the Kulldorff's space-time scan statistical method [24]. This method makes it possible to identify clusters of the geographical area under study, where ASF outbreaks (or other studied phenomenon) were grouped more densely than would be expected according to the null hypothesis, which assumes their random distribution. The analysis uses a cylindrical moving scan window where the vertical dimension represents time. As input data, point objects, i.e. ASF outbreaks, are tested, information on the number of cases is given for each outbreak.

The spatiotemporal cluster analysis reveals circular regions (clusters), within which an increased number of ASF outbreaks was detected (as compared with a hypothetical random distribution). Additional characteristics of the clusters are: radius, start and end date, duration, statistical significance (*p*-value), the ratio between the observed number and the expected number of outbreaks within the clusters (ODE). The last characteristic can be considered as a relative risk of outbreak occurrence within the cluster, as compared with the outbreaks registered outside. The SaTScan v8.0 software[3] was used for the cluster analysis, ArcMap 10.8.1 (Esri, USA) was used to visually map the obtained results.

RESULTS

Retrospective analysis of ASF outbreaks in wild boars in the Russian Federation, in 2007–2022. Current ASF outbreaks reported in wild boars in Russia affect small areas, such as hunting farms, with the virus showing a strong tendency to establish itself in the population within a particular area, i.e. to become enzootic. The enzootic process in ASF outbreaks, confirmed by laboratory tests of the material

[1] FGBI "Center for Veterinary Medicine". Epidemic situation. Available at: https://xn----8sbfkcavba6bf4aedue4d.xn--p1ai/o-nas/informatsiya/epizooticheskaya-obstanovka (date of access: 23.01.2023).

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[3] SaTScanTM v8.0: Software for the spatial and space-time scan statistics. 2009. Available at: https://www.satscan.org (date of access: 23.01.2023).

Table 1
Characteristics of ASF outbreak clusters in wild boars found dead in the Subjects of the Russian Federation, 2007–2022

Cluster No.	Cluster radius, km	Number of ASF outbreaks observed	Number of ASF outbreaks expected	ODE	Cluster started on	Cluster ended on	Cluster lasted for, days	*P*-value
1	157.88	34	2.9	11.72	02.08.2015	23.07.2016	356	< 0.001
2	82.22	35	3.3	10.60	04.02.2018	25.05.2019	414	< 0.001
3	121.25	45	6.5	6.92	23.02.2020	24.10.2020	244	< 0.001
4	142.14	24	1.36	17.64	04.11.2007	10.10.2009	706	< 0.001
5	158.22	15	0.53	28.30	26.06.2011	04.08.2012	405	< 0.001
6	158.96	32	5.57	5.75	29.04.2012	06.12.2014	951	< 0.001
7	146.71	16	1.02	15.69	16.07.2017	18.11.2017	125	< 0.001
8	68.97	21	2.2	9.55	18.08.2019	22.02.2020	188	< 0.001
9	126.48	11	0.46	23.91	22.11.2009	21.08.2010	272	< 0.001
10	145.87	9	0.23	39.13	26.09.2021	22.01.2022	118	< 0.001
11	40.09	8	0.15	53.33	21.12.2014	28.03.2015	97	< 0.001
12	118.03	12	0.88	13.64	29.07.2018	28.09.2019	426	< 0.001
13	90.69	13	1.17	11.11	25.10.2020	03.04.2021	160	< 0.001
14	88.42	6	0.09	66.67	07.06.2020	25.07.2020	48	< 0.001
15	114.54	12	1.06	11.32	07.07.2013	31.08.2013	55	< 0.001
16	127.17	5	0.05	100.00	17.07.2022	23.07.2022	6	< 0.001
17	99.65	9	0.5	18.00	29.10.2017	07.07.2018	251	< 0.001
18	105.43	8	0.35	22.86	25.10.2020	12.12.2020	48	< 0.001
19	9.86	5	0.06	83.33	29.06.2014	19.07.2014	20	< 0.001
20	79.69	7	0.35	20.00	29.09.2019	28.12.2019	90	< 0.001
21	68.13	5	0.11	45.45	24.11.2013	08.03.2014	104	< 0.001
22	2.11	3	0.02	150.00	07.01.2018	13.01.2018	6	< 0.001
23	21.14	5	0.15	33.33	28.08.2016	10.12.2016	104	< 0.001
24	159.34	12	1.97	6.09	13.09.2020	05.02.2022	510	< 0.001

ODE – observed/expected (this is the ratio of the observed number to the expected number of ASF outbreaks within the cluster, given that the distribution is consistent with the null hypothesis, i.e. the value of the indicator determines the relative risk of new outbreaks within the cluster).

from the dead and hunted boars in the affected RF Subjects, is characterized by sporadic outbreaks in the same geographical areas. History of ASF outbreaks in wild boars is shown in Figure 1.

As we can see, there is a positive trend in infection detection both in dead and hunted animals. This trend may be explained by an increase in the number of the tested animals and by the improvement of veterinary surveillance in the RF Subjects[4]. Despite this, there are differences in the number of ASF outbreaks detected among dead wild boars (51.3% of the total number of the registered ones) and hunted wild boars (48.7%).

Spatiotemporal cluster analysis of ASF outbreaks in wild boars in the RF Subjects (in 2007–2022). Twenty four reliable clusters were identified by the cluster analysis of ASF outbreaks registered in dead wild boars in the affected regions of the Russian Federation (from 2007 to 2022). The peculiar characteristics of the clusters, as shown by the SaTScan software, are given in Table 1.

As Figure 2A shows, ASF clusters were mainly distributed in the center of the European part of Russia, as was demonstrated by the tests of material taken from dead wild boars. These clusters are located in the central and northwestern regions of the European part of the Russian Federation. In the Far East (Fig. 2B), the long-term presence and registration of ASF outbreaks in some parts of the Primorsky Krai and nearby result from a dense population of wild boars (more than 1 animal per 1000 ha)[5].

The spatiotemporal analysis has shown that the following geographical territories in the following clusters demonstrate the greatest probability of ASF registration in the wild boars who pose a relative risk of the disease transmission (Table 1): No. 11 (ODE = 53.33), No. 14 (ODE = 66.67), No. 16 (ODE = 100.00), No. 19 (ODE = 83.33), No. 22 (ODE = 150.00). Clusters No. 2, 4, 6, 12, 24 were characterized by the longest persistence of ASF agent associated with the virus persistence in the environment.

[4] FGBI "Center for Veterinary Medicine". Epidemic situation. Available at: https://xn----8sbfkcavba6bf4aedue4d.xn--p1ai/o-nas/informatsiya/epizooticheskaya-obstanovka (date of access: 23.01.2023).

[5] FNITS Hunt. Hunting resources. Available at: http://www.ohotcontrol.ru/resource (date of access: 23.01.2023).

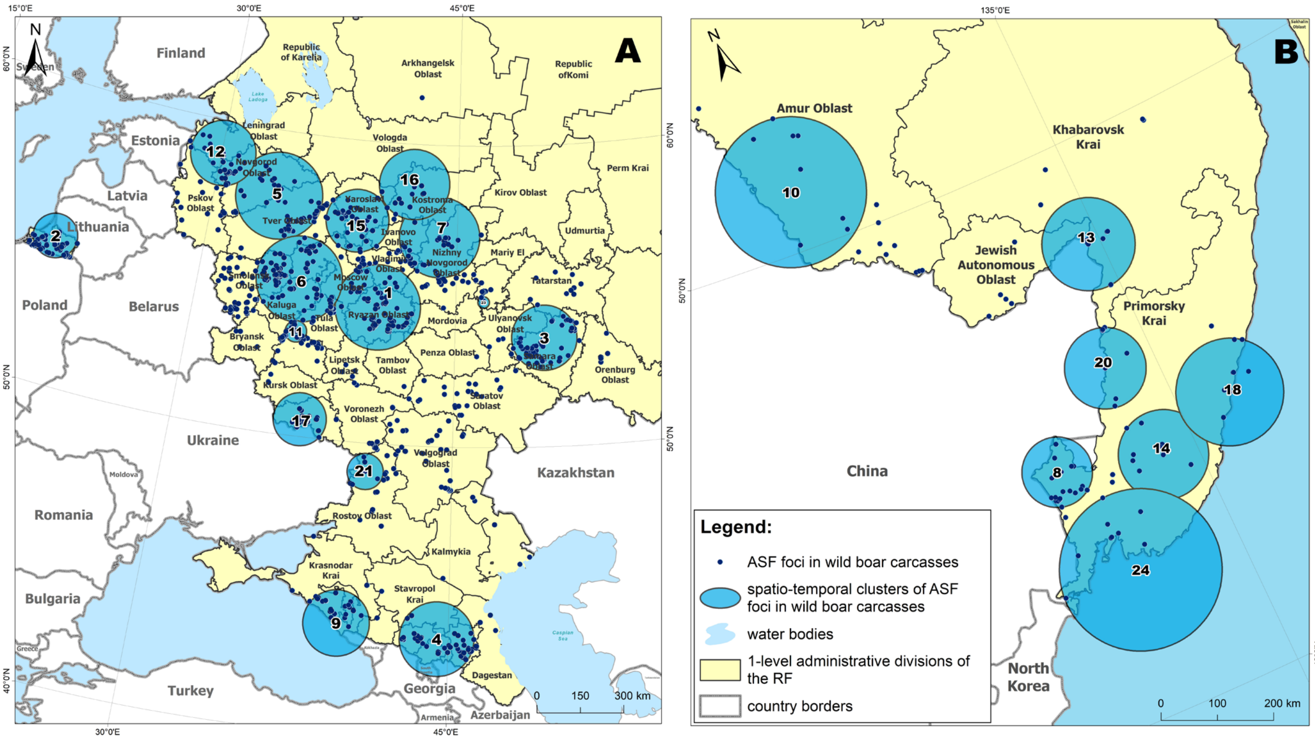

Fig. 2. Clusters of detected ASF outbreaks reported in the wild boar population (found dead) in the ASF-infected regions of the Russian Federation: A – European part; B – Far East (2007–2022)

The spatiotemporal analysis of ASF outbreaks (from 2007 to 2022) revealed 22 reliable clusters following detection of ASF pathogen or antibodies to the virus in hunted wild boars. Their main characteristics are given in Table 2. Based on the analysis results, it was determined that the greatest probability of new ASF epizooties (relative risk) is observed in the territories of the following clusters: No. 9 (ODE = 66.67), No. 11 (ODE = 71.43), No. 13 (ODE = 35.29), No. 16 (ODE = 50.00), No. 20 (ODE = 150.00), No. 21 (ODE = 57.14). Clusters No. 4, 5, 10, 12, 14, 18 are the longest to preserve ASF pathogen. Within the radius of these clusters, local enzootic territories were formed in the RF Subjects of the Far East, the Volga Region and the Center of the European part of the Russian Federation (Fig. 3A and 3B).

Based on the analysis of ASF clusters in wild boars, a steady spatiotemporal transmission trend is observed: the beginning of epizooties was observed in the North Caucasus and Southern Federal Districts (southern zone) – clusters No. 4, 8, 11. Later, there was a shift of clusters to the central and northern regions of the Russian Federation – clusters No. 5, 10, 15, 17, 19, 22, 23, their territories are characterized by higher animal population density. In recent years, the ASF epizooty has significantly expanded its geographical scope up to the Far East, where a significant number of ASF outbreaks in wild boars were registered from 2019 to 2022.

DISCUSSION

Wild boars play an important role in ASF epizootic cycle as regards the intra-population transmission, and potential transmission to domestic animals. Epizootological surveillance of ASF in wild boars is ensured either by testing all sick or dead animals for the virus genome or for antibodies to the virus (passive monitoring), or by testing all harvested wild boars, i.e. trapped, drive-hunted or shot dead during hunting or with the purpose of the population control (active monitoring) [2].

Information collected by the European Food Safety Agency (EFSA) from the Baltic States and Poland, indicates that passive surveillance increases a likelihood of earlier ASF detection. According to the data provided by many foreign researchers, most primary ASF cases in wild boars were registered during passive observation [25–27].

Research into ASF transmission in Eastern European countries has shown that the disease can persist with very low prevalence among susceptible animals, even if the density of wild boar population is low due to intensive hunting. Since ASF in wild boars has now become enzootic for many European countries, the question still remains unanswered, which type of monitoring (passive or active) is most effective to detect the virus, taking into account low prevalence and low population density. This is especially important, given that most countries, including the Russian Federation, are trying to eradicate ASF through progressive management of pig population aimed at reduction of wild boars [28, 29]. Even with a very low population density, there is a window of uncertainty, when ASF still circulates in animals, but practically is not detected, which complicates any further management, including a possible strategy of the disease eradication [30].

An idea was put forward by scientists from many countries that highly lethal animal infections, such as ASF, are self-limiting, which means that an epizooty rapidly reduces the number of susceptible populations due to the mass mortality [31]. The faster ASF spreads, the faster it reduces the wild boar population. If such

Table 2
Characteristics of spatiotemporal ASF outbreak clusters reported in wild boars hunted in the infected regions of the Russian Federation, 2007–2022

Cluster No.	Cluster radius, km	Number of ASF outbreaks observed	Number of ASF outbreaks expected	ODE	Cluster started on	Cluster ended on	Cluster lasted for, days	*P*-value
1	151.99	79	16.80	4.70	15.09.2013	24.05.2014	251	< 0.001
2	147.60	38	3.65	10.40	16.08.2015	30.07.2016	349	< 0.001
3	153.10	28	2.22	12.61	01.07.2012	23.03.2013	265	< 0.001
4	152.56	24	1.44	16.67	18.11.2007	02.01.2010	776	< 0.001
5	80.57	19	1.44	13.19	05.11.2017	18.05.2019	559	< 0.001
6	158.84	11	0.40	27.50	26.09.2021	30.10.2021	34	< 0.001
7	66.25	12	0.69	17.39	22.10.2017	28.04.2018	188	< 0.001
8	158.69	9	0.37	24.32	07.03.2010	19.02.2011	349	< 0.001
9	24.84	6	0.09	66.67	04.01.2015	07.02.2015	34	< 0.001
10	145.18	11	0.74	14.86	14.11.2021	19.11.2022	370	< 0.001
11	18.83	5	0.07	71.43	09.06.2013	22.06.2013	13	< 0.001
12	158.04	10	0.85	11.76	02.02.2020	20.02.2021	384	< 0.001
13	42.11	6	0.17	35.29	14.07.2019	19.10.2019	97	< 0.001
14	119.05	13	1.67	7.78	30.06.2019	02.01.2021	552	< 0.001
15	18.06	6	0.20	30.00	31.03.2013	20.07.2013	111	< 0.001
16	119.70	5	0.10	50.00	17.01.2021	04.03.2021	76	< 0.001
17	84.63	6	0.21	28.57	17.09.2017	16.12.2017	90	< 0.001
18	141.01	6	0.23	26.09	17.01.2010	12.02.2011	391	< 0.001
19	155.43	6	0.29	20.69	27.10.2019	18.01.2020	83	< 0.001
20	42.10	3	0.02	150.00	24.11.2019	30.11.2019	6	< 0.001
21	144.23	4	0.07	57.14	12.01.2020	07.03.2020	55	< 0.001
22	153.55	5	0.18	27.78	14.08.2016	12.11.2016	90	< 0.001

ODE – observed/expected (this is the ratio of the observed number to the expected number of ASF outbreaks within the cluster, given that the distribution is consistent with the null hypothesis, i.e. the value of the indicator determines the relative risk of new outbreaks within the cluster).

an infected population is simultaneously shot for sanitary or recreational purposes, then the number of wild boars dramatically reduces. Following the decrease in the number of animals, number of interspecies contacts also reduces, and epizooties turn into enzootic outbreaks. Eventually, ASF virus hides due to hunting activities. However, its re-emergence within a few months after lurking in the environment shall be naturally expected. Thus, the epizootological cycle of ASF in wild boars demonstrates that the virus has become enzootic in the affected territories and regularly spills over into disease-free areas [6, 29, 32].

The direct transmission can episodically peak after the breeding season, when the size of the animal population doubles and the growing animals (2–6 months old) explore the habitat, thus, intensifying interspecies contacts; or as a result of animal regrouping or gathering around feedlots [33–35].

Based on the data available in literature and following our own analysis of all the registered outbreaks, it was concluded that the passive monitoring reveals more ASF outbreaks than the active one, and the search for remains of wild boars proportionally increases the probability to detect infected wild boars [34, 36]. Therefore, further spread of ASF in the wild shall be mainly prevented by an active search for dead animals and notification of the relevant veterinary authorities. Such an approach is crucial for understanding epizootological situation at any phase of ASF epizooty, regardless of the wild boar population density [37].

The ASF clusters identified after testing material from hunted wild boars are mainly isolated from each other and look like non-overlapping geographical locations (Fig. 3A and 3B), which means the disease registered outbreaks are evenly distributed, very likely, due to established hunting quotas.

The wild boar hunting quota is set based on the density and total number of animals, in accordance with the approved regulations on permissible withdrawal, and is compared with the one indicated in the application submitted by hunting provider. Therefore, the potential number of wild boars is either kept at a constant level to preserve and regulate the number of animals, or is inflated to meet the interests of hunting providers by increasing the number of the set quotas.

The ASF clusters identified after testing biomaterial from dead animals (Fig. 2A and 2B), generally do not coincide with the clusters identified after testing the hunted

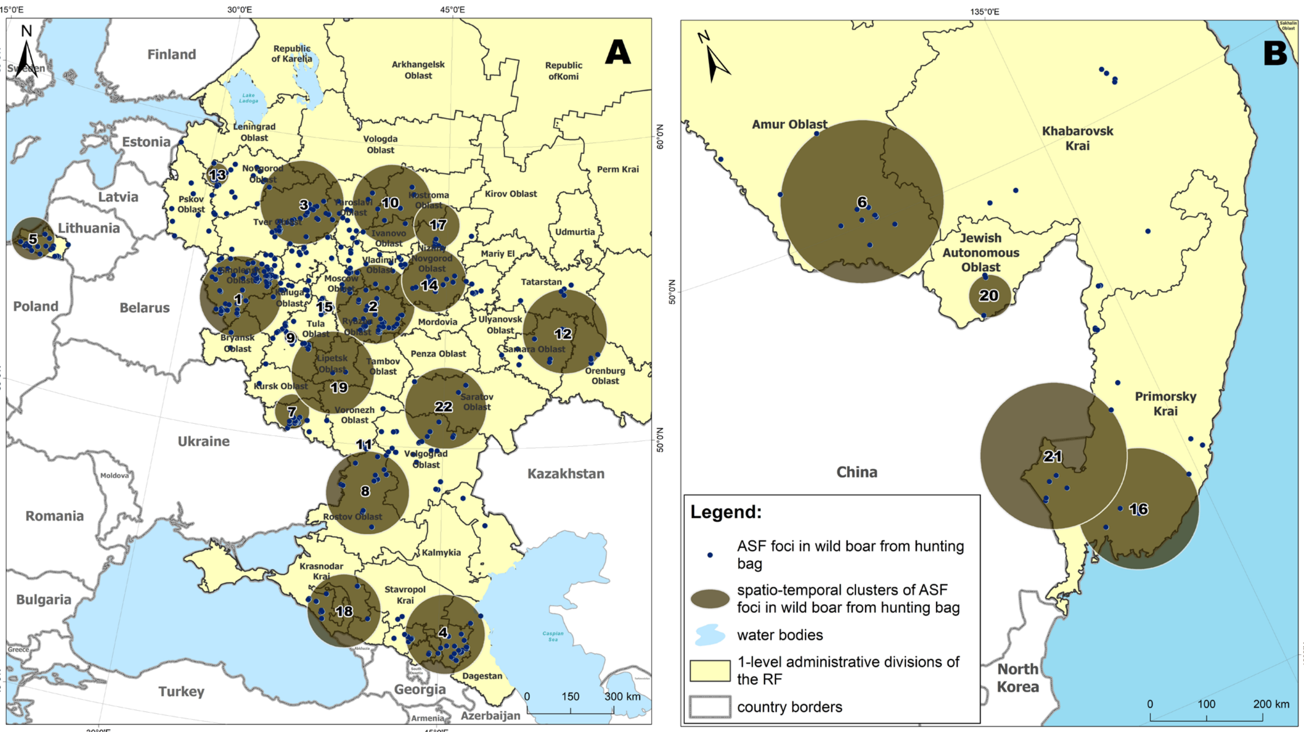

Fig. 3. Clusters of detected ASF outbreaks reported in the wild boar population (hunted animals) in the ASF-infected regions of the Russian Federation: A – European part; B – Far East (2007–2022)

boars, which may suggest ASF virus circulation in the non-hunting territories. It may also mean that not all samples from the shot animals are sent for laboratory tests; dead boars are detected late and are untimely destroyed by owners/tenants of hunting sites without laboratory test results.

As the FGBI "Center for Veterinary Medicine" informs on the number of registered ASF outbreaks, most boars who died from ASF were found in the summer-autumn period. This fact can be apparently associated with active human economic activity, including hunting. The space-time non-coincidence between ASF clusters (both in wild boars dead from the disease or shot), may prove the effectiveness of passive monitoring measures, and makes it possible to identify significantly more infected animals, thus, expanding the ASF detection scope.

The short-term ASF clusters identified in the spatiotemporal analysis and registered after detection of dead animals; suggest that the pathogen currently circulates in the wild boars in the areas of the most affected subjects of the Russian Federation. At the same time, the relative risk of registering new ASF outbreaks in short-term clusters is much higher than that in the long-term ones, presumably associated with such major risk factors of ASF transmission as human economic activity, migration of wild boars, and poor biosafety during hunting.

CONCLUSION

The studies show that measures taken to prevent the disease in wild susceptible animals in the territories that have long been disease-affected shall entail active search, detection and safe disposal of dead boars (or their remains). It is also required to inform potentially interested parties (such as hunters, farmers, veterinarians) about the importance of these activities. Moreover, it is necessary to sustainably reduce the abundance of wild boars. The spatiotemporal cluster analysis revealed local epizooties, helped to study peculiarities of their emergence in the context of dividing ASF outbreaks into groups following tests of biomaterial from the detected dead and hunted wild boars or their remains. Understanding the trends and patterns of ASF transmission in the wild boars, makes it possible to improve the measures taken within the boundaries of the risk zone where the epizooties may occur.

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