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Spatio-temporal analysis of rabies in animals in Ukraine over 2019–2023

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Rabies is an extremely dangerous zoonotic disease caused by a neurotropic virus of the genus *Lyssavirus*. All mammals, including carnivores and omnivores, are susceptible to this disease. Foxes, dogs, cats, and other wild and domestic animals require special attention with regard to rabies. The aim of this study is a comprehensive spatial and temporal analysis of rabies cases among animals in Ukraine from 2019 to 2023, with a focus on identifying high-risk areas and trends over time. A retrospective epidemiological analysis of rabies incidence among different animal species in Ukraine for the period 2019–2023 was conducted. Data were collected from reports of regional laboratories of the State Service of Ukraine on Food Safety and Consumer Protection, research data from the Research Institute of Laboratory Diagnostics and Veterinary and Sanitary Expertise and included confirmed rabies cases among different animal species such as foxes, cats, dogs, cattle and others. The Kernel Density Estimation (KDE) method was used to analyze the spatial distribution and intensity of rabies cases, and the directional distribution method was used to estimate the distribution and central tendency of rabies cases. Data visualization was performed using Quantum GIS software. The analysis revealed 5,405 rabies cases over the five-year period, with the highest density of cases in the Central and Northern Regions, particularly in Poltava, Kyiv, and Kharkiv oblasts. In 2020 and 2021, there was a marked spread of rabies cases to the Southern and Eastern Regions. Core density assessment maps showed consistently high levels of rabies intensity in the Central and Northern Regions, with some increase in the Southern Regions in 2020–2021. Foxes were the most affected animal species, accounting for 39.5% of cases, followed by cats (27.8%) and dogs (23.1%). The spatial and temporal analysis highlights persistent high levels of rabies in central and northern Ukraine, with new hotspots in the south and east. This study emphasizes the urgent need for targeted rabies control measures, including vaccination and monitoring, especially in identified high-risk areas. Effective rabies control requires a combination of improved diagnostic tools, affordable vaccines, and public awareness campaigns to reduce the spread of the disease among domestic and wild animals.

Keywords: epizootic; zoonotic disease risks; *Lyssavirus*; pathogen sources; One Health; mapping; GIS.

Introduction

Rabies is an extremely dangerous zoonotic disease caused by a neurotropic virus of the genus *Lyssavirus*. It is believed that all mammals are susceptible to this disease (Warrell & Warrell, 2015; Troupin et al., 2016; Parize et al., 2018). Rabies virus circulation is maintained by reservoir animals on many continents, including predatory and carnivorous animals (dogs, foxes, raccoon dogs, raccoons, mongooses, ferrets, badgers, skunks, etc.) (Fooks et al., 2014). In nature, *Lyssaviruses* are also supported by bat hosts (bats) (Troupin et al., 2016; Fooks et al., 2017; Parize et al., 2018).

According to rabies scientists, rabies also belongs to the group of transmissible diseases that are of major importance for the public economy and health care, as well as in the international trade of animals and animal products (Kumar et al., 2023; Lu et al., 2023). Currently, rabies is a particular burden for developing countries, African and Asian countries. According to WHO experts, the risk of human infection with rabies is quite high in Eurasia, southern Latin America and Africa. Rabies is widespread almost all over the world, with the exception of Australia and Antarctica (Kumar et al., 2023). Canine rabies poses a threat to more than 3.3 billion people worldwide, as well as to domestic and wild animals. Researchers classify the disease as belonging to the group of neglected

tropical and zoonotic diseases. Today, the disease is a serious global problem for health authorities in more than 150 countries and territories (Kumar et al., 2023). Rabies, as a disease, is characterized by almost absolute mortality rates, as fewer than 20 properly documented cases of human survival in the treatment of this disease have been reported worldwide (Jackson, 2016; Subramaniam, 2016; Rupprecht et al., 2017).

This disease kills more than 59,000 people worldwide every year. It should be noted that 95% of rabies cases are reported in Asia and Africa (Hampson et al., 2015; Coetzer et al., 2019). Rabies most actively affects children, with 40% of them under the age of 15 (Cleaveland et al., 2002). Deaths can be prevented with adequate post-exposure prophylaxis using immunoglobulins and vaccines (WHO, 2013), but access to these means is difficult for the majority of the population in developing countries (Nel, 2013; Dobet et al., 2014; Hampson et al., 2015). The annual global economic losses from rabies, for example, caused by dogs alone, amount to 8.6 billion US dollars (Hampson et al., 2015).

Rabies researchers predict that human rabies will be eliminated in the twenty-first century. The goal is to eliminate the disease by preventing the transmission of the virus between land animals (domestic and wild) and humans. Realizing this vision requires a combination of improved diagnostic tools in the veterinary and medical infrastructure, access to cheap

and effective vaccines, antiviral drugs and immunoglobulins, and improved educational practices and awareness of rabies in endemic regions around the world (Banyard et al., 2013). Experts from countries where rabies was eliminated paid special attention to enhanced disease surveillance and modern diagnostics, placed significant emphasis on the use of preventive vaccination (both domestic and wild animals), paid considerable attention to the control of wildlife and farm animals, raised public awareness and conducted educational activities on the dangers of the disease (Banyard et al., 2013; Vigilato et al., 2013). Rabies caused by dogs is planned to be eliminated globally by 2030 in all endemic areas (Abela-Ridder et al., 2016). Rabies in wild animals will require even more effective control to prevent the virus from re-entering domestic dogs from wildlife reservoirs (Elmore et al., 2017). Successes in the elimination of canine rabies in Europe in 1978–2010 and in some regions of Latin America show that the fight against this disease can be quite effective (Abela-Ridder, 2015).

Despite the measures taken to control and spread rabies, it has not yet been possible to eliminate the disease even in certain regions of our country. Many aspects of rabies in Ukraine are not fully understood. In previous scientific works, we analyzed the epizootic situation in Ukraine for the period 1999–2018 (Komienko et al., 2019). The current work characterizes the rabies epizootic situation over the past 5 years using map visualization with Quantum GIS.

Materials and methods

The authors of the article conducted a retrospective epidemiological analysis of the incidence of rabies in animals in Ukraine for the period 2019–2023. The study characterized the epidemiological situation of rabies among different species of animals (wild, domestic, domesticated): red foxes (*Vulpes vulpes* Linnaeus, 1758), cats (*Felis catus* Linnaeus, 1758), dogs (*Canis lupus familiaris* Linnaeus, 1758), cattle (*Bos taurus* Linnaeus, 1758), sheep (*Ovis aries* Linnaeus, 1758), goats (*Capra hircus* Linnaeus, 1758), horses (*Equus caballus* Linnaeus, 1758), European hedgehogs (*Erinaceus europaeus* Linnaeus, 1758), bats (Chiroptera Blumenbach, 1779), European pine martens (*Martes martes* Linnaeus, 1758), brown rats (*Rattus norvegicus* Berkenhout, 1769), European badgers (*Meles meles* Linnaeus, 1758), raccoon dogs (*Nyctereutes procyonoides* Gray, 1834), wolves (*Canis lupus* Linnaeus, 1758), European hamsters (*Crictus crictus* Linnaeus, 1758), golden jackals (*Canis aureus* Linnaeus, 1758), European hares (*Lepus europaeus* Pallas, 1778), red squirrels (*Sciurus vulgaris* Linnaeus, 1758), roe deer (*Capreolus capreolus* Linnaeus, 1758), common least weasels (*Mustela nivalis* Linnaeus, 1766), ferrets (*Mustela putorius furo* Linnaeus, 1758), European beavers (*Castor fiber* Linnaeus, 1758), Eurasian otter (*Lutra lutra* Brisson, 1762), wild boars (*Sus scrofa* Linnaeus, 1758), European moles (*Talpa europaea* Linnaeus, 1758), house mice (*Mus musculus* Linnaeus, 1758), alpine marmots (*Marmota marmota* Linnaeus, 1758).

The source of data for the analysis of rabies outbreaks in Ukraine among different animal species was the reports of regional laboratories of the State Service of Ukraine on Food Safety and Consumer Protection (SSUFSCP), research data from the Research Institute of Laboratory Diagnostics and Veterinary and Sanitary Expertise (SRILDVSE) (Kyiv, Ukraine). The data from the 1–Vet and 2–Vet reports for 2019–2023 were systematized and analyzed. All rabies cases presented in the publication are confirmed by diagnostic tests performed in accredited laboratories (Immunofluorescence Assay, bioassay on laboratory animals). The sample did not contain data from the temporarily occupied territories of the Autonomous Republic of Crimea, Sevastopol and parts of Donetsk and Luhansk regions. A total of 66,781 brain samples from different species of animals were analyzed, of which 5,405 cases of positive rabies diagnosis were identified, among which the percentage of positive rabies tests in red foxes was 4.2%, while among domestic carnivores this figure reached 18.8%. Cats showed 21.3% of positive tests, and dogs – 16.4%. A much higher level of positive rabies tests was observed among farm animals, where this figure reached 68.2%, in particular among cattle – 75.9%, small cattle – 43.9%, and horses – 58.8%. Other animals demonstrated 9.6% of positive rabies tests, in particular, among European hedgehogs this figure is 1.6%, among bats – 2.7%, European pine martens – 33.7%,

brown rats – 2.5%, European badgers – 48.5%, raccoon dogs – 13.2%, wolves – 8.0%, European hamsters – 3.8%, golden jackals – 9.7%, European hares – 5.1%, red squirrels – 3.3%, roe deer – 11.1%, ferrets – 14.3%, European beavers – 12.0%, Eurasian otters – 33.3%, and wild boars – 30.8%. European moles, common least weasels, and polecats did not show any positive tests, and among house mice, positive tests amounted to 1.1%. In general, the percentage of positive rabies tests among all samples tested was 8.1%.

Positive samples underwent descriptive statistical analysis and were categorized by year, animal species, and administrative locations with geospatial coordinates (longitude and latitude). The overall dynamics of rabies cases, dynamics by animal species, and characteristics of the rabies epizootic process were also determined, including density and localization. In other words, the analysis focused only on confirmed positive cases of rabies without control of negative samples. MedCalc software (version 22.017, MedCalc Software Ltd, Ostend, Belgium) was used for statistical analysis of the data and calculation of the chi-square test to assess the statistical significance of changes between the percentage of annual positive cases by animal species during the study period. Chi-square was determined for the group in which the value of all indicators was higher than $n = 5$.

Information on the total number of susceptible animals was obtained from the reports of the State Service of Ukraine for Food Safety and Consumer Protection and reports of the State Statistics Service of Ukraine (<http://ukrstat.gov.ua>). Cartographic visualization was performed using Quantum GIS 3.28.7 software (DIVA, 2023), an open source software available for download at www.qgis.org/ru/site/forusers/download.html. The Heatmap tool was used to identify and visualize clusters of rabies cases by year and animal species. This tool converts (smooths) a point layer into a continuous surface of point density. The main parameter of this tool is the search radius, which controls the degree of smoothing. The optimal search radius was calculated using the method proposed by Murray (2010). The pixel size of the output raster was set to 100 m. Other parameters were left as default. Vector layers of administrative boundaries of Ukraine for oblasts and rayons were obtained from the geoBoundaries database: Global Database of Political Administrative Boundaries; QGIS provides information on the boundaries of Ukrainian oblasts as of 2023 year.

Results

During the period 2019–2023, 5,405 rabies cases were registered in Ukraine. In 2019, 1,437 cases were registered, in 2020 – 1,277, in 2021 – 848, in 2022 – 599, in 2023 – 1,244 cases (Fig. 1). The decrease in the number of reported rabies cases is explained by the presence of hostilities in our country, sometimes even the cessation of diagnostic tests and preventive vaccinations, both among wild and domestic animals.

The study found that the percentage of positive cases among different groups of animals fluctuated significantly during 2019–2023 (Table 1). Statistical analysis, in particular the chi-square test, confirmed that these fluctuations were statistically significant for some study groups. Among red foxes, there was a downward trend in the percentage of positive cases from 4.9% in 2019 to 2.7% in 2021, but in 2023 there was a sharp increase to 12.5%. The chi-square analysis for this group showed the highest statistical significance of the difference ($\chi^2 = 433.3$, $df = 4$, $P < 0.0001$), which emphasizes the significance of the changes in this population. For domestic carnivores (dogs and cats), the overall trend was upward, with the highest rate of 30.5% in 2023 compared to 13.4% in 2019. This group also demonstrated the high statistical significance of the changes ($\chi^2 = 345.8$, $df = 4$, $P < 0.0001$), indicating a steady upward trend in the incidence. Farm animals (cattle, sheep, goats, horses) showed the highest percentage of positive cases among all groups, with peak values of 75.7% in 2020 and 74.7% in 2023. The lowest rate for this group was recorded in 2022 and amounted to 52.7%. Although the chi-square value was lower compared to other groups, the fluctuations were still statistically significant ($\chi^2 = 17.8$, $df = 4$, $P = 0.0014$). The other animal groups showed the smallest fluctuations, but also had statistically significant changes ($\chi^2 = 9.5$, $df = 4$, $P = 0.0500$). The lowest rate was recorded in 2020 (6.8%), and the highest in 2023 (14.4%).

It is worth noting that for all animal groups, 2023 was characterized by the highest rates of positive cases, which may indicate a general upward trend in the incidence during this period. These results emphasize the importance of continuous monitoring and taking appropriate measures to control the disease among different animal groups.

Table 1
Percentage of positive test results for rabies of different species in Ukraine in 2019–2023

Animal species	Positive examination results, %.					2019–2023
	2019	2020	2021	2022	2023	
Red fox	4.9	4.1	2.7	2.9	12.5	4.2***
Cat	16.0	20.7	17.5	18.7	33.9	21.3***
Dog	11.0	17.1	13.5	15.6	26.9	16.4***
Cattle	84.7	80.5	74.0	58.0	77.7	75.9***
Sheep	28.6	57.1	41.2	38.5	73.7	47.6
Goat	30.0	55.6	22.2	28.6	46.1	37.5
Horses	50.0	100.0	33.3	50.0	75.0	58.8
European hedgehog	6.3	0.0	0.0	0.0	0.0	1.6
Bat	8.3	0.0	0.0	0.0	0.0	2.7
European pine marten	24.0	22.2	20.0	53.8	52.4	33.7
Brown rat	2.4	2.8	3.0	5.3	0.0	2.5
European badger	31.6	66.7	100.0	33.3	100.0	48.5
Raccoon dog	17.5	8.5	10.7	4.3	41.7	13.2
Wolf	14.3	0.0	4.0	0.0	16.7	8.0
European hamster	9.4	0.0	0.0	5.3	4.8	3.8
Golden jackal	12.5	5.9	12.3	0.0	66.7	9.7
European hare	22.2	0.0	0.0	0.0	0.0	5.1
Red squirrel	0.0	3.2	11.1	0.0	0.0	3.3
Roe deer	0.0	50.0	0.0	0.0	0.0	11.1
Common least weasel	0.0	0.0	0.0	0.0	0.0	0.0
Ferret	0.0	33.3	33.3	0.0	0.0	14.3
European beaver	0.0	0.0	18.2	0.0	25.0	12.0
Eurasian otter	0.0	0.0	100.0	0.0	0.0	33.3
Wild boar	0.0	25.0	0.0	50.0	50.0	30.8
European mole	0.0	0.0	0.0	0.0	0.0	0.0
House mouse	0.0	0.0	0.0	7.7	0.0	1.1
Alpine marmot	0.0	0.0	0.0	0.0	0.0	0.0
Total	6.8	7.2	5.8	7.0	24.5	8.1

Note: *** – $P < 0.001$ indicates a statistically significant change in the detection of positive results during the study period according to the chi-square analysis.

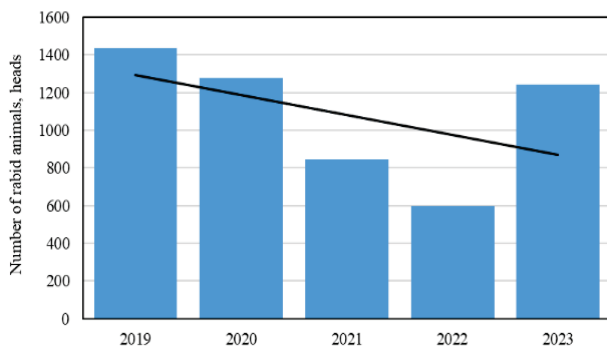


Fig. 1. Dynamics of rabies cases among animals in Ukraine (2019–2023 years), $n = 5,405$

The numbers of rabies cases in animals of different species for 2019–2023 (Fig. 2), in turn, show a downward trend for red foxes, and upward trends for domestic carnivores (dogs and cats) and farm productive animals. Although the number of wildlife cases detected is decreasing, this is probably not due to a decrease in the intensity of the epizootic process, but depends on the number of studies conducted. The increase in the number of detected cases among domestic animals confirms this assumption, along with the sharp increase in the percentage of positive rabies tests in red foxes in 2023.

From the data shown in Figure 3 clearly shows the seasonality of rabies in all animal species. Thus, the largest number of sick animals in the analyzed years was detected in the period from September to February, respectively 364, 494, 720, 948, 564, 515. The smallest number of sick animals was detected from May to September, respectively – 309, 255,

223, 212, 265, 289. The peak values of the number of sick animals occurred in November–December, the minimum values of this indicator were recorded in May–June. Thus, the ratio of sick animals in these places was 1:8.72–1:11.31 in 2019, 1:2.34–1:5.38 in 2020, 1:1.73–1:3.82 in 2021, 1:1.97–1:1.93 in 2022, and 1:3.2–1:2.12 in 2023. The ratio of these months for all five years is 1:3.09–1:4.47.

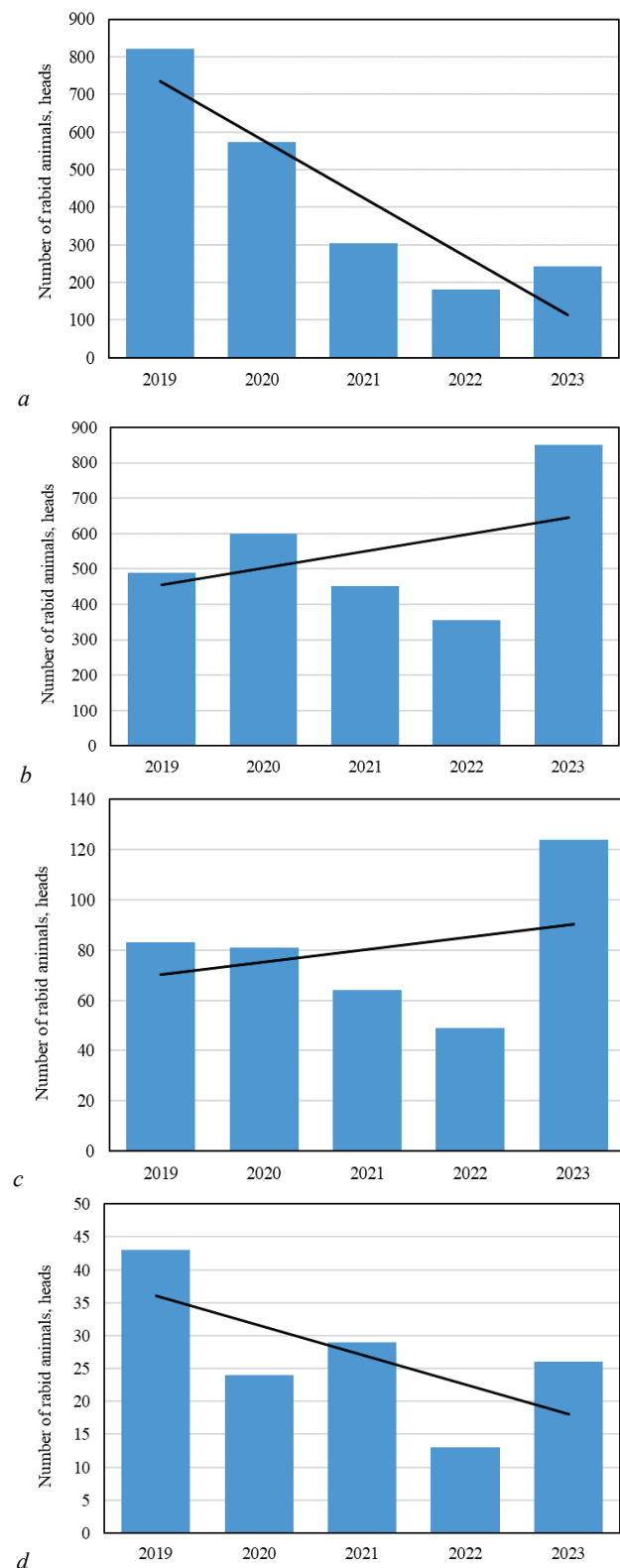


Fig. 2. Epidemic curves of rabies cases among different animals in Ukraine 2019–2023: a – red foxes ($n = 2,122$); b – domestic carnivores ($n = 2,748$); c – farm animals (cattle, small ruminants, horses) ($n = 401$); d – other animals ($n = 135$)

Analyzing the data in Figure 4, it should be noted that 28 species of animals were affected by rabies during the study period. Of these, 7 species were domestic and pets and 21 species were wild animals. The disease was detected among domesticated animals: cats, dogs, cattle, sheep, goats, horses, European hamsters; among wild animals: red foxes, European hedgehogs, bats, European pine martens, brown rats, European badgers, raccoon dogs, wolves, golden jackals, European hares, red squirrels, roe deer, common least weasels, ferrets, European beavers, Eurasian otters, wild boars and house mice. Domestic animals accounted for 3,149 cases (58.3%) in total, and wild animals – 2,257 or 41.7%.

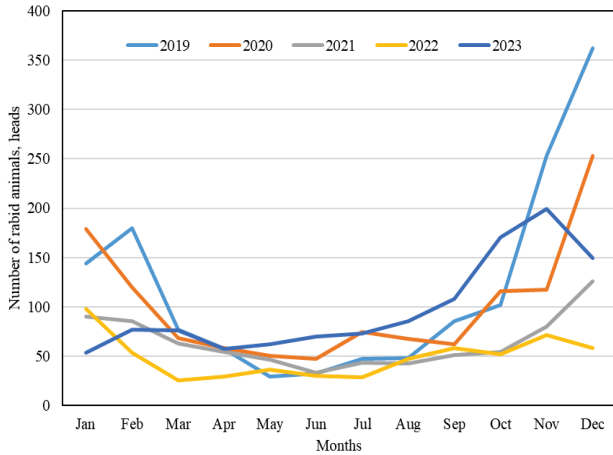


Fig. 3. Epidemic curves of rabies cases among animals in Ukraine, by month, 2019–2023, n = 5405

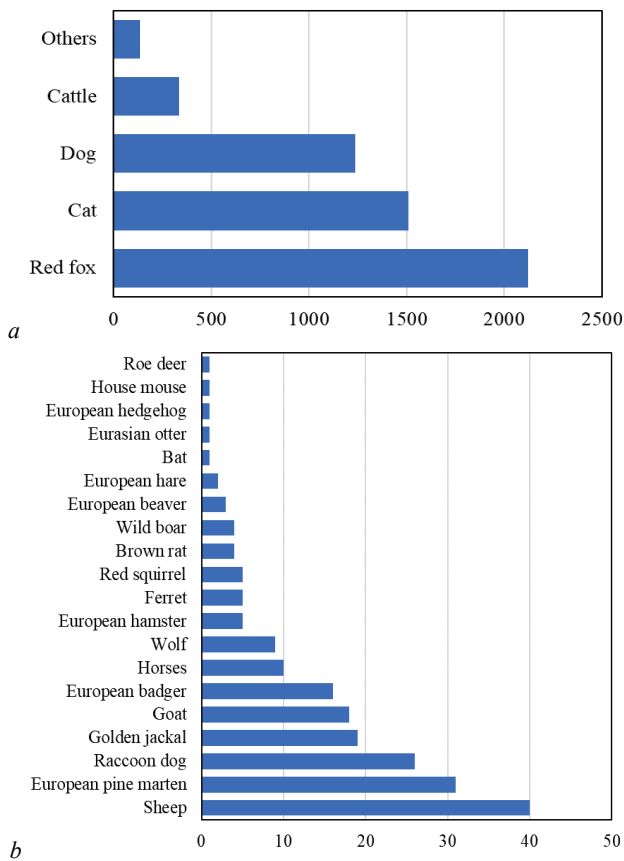


Fig. 4. Species composition of rabies in animals in Ukraine (2019–2023 years): a – dominant species b – structure of others

In general, the largest number of animals among the affected species was observed among red foxes – 2,122 head or 39.3% of samples, cats – 1,510 or 27.9%, dogs – 1,238 or 22.9%, cattle – 333 or 6.2%, small ruminants – 58 or 1.1%, European pine martens – 31 or 0.6%, European bad-

gers – 16 or 0.3%, raccoon dogs – 26 or 0.5%, golden jackals – 19 head or 0.43% of samples. Red foxes occupy a dominant position among sick wild animals of various species. Among them, 2,122 cases were observed during the analyzed period, which is 94.0% of all wild animals. Among domestic animals, the largest number of rabies cases was observed among cats and dogs, which amounted to 1,510 (48.0%) and 1,238 (39.3%) cases, respectively.

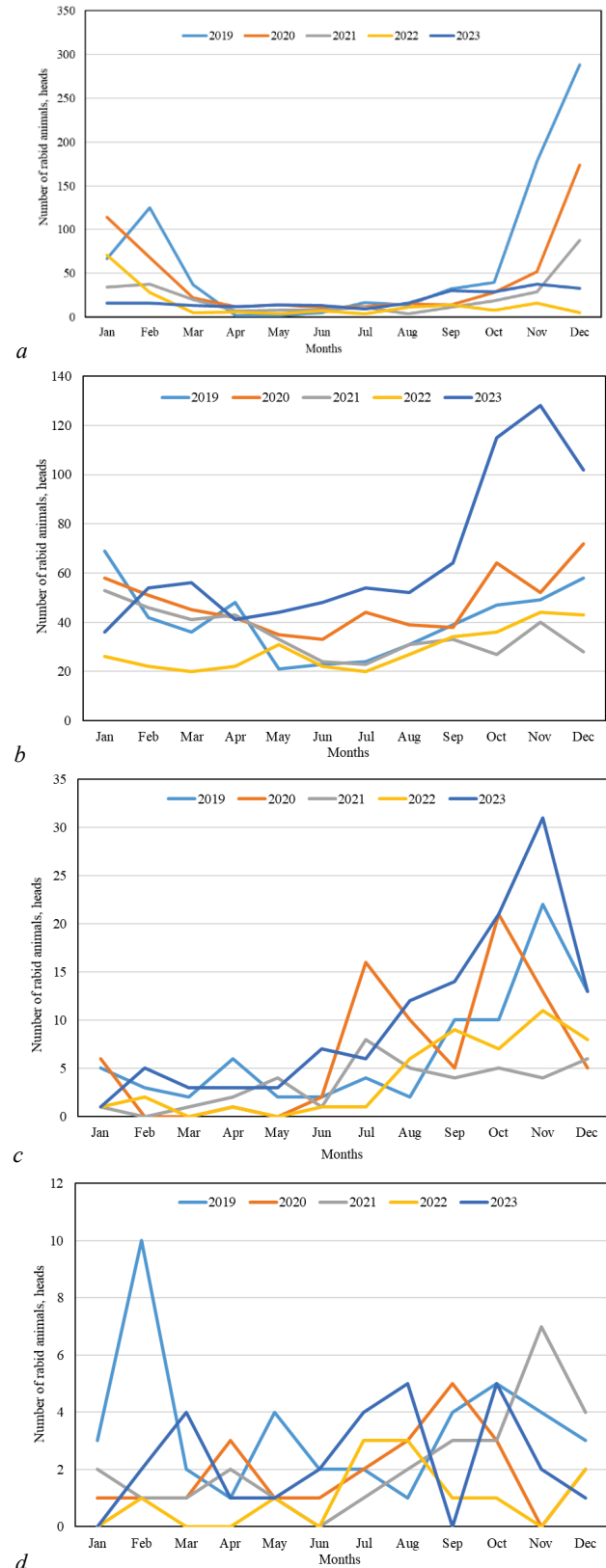


Fig. 5. Epidemic curves of rabies cases in Ukraine, by month (2019–2023): a – red foxes (n = 2122); b – domestic carnivores

($n = 2748$); c – farm animals (cattle, small ruminants, horses)
 ($n = 401$); d – other animals ($n = 135$)

Figure 5 shows the incidence of animals of different species by month for the analyzed period. The peak trends in the incidence among red foxes coincide with the peak trends in the seasonality of rabies. The leading role of the red fox as a source and reservoir of the infectious agent for this disease is confirmed by the actual overlap of trends in the graphs of incidence among domestic carnivores, farm animals, and other species of diseased animals. In some years, we observe an increase in the incidence among certain species even in the summer months, which, so to speak, does not fit into the specified framework of “fox-seasonality,” but given the length of the incubation period for rabies, such things only confirm our thesis about the presence of these trends. After all, in 70% of sick domestic animals, the incubation period for rabies lasts from 15 to 60 days after being bitten or mauled by a sick animal.

During the analyzed period (2019–2023), diagnostic institutions of the State Service of Ukraine for Food Safety and Consumer Protection received 66,781 samples of biological material suspected of rabies from different species of animals, 5,405 or 8.1% of the samples were positive.

The number of studies is steadily decreasing from year to year (a steady trend). Thus, in 2019, 21,035 samples of biological material or 31.5% of the total number were tested, in 2020 – 17,623 or 26.4%, in 2021 – 14,534 or 21.8%, in 2022 – 8,502 or 12.7%, in 2023 5,087 samples of biological material or 7.6% were tested. This trend is explained primarily by a 90% reduction in the number of district diagnostic laboratories, which in most cases sent materials for testing to regional diagnostic institutions and institutes. Based on the results of the data analysis, we have compiled “Maps of the distribution of rabies cases in 2019–2023 years”, which visualize the number of rabies cases of Ukrainian regions using different color intensity for each region.

The analysis of the spatial and temporal distribution of rabies cases in Ukraine in 2019–2023 (Fig. 6) shows that in 2019, rabies cases were widespread throughout Ukraine, with the highest concentration in the Central and Eastern regions. In particular, Poltava, Kharkiv, and Dnipropetrovska oblasts showed the highest levels, with rates ranging from 70–346 cases. Western regions such as Lviv and Volyn had significantly lower rates, with less than 20 cases. In 2020, there was an overall increase in rabies cases compared to the previous year.

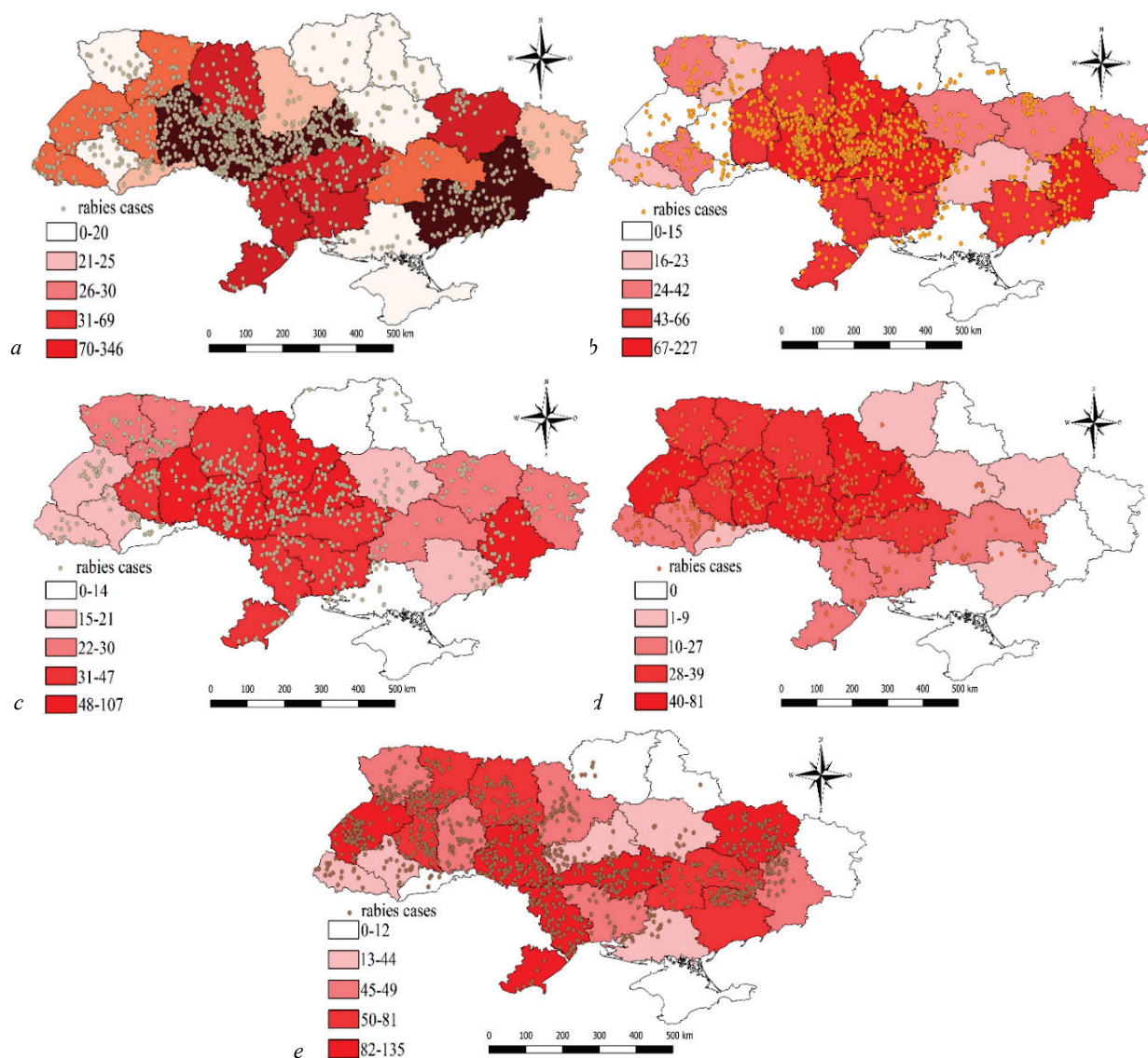


Fig. 6. Maps of the distribution of rabies cases in 2019–2023 years: a – 2019; b – 2020; c – 2021; d – 2022; e – 2023

High incidence rates remain in the Central and Eastern regions, but with a higher intensity. In particular, Chernihiv and Kyiv oblasts showed a significant increase, reaching 67–227 cases. Western regions continued to show relatively low rates, although some of them, such as Lviv, also showed a slight increase in the number of cases. In 2021, the highest ra-

bies incidence rates were observed in the Central and Northern regions of Ukraine. Vinnytsia, Kyiv and Kharkiv oblasts showed the highest levels, reaching up to 107 cases. At the same time, the Western regions, in particular Zakarpattia, showed relatively low incidence rates (0–14 cases). In 2022, the distribution of rabies cases showed stable rates in the Central

and Northern regions of Ukraine, although the overall incidence rate decreased slightly compared to 2021. The highest rates remain in the Central regions, such as Vinnytsia and Kyiv, with up to 81 cases. The Southern and Eastern regions, including Odesa and Donetsk, also show elevated levels of rabies cases. In 2023, there is an overall decrease in the number of rabies cases in most regions of Ukraine. However, the Central and Southern regions remain the most affected, with particularly high rates in Kirovohrad oblast, where the number of cases reached 135. The Western regions continue to show the lowest incidence rates, in particular Zakarpattia and Chernivtsi oblasts.

The general trend over the observation period was to maintain a consistently high incidence rate in the Central and Eastern regions of the country, while the Western regions showed consistently lower incidence rates.

The analysis of the spatial and temporal distribution of rabies cases using the kernel density estimation in 2019–2023 demonstrates trends in the intensity of the epizootic process and the presence of hot spots in Ukraine (Fig. 7). In 2019, the kernel density estimates indicate high concentrations of rabies cases in the Central and Northern regions of Ukraine. The highest density is observed in Poltava, Kyiv and Kharkiv oblasts, where the coloration intensity is the most intense. Southern and Western regions show a lower density of cases, with the least intense coloration. In 2020, the rabies case density pattern changed. The highest concentration

remains in the Central regions, but has increased in the Southeastern Regions, such as Dnipropetrovska and Zaporizka oblasts. Compared to 2019, the Western regions remain with a relatively low density of cases. In 2021, the high density of rabies cases continued in the Central and Northern Regions of Ukraine. The rates in Poltava, Kyiv and Kharkiv oblasts remain high. The Southern regions show a slight increase in the density of cases, which indicates the unfolding of the epizootic process in these areas. In 2022, the trend continued, with a high concentration of cases in the Central and Northern Regions, with Vinnytsia and Kyiv oblasts showing the highest density of cases. The Southern and Western Regions showed lower rabies case densities. In 2023, the pattern of rabies case density shows a slight decrease compared to previous years, but the Central Regions are still the most affected regions. The highest density is observed in Poltava, Kyiv and Kharkiv oblasts.

An assessment of the density of the rabies core in Ukraine for the period from 2019 to 2023 indicates consistently high levels of epizootic intensity in the Central and Northern regions. The highest density of cases during all years of observation is concentrated in Poltava, Kyiv and Kharkiv oblasts. The Southern and Western regions show lower levels of incidence, although some increase in the density of cases was observed in the Southern Regions in 2020–2021.

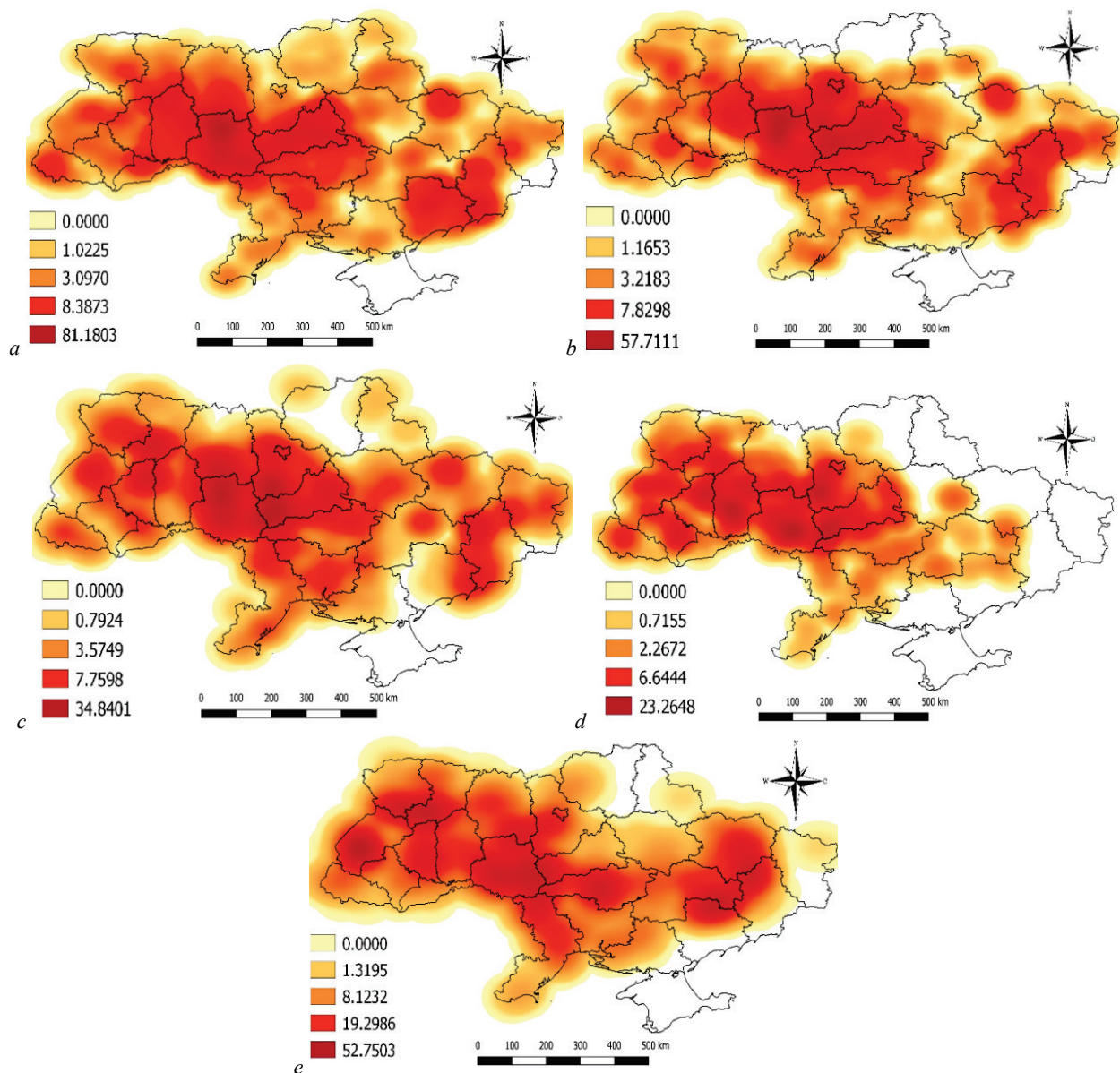


Fig. 7. Kernel density estimation of rabies cases in 2019–2023 years: *a*–2019; *b*–2020; *c*–2021; *d*–2022; *e*–2023, areas with the highest density of rabies cases are highlighted in more intense color, and areas with the lowest density are highlighted in less intense color

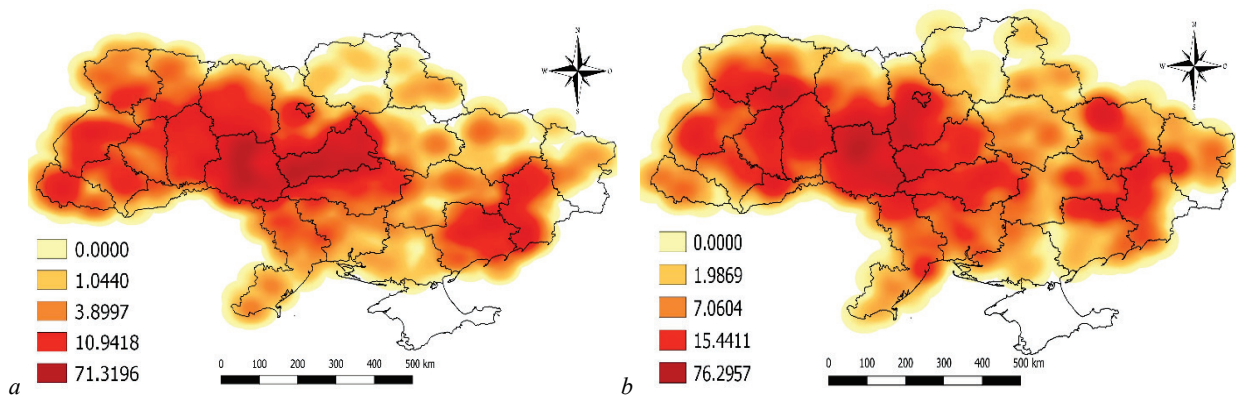


Fig. 8. Kernel density estimation of rabies cases in red foxes and domestic carnivores in 2019–2023 years: *a* – red foxes; *b* – domestic carnivores (dogs and cats), areas with the highest density of rabies cases are highlighted in more intense color, and areas with the lowest density are highlighted in less intense color across all years

Spatial and temporal estimation of the density of the rabies core among foxes for the period 2019–2023 (Fig. 8) shows that the highest density of cases is observed in the Central and Northern Regions of Ukraine, in particular in Poltava, Kyiv and Kharkiv oblasts. Southern and Western regions have significantly lower case densities, which is reflected in the less intense colors. The lowest densities are observed in the Western regions, such as Zakarpattia and Lviv oblasts, where the density of cases is almost non-existent. The highest density of rabies cases among domestic carnivores (dogs and cats) is also concentrated in the Central and Northern regions, with the highest color intensity in Kyiv, Poltava, and Kharkiv oblasts. However, unlike foxes, there is a significant concentration of cases among domestic carnivores in the Southern regions, particularly in Odesa oblast. Western regions continue to have the lowest density of cases.

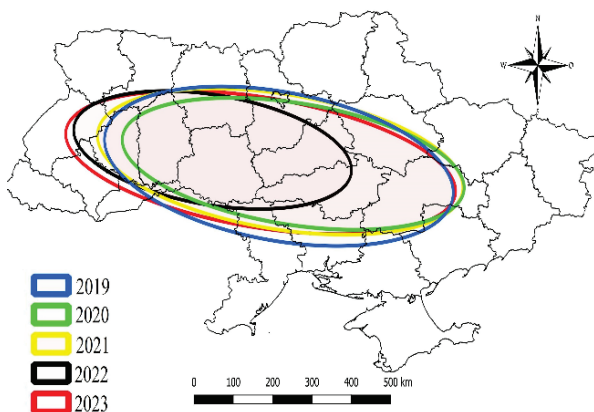


Fig. 9. Ellipse of standard deviations of rabies cases in 2019–2023 years: different colors indicate the ellipse of standard deviations in different years of observation

Figure 9 shows the distribution of rabies cases in Ukraine using standard deviation ellipses for the period from 2019 to 2023. Each ellipse represents the directional distribution of rabies cases for a given year, showing the areas with the highest and lowest density of cases. In 2019, the ellipse covers the Central and Northern Regions of Ukraine, concentrating high rates of rabies cases in Poltava, Kyiv and Kharkiv oblasts, in 2020, the ellipse expands to the east, also including Eastern Regions such as Donetsk and Luhansk, indicating an intensification of the epizootic process in these regions. In 2021, there is an upward trend in rabies epizootics in some Southern Regions, and in 2022, the ellipse covers Southern Regions such as Odesa oblast, indicating an increase in the number of rabies cases in these regions. In 2023, the ellipse covers almost the entire territory of Ukraine, focusing on the Central and Northern Regions. The analysis indicates that over the five-year period, rabies cases are concentrated mainly in the Central, Northern and Eastern Regions of Ukraine, with an increase in the incidence in the Southern Regions.

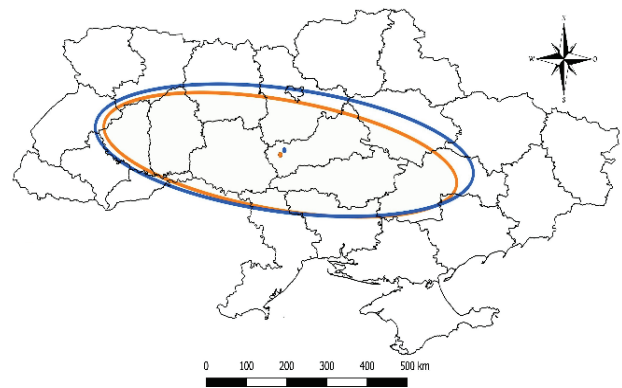


Fig. 10. Ellipse of standard deviations of rabies cases in 2019–2023: blue ellipse – standard deviations among domestic carnivores (dogs and cats); orange ellipse – standard deviations among red foxes; blue dot – the mean center of rabies cases among domestic carnivores; orange dot – the mean center of rabies cases among red foxes

The ellipses of standard deviations for rabies cases among red foxes and domestic carnivores (dogs and cats) for the period from 2019 to 2023 (Fig. 10) show that the main center of rabies cases among red foxes is located in the Central regions of Ukraine, including Poltava, Kyiv and Kharkiv oblasts. This ellipse also includes a part of the Southern regions, indicating a wide territorial distribution of rabies among the fox population. At the same time, there is a more southern distribution of rabies cases among domestic carnivores, with the main center in the Southwestern regions.

Discussion

The analysis of the rabies epizootic situation for the period 2019–2023 shows that the rabies epidemic in Ukraine continues. We do not observe any downward trend in the number of rabies outbreaks among wild, farm and domestic animals. During the analyzed period, 5,405 cases of rabies were registered among different species of animals, an average of more than 1,000 for each year under study. The decrease in rabies cases in 2022 (599 cases) is explained by the hostilities on the territory of Ukraine, respectively, incomplete diagnostic tests and specific prevention (vaccination), both among domestic and wild animals.

The analysis shows that the rabies epidemic in Ukraine is of natural origin. Red foxes (39.5% of the total) are considered to be the leading reservoirs and sources of the infectious agent, European pine martens, raccoon dogs, golden jackals, European badgers and to a lesser extent other animals play a minor role in maintaining the infection. As a result of uncontrolled breeding of dogs and cats, the number of stray animals increases seasonally and, accordingly, the number of cases also among these species (23.1% and 27.8%, respectively) and to a lesser extent among farm animals (cattle, goats, sheep, etc.). It is the seasonal component in the

biology of the red foxes that explains the dynamics of the intensification of the rabies epizootic process during these periods. Until rabies control in the wild is properly established (comprehensive coverage of red foxes and other wild animals with oral vaccinations, population density control, etc.), experts will not be able to actively influence the epizootic manifestation of rabies. Unconditional compulsory immunization of cats and dogs is also a priority for the veterinary medicine service in rabies control. In order to control rabies in dogs and cats, it is necessary to carry out continuous epizootic monitoring (Blanton et al., 2011; Korniienko et al., 2020). Such activities are carried out on an ongoing basis, because the epizootic situation with rabies must be constantly monitored and preventive measures to prevent this disease must be taken in a timely manner.

If stray animals are present, they should be vaccinated and post-vaccination titers should be investigated. At least 70% of the dog population should have a level of anti-rabies antibodies of 0.5 IU/cm³ after immunization in rabies-prone areas (Cleaveland et al., 2014). In our country, dogs and cats owned by their owners are vaccinated annually, but there is no effective system for monitoring and controlling the effectiveness of such measures.

Consequently, in different countries, the elimination of rabies has been achieved through mass vaccination (Taylor & Nel, 2015). However, in those countries where the vaccination coverage of up to 70% was not maintained, a situation of risk of re-infection is created. In 2017, it was estimated that worldwide vaccination coverage against rabies was less than 20%, with the exception of the Americas, which is an endemic region for this disease (Rupprecht et al., 2017). There is considerable geographic heterogeneity in dog rabies, dog bites, and human rabies, which has been shown in a large number of studies (Mshelbwala et al., 2021). In developing countries that are endemic regions, the cost of vaccination is expensive for the population and access to it is difficult, especially in rural areas, where the highest incidence is observed (Kaneko et al., 2021; Manzano et al., 2024). In Europe, rabies was eliminated in 24 countries between 1980 and 2010 through oral vaccination programs in the wild, as the disease was mediated by foxes in large areas of Western and Central Europe (Freuling et al., 2013). Given the fact that the disease is practically not recorded in Western Europe, as it was eliminated in dogs in the early twentieth century and then in foxes in the 1980s (Müller et al., 2015), the status of welfare is maintained by strict measures to regulate the number of wild carnivores and strict control measures in the health care system (Stahl et al., 2014).

In addition, we can say that there is a permanent evolution of natural fecundity (Blanton et al., 2011). Regulation of the number of wildlife populations by means of shooting is ineffective. As a result, epizootics of this disease have become a regulator of coevolutionary processes. The biological characteristics of wildlife reservoirs, which are primarily related to seasonal components, are becoming increasingly important. Reservoir animals from the wild (for Ukraine, these are primarily red foxes, raccoon dogs, wolves, golden jackals) enter the territory of villages, garden associations, city outskirts, landfills, and garbage dumps, where they come into contact with dogs, cats, and various types of livestock (Polupan et al., 2019; Rudoi et al., 2023; Polupan et al., 2024).

As rabies is a preventable disease, it is important that the One Health risk mitigation plans include education campaigns and assessment of knowledge and practices (Mapatse et al., 2022). Significant efforts are also needed to implement public health measures to support control of infectious diseases, including rabies in domestic and wild animals (Stankov et al., 2021). The social and economic burden of rabies among humans is difficult to quantify, as rabies needs to be addressed at the community level by raising awareness of the disease. The latter will improve the situation with controlling the disease, in addition to controlling wild and domestic animal populations. Raising people's awareness of their actions in case of possible infection will help reduce mortality. Moreover, it is important to provide such knowledge to both adults and children (students in schools) (Sambo et al., 2014).

In recent years, the epizootic situation with this zoonotic disease has become more complicated in a number of regions of our country, as we identify regions with its territorial affiliation. On the one hand, there has been a significant reduction in the network of district veterinary laboratories, and as a result, much less biological material for research is sent to

regional (oblast) veterinary laboratories. While in 2019, 21,035 samples of biological material were examined from animals of all species (wild, agricultural and domestic), in 2023 only 5,087 were examined (a decrease of more than 4 times).

The fight against the rabies epidemic in our country continues. However, the dominance of foxes (39.5%), dogs (23.1%) and cats (27.8%) among the different types of sick animals in the statistics shows that we are not fully ensuring the component of preventive vaccinations of these animals. After all, it was due to 70% vaccination coverage of dogs and full coverage of wildlife with oral vaccinations that this disease was eliminated in Western Europe. Thus, social and natural factors have been formed in Ukraine that determine the high incidence of rabies, and it is necessary to find ways to combat this disease (Korniienko, 2019).

The risk of infection of animals and humans is extremely high in our country, and rabies is now perceived as a threat. Therefore, it is necessary to strictly follow the recommendations for rabies risk management (Rabies Risk Assessment Report, 2021). Information and education are needed at different levels to eliminate unjustified complacency among veterinarians and healthcare professionals and to identify real risks. Targeted information on rabies risk and preventive measures in Ukraine for animals and humans, carried out by the veterinary medicine service of our country, do not sufficiently contribute to the prevention of rabies among animals and save lives.

By developing and implementing more cost-effective One Health strategies, more effective results in rabies elimination in disadvantaged countries can be achieved. The WHO target of "Zero rabies deaths by 2030" is being met by many countries, including Ukraine, by establishing long-term herd immunity in dogs (Knobel et al., 2013), the use of mass vaccination campaigns for wildlife (oral vaccination), management of animal populations, epidemiological surveillance and effective post-exposure prophylaxis for humans and community education (Freuling et al., 2013; Shen et al., 2023). The most effective strategy for rabies control and prevention involves the provision of financial and logistical resources and the application of the One Health concept and intersectoral cooperation between veterinary and human medicine professionals (Nadal et al., 2022).

Conclusion

During the analyzed period of 2019–2023, 5,405 rabies outbreaks were registered in Ukraine. On average, more than 1,000 outbreaks per year were registered over the years. The dominance in the rabies statistics of red foxes (39.5%), dogs (23.1%) and cats (27.8%) (for the analyzed period) among different types of sick animals shows that the component of preventive vaccinations of these animals is not fully provided in our country. The regulator of the co-evolutionary processes of rabies in our country is the epizootics of this disease. However, there has been an alarming increase in rabies cases among domestic carnivores, particularly cats and dogs, which emphasizes the critical importance of maintaining a high level of vaccination coverage for these pets to contain the spread of rabies.

A spatial analysis of rabies outbreaks in Ukraine from 2019 to 2023 shows a consistently high incidence of rabies in the Central and Northern Regions, particularly in Poltava, Kyiv, and Kharkiv oblasts. Despite efforts to control the disease, these regions remain critical foci of rabies transmission, indicating the need to strengthen control measures, including intensified vaccination campaigns and continuous monitoring of the epizootic process.

The analysis of the number of animals examined highlights the impact of socio-political factors, and the decrease in the number of biological materials from animals suspected of rabies (during the analyzed period) by more than 4 times is of concern. This is a consequence of military operations, disruption of routine diagnostic activities and vaccination programs, and reduction of the network of diagnostic laboratories. Accordingly, this component requires the restoration of strict control and maintenance of the veterinary public health infrastructure capable of supporting basic disease control operations even under adverse conditions.

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