

Regulatory Mechanisms in Biosystems

ISSN 2519-8521 (Print)
ISSN 2520-2588 (Online)
Regul. Mech. Biosyst.,
2023, 14(4), 570–575
doi: 10.15421/022383

Lyme borreliosis in humans and dogs: One Health perspective

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Article info

Received 24.09.2023

Received in revised form 01.11.2023

Accepted 16.11.2023

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Panteleienko, O. V., Chermenko, L. M., Vydayko, N. B., Ukhovskiy, V. V., Melnyk, A. Y., & Tsarenko, T. M. (2023). Lyme borreliosis in humans and dogs: One Health perspective. *Regulatory Mechanisms in Biosystems*, 14(4), 570–575. doi:10.15421/022383

Epidemiological and statistical methods were used to analyze the epidemiological situation regarding Lyme borreliosis in humans and domestic dogs in Ukraine. The data of the Central Health Service of the Ministry of Health of Ukraine on the incidence of Lyme borreliosis in humans over the last 20 years of passive epidemiological observation (2003–2022) were analyzed, and time trends and seasonal dynamics of incidence were studied. The prevalence of Lyme borreliosis among domestic dogs over the last decade (2013–2022) was analyzed based on data from a survey of veterinarians. Cross-regional geographic trends in the prevalence of Lyme borreliosis in humans and domestic dog populations are compared. The obtained data indicate an increasing trend in the incidence of Lyme borreliosis in Ukraine over the past two decades. The peak of incidence was recorded in 2018 – 12.77 cases per 100,000 population. Over the 5 years, from 2018 to 2022, Ukraine experienced the highest level of Lyme disease incidence, which was 45.16 cases per 100,000 population and statistically higher than the incidence rates in 2003–2007 (2.86 cases per 100,000 population) and 2008–2012 (13.33 cases per 100,000 population), confirming a trend of increasing disease prevalence over the years. Seasonal dynamics are observed, with the highest incidence rates occurring during the summer months, especially in June, July, August, and the early autumn month of September, as indicated by a seasonal disease index exceeding one. The study revealed geographical variations in the prevalence of Lyme borreliosis among both humans and domestic dogs. Over the past 10 years, from 2013 to 2022, regions of Northern and Central Ukraine, including Kyiv, Sumy, Chernihiv, Cherkasy, Vinnytsia, and Poltava oblasts, have shown relatively higher rates of Lyme borreliosis in both humans and domestic dogs. Conversely, the southern regions of Ukraine consistently report lower incidence rates of Lyme borreliosis in both populations, especially in Odesa, Mykolaiv and Kherson oblasts. The similarity of the geographical distribution of Lyme borreliosis among humans and domestic dogs is confirmed statistically. The study findings highlight the growing public health burden of Lyme borreliosis and the importance of ongoing disease surveillance. In addition, they highlight the valuable contribution of veterinary data on the incidence of Lyme borreliosis in domestic dogs, providing a passive but important source of additional information. In addition, the study results provide valuable information on the geographic distribution of Lyme borreliosis in both humans and domestic dogs, which will aid in the development of targeted intervention strategies aimed at mitigating the impact of the disease in selected high-risk regions. A deeper understanding of the epidemiological aspects of the disease will contribute to the development of science-based strategies for the prevention and control of Lyme borreliosis, in accordance with the concept of One Health.

Keywords: Lyme borreliosis; epidemiological surveillance; One health; public health; animal health.

Introduction

“One Health” is a comprehensive approach to addressing health issues in humans, animals, and the environment on a single platform. Based on the One Health concept, the WHO, OIE, and FAO organizations have proposed the “Tripartite Collaboration on Zoonotic Diseases” as a tool for implementing relevant measures and principles at the local, national, and global levels. The experience of several countries indicates the advantages of using an interdisciplinary approach to eliminate health threats in the “human – animal – environment” interface. Zoonotic disease control issues cannot be effectively addressed by the efforts of a single sector or discipline alone. Collaboration among all sectors and profiles responsible for human health, animal health, and the environment is required. The One Health approach should be applied not only in the face of current zoonotic threats and should not be discontinued after an emergency situation has been resolved but should be carried out in a routine and sustainable manner. Zoonotic transmissible diseases are the subject of application of the principles of the One Health concept (Ghai et al., 2022). One of the most

common vector-borne zoonoses is Lyme borreliosis (LB), which is a widespread disease in Europe and the United States caused by spirochetes known as the *Borrelia burgdorferi* sensu lato complex (*B. burgdorferi* s. l.). The *B. burgdorferi* s. l. complex currently includes about 21 genotypes, but *B. burgdorferi* sensu stricto, *B. garinii* and *B. afzelii* are considered the most important genotypes in the development of clinical LB infection (Steere et al., 2016; Barbour & Qiu, 2019; Vandekerckhove et al., 2019). *Borrelia* is transmitted by ticks of the Ixodidae family, which throughout their life cycle, except for the egg stage, feed on the blood of lizards, birds, various animal species and humans (Žáková et al., 2020). Humans and companion animals accidentally enter the epizootic cycle of *B. burgdorferi* s. l. through the bites of ixodid ticks and are not part of natural foci of LB. In Europe, including Ukraine, *I. ricinus* ticks play a significant role in the spread of LB pathogens, and in America, mainly *I. scapularis* (Rizzoli et al., 2014; Rubel et al., 2016; Rogovskyy et al., 2017). The geographical range of ixodid ticks is expanding under the influence of environmental factors, especially global warming and changes in human land use (Medlock et al., 2013; McVicar et al., 2022). As a

result, the risk of LB infection is increasing. Thus, the problem of the spread of LB involves a complex interaction between humans, wildlife, pets, ticks and the environment (Springer et al., 2020). To fight LB, we must consider not only the clinical aspects of the disease, but also develop a comprehensive approach to reducing the risk of infection of humans and companion animals with *Borrelia*. Therefore, research on borreliosis infection should have an interdisciplinary perspective, in line with the One Health concept. This approach recognizes the interconnectedness of human, animal and environmental health, which is essential for effective LB management.

In Ukraine, passive surveillance for LB in humans has been conducted since 2000, resulting in an average of more than 2 500 laboratory-confirmed diagnoses annually (Nebogatkin & Shulhan, 2020). However, it is important to recognize that these statistics may underestimate the actual incidence. According to the Centers for Disease Control and Prevention (CDC), the true extent of LB may be higher than reported (Kuehn, 2013). Therefore, independent risk studies are an important complement to surveillance results. Currently, there is no specific prevention of LB in humans. The only vaccine previously offered in the United States, LYME-Rix, was discontinued in 2002 due to limited consumer demand (Poland, 2011). Several Lyme vaccines for dogs are available on the veterinary market, including Biocan B, Borrelim 3 and Nobivac Lyme. However, in Ukraine, vaccination against LB is not consistent and is not integrated into animal vaccination protocols.

Dogs are more likely than humans to come into contact with ticks in the natural environment and are more likely to be exposed to LB pathogens (Duncan et al., 2005). After *B. burgdorferi* s. l. enters the dog's body, a powerful immune response develops. Only 5–10% of 75% of dogs seropositive for borrelia develop clinical Lyme borreliosis, in other cases the disease is subclinical. It has been previously reported that the seroprevalence of LB in dogs in Europe ranges from 0.0% to 57.5% in regions with different levels of endemicity (Panteleienko et al., 2021). However, given the large number of wild reservoir hosts, the direct impact of dogs on the natural epidemiological cycle is likely to be minimal (Springer et al., 2020).

The purpose of this study is to conduct a comprehensive study of LB in Ukraine, which includes the study of disease trends among humans as well as among the domestic dog population. In addition, the study aims to identify correlations between the prevalence of LB in the human population and in the dog population, to determine interregional geographical trends in the prevalence of LB in Ukraine, time trends and seasonal dynamics, and to assess the potential application of the One Health concept in the management of LB in Ukraine.

Materials and methods

Data collection. At our official request to the Center for Public Health of the Ministry of Health of Ukraine, we received summary data for 2003–2022 on the incidence of LB in different regions of Ukraine. In addition, from the official website of the Center for Public Health of the Ministry of Health of Ukraine, we used publicly available summary data on the incidence of LB for each month in Ukraine, starting in 2017.

The baseline data on the number of cases of LB in domestic dogs were partially taken from our previous study of the results of a survey of veterinarians (Panteleienko et al., 2022). For this study, the data were converted from the number of cases of LB in dogs to an intensity rate per 100 thousand domestic dogs for each region of Ukraine over a 10-year period (2013–2022). In order to find out the approximate size of the pet dog population in the administrative regions of Ukraine, the data were extrapolated, assuming that the number of dogs owners is close to the size of the pet dog population. This is reported in the open data of a survey conducted by Kantar TNS and published by BBC News Ukraine (BBC News Ukraine, 2019), which states that approximately 44% of respondents own dogs. The data on the average population size in the regions of Ukraine were obtained from open data on the website of the State Statistics Service of Ukraine (2023) under the Creative Commons Attribution 4.0 International, 2023 license.

Temporal analysis of the incidence of LB in humans. To assess the temporal trends in the incidence of LB, we analyzed the dynamics of the

incidence by year from the beginning of the observation period from 2003 to 2022. We also analyzed the dynamics of the incidence of LB by five-year observation periods: 2003–2007, 2008–2012, 2013–2017, and 2018–2022. For each of the five years of observation, the average value of intensive morbidity rates per 100 thousand humans was calculated.

Seasonality of morbidity. To analyze the seasonality of Lyme borreliosis, we calculated the seasonal dynamics of the incidence of LB from January 2017 to December 2022 in the form of a seasonal index. To calculate the seasonal index, the following steps were taken: calculate the average value for each month for all years from 2017 to 2022; calculate the total average of all values; calculate the seasonal index for each month by dividing the average value for that month by the total average. A seasonal index higher than 1 indicates that this month usually has a higher than overall average incidence rate, while an index lower than 1 indicates that it usually has a lower than overall average incidence rate.

Regional and geographical dynamics of the incidence of LB in humans and domestic dogs. At this stage, we analyzed the prevalence of BL in the human and domestic dog populations by calculating the average value of intensive incidence rates per 100 thousand population over the past 10 years (2013–2022). The interregional difference in the incidence of LB among humans and domestic dogs was determined. Administrative regions were conditionally divided into 5 geographic zones, in particular: 1 – Northern Ukraine: Zhytomyr, Kyiv, Chernihiv, Sumy regions; 2 – Eastern Ukraine: Kharkiv, Luhansk, Donetsk regions; 3 – Center of Ukraine: Vinnytsia, Cherkasy, Poltava, Kirovohrad regions; 4 – Western Ukraine: Volyn, Rivne, Lviv, Ternopil, Zakarpattia, Ivano-Frankivsk, Chernivtsi, Khmelnytsky regions; 5 – Southern Ukraine: Dnipro, Zaporizhzhia, Mykolaiv, Odesa, Kherson regions and the Autonomous Republic of Crimea.

Statistical analysis. The normality of the data distribution was checked using the Shapiro-Wilk test. To determine the statistical difference in the intensity of the incidence of LB between the years of observation and the difference in the intensity of the incidence of LB between regions, the Kruskal-Wallis test and Dunn's test was used. The results were considered statistically significant if the p-value was less than 0.05. Simple linear regression was used to determine the dynamics of the growth of the incidence of LB over the years. The correlation between years (time) and the incidence of Lyme borreliosis, as well as the correlation between the incidence of human LB and the incidence of dog LB was determined using the Spearman correlation coefficient. For statistical analysis, the Jamovi computer program (Australia, 2023, version 2.4) was used [obtained from www.jamovi.org].

Mapping. The maps were created using Microsoft Excel on the basis of Bing, GeoNames, Microsoft, Navinfo, TomTom, Wikipedia.

Results

The analysis of the dynamics of LB incidence showed that the lowest level was registered at the beginning of the observation period in 2003 with a rate of 0.4 cases per 100,000 population ($0/_{0000}$). In 2007 and 2013, there was an increase in the incidence of LB to 0.99 $0/_{0000}$ and 4.25 $0/_{0000}$, respectively. The incidence rate in these years was statistically higher than in previous years of observation ($P < 0.01$). In general, the incidence of LB in Ukraine has been gradually increasing over the years, reaching its peak in 2018 at 12.77 $0/_{0000}$.

Over the last 20 years (2003–2022) of epidemiological surveillance, the highest incidence rates of LB were recorded in Kyiv city (13.00 $0/_{0000}$), Cherkasy (12.19 $0/_{0000}$), Kyiv (10.43 $0/_{0000}$) and Sumy (9.03 $0/_{0000}$) regions, and the lowest in Zaporizhzhia, Mykolaiv, Odesa and Kherson regions – from 0.35 $0/_{0000}$ to 1.62 $0/_{0000}$. In other regions of Ukraine, the incidence of LB ranged on average from 2.15 $0/_{0000}$ to 7.6 $0/_{0000}$ (Fig. 1).

Each five-year period of epidemiologic surveillance of LB incidence since 2003 has shown an upward trend in incidence (Fig. 2). During the first five years of epidemiologic surveillance (2003–2007), the total incidence rate was 2.86 $0/_{0000}$. In the next five years (2008–2012), the incidence increased 4.7-fold, reaching 13.33 $0/_{0000}$, but no statistical difference was found between these periods ($P = 0.3446$). In 2013–2017, the incidence of LB increased by 2.4 times (31.72 $0/_{0000}$) compared to the previous five-year observation period, 2008–2012, and was statistically different at

$P = 0.0362$, and the incidence was 11 times higher than in the first five years of observation, 2003–2007 ($P = 0.0011$). Over the past five years, from 2018 to 2022, the incidence of LB in Ukraine increased to 45.16 ‰, which is 1.4 times higher than in 2013–2017 ($P = 0.1622$), 3.4 times higher than in

2008–2012 ($P = 0.0004$), and 15.8 ‰ times higher than in 2003–2007 ($P = 0.00002$). Linear regression analysis showed a consistent increase in LB incidence over the years, with a strong positive relationship between years and incidence ($R = 0.87$; $P < 0.001$; $\beta = 0.56$).

Regions	Years of epidemiological surveillance (2003–2022)																			
	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Cherkasy	0.36	0.36	0.95	1.48	2.77	3.55	4.50	6.61	8.36	8.89	10.76	9.96	24.28	13.86	25.98	41.46	25.40	17.04	13.21	24.09
Kyiv	0.00	0.00	0.22	0.34	0.91	0.00	2.89	4.12	5.54	5.26	7.24	7.81	15.70	11.84	17.55	30.08	29.00	22.25	18.76	29.06
Sumy	0.62	0.39	1.03	2.01	1.47	4.13	3.77	3.98	5.81	5.18	6.00	4.21	13.44	11.50	17.37	23.04	22.89	18.16	15.10	20.55
Vinnitsia	0.17	0.29	0.00	0.58	0.30	0.95	2.22	4.96	4.75	4.65	5.78	5.31	11.79	10.48	15.11	32.65	23.90	8.05	6.05	14.06
Ternopil	0.00	0.00	0.27	0.63	0.45	1.45	2.65	2.75	5.53	5.46	6.59	6.80	10.75	10.50	15.53	17.43	19.92	9.21	10.33	25.80
Poltava	0.12	0.19	0.00	0.89	1.10	1.37	1.38	0.60	1.88	3.58	3.27	3.01	10.55	8.74	14.88	17.69	17.43	11.20	11.38	26.91
Chernihiv	0.00	0.00	0.00	0.00	1.21	2.10	2.48	3.06	6.63	3.40	4.91	5.80	8.13	10.60	10.42	14.25	17.10	5.21	3.97	17.56
Lviv	1.00	1.24	1.28	2.33	1.95	2.31	3.31	3.83	4.82	3.13	4.16	5.39	7.22	5.95	12.32	13.00	9.60	6.75	5.29	11.21
Zhytomyr	0.00	0.00	0.00	0.00	0.00	0.23	0.23	1.78	3.19	4.22	3.69	4.10	5.38	5.41	9.21	12.25	12.09	9.75	7.11	13.04
Rivne	0.17	0.09	0.17	0.09	0.17	0.26	1.22	3.48	2.35	3.91	3.90	2.08	6.82	7.15	8.27	12.31	8.28	5.36	5.38	10.46
Kharkiv	0.24	0.10	0.53	0.74	0.89	1.07	1.62	1.92	1.92	2.96	3.59	2.05	8.38	5.19	6.84	13.07	10.79	5.11	5.56	3.06
Dnipropetrovsk	0.22	0.09	0.31	0.40	0.78	0.70	1.74	1.96	3.37	3.87	2.23	2.63	9.21	7.21	8.80	8.40	7.25	3.84	3.18	6.12
Khmelnytsky	0.00	0.00	0.00	0.00	0.22	0.22	0.45	0.15	0.68	0.83	0.91	2.82	3.91	2.54	8.98	14.12	11.33	6.66	4.47	7.09
Donetsk	0.93	0.97	1.38	1.07	2.04	2.87	3.80	4.23	5.34	5.61	6.88	2.18	4.66	3.22	4.96	4.42	3.56	2.58	4.22	0.37
Chernivtsi	0.33	0.11	0.00	0.22	0.11	0.44	0.22	0.89	0.44	1.44	0.67	1.77	3.31	3.20	7.40	4.65	4.77	6.45	12.42	
Ivano-Frankivsk	0.14	0.14	0.29	0.36	0.65	0.65	1.16	0.94	0.87	1.82	2.25	1.89	2.90	2.83	4.71	4.28	4.51	2.48	1.83	12.37
Zakarpattia	0.08	0.32	0.32	0.48	0.24	0.40	1.05	0.73	0.81	1.45	1.12	0.96	2.55	2.71	2.39	7.56	6.61	4.15	2.64	6.89
Kirovograd	0.00	0.00	0.00	0.09	0.09	0.00	0.68	0.69	0.49	0.40	0.60	0.51	2.85	1.85	4.34	7.92	8.00	4.79	3.02	6.68
Volyn	0.00	0.00	0.00	0.19	0.58	0.48	0.77	0.48	0.87	0.58	0.97	0.87	1.93	2.98	3.75	4.24	5.70	0.48	1.26	6.25
Luhansk	0.00	0.00	0.08	0.16	0.37	0.55	1.79	2.36	1.82	2.19	3.22	0.36	1.52	1.08	2.09	2.83	1.76	1.91	2.86	0.09
Zaporizhzhya	0.00	0.31	0.58	0.48	1.08	0.65	0.65	1.32	0.66	0.50	1.01	1.79	2.76	1.42	2.40	2.13	2.32	1.41	1.48	1.38
Mykolaiv	0.00	0.08	0.08	0.00	0.00	0.00	0.17	0.33	0.76	0.85	0.68	0.68	1.03	0.95	2.16	2.26	1.93	0.35	0.45	0.63
Odesa	0.00	0.00	0.00	0.04	0.00	0.71	0.25	0.25	0.55	0.72	0.42	0.25	0.34	0.63	0.97	1.64	1.52	0.21	0.72	0.64
Kherson	0.34	0.00	0.00	0.00	0.71	0.27	0.36	0.18	0.64	0.37	0.18	0.09	0.75	1.13	0.75	0.57	0.19	0.19	0.10	0.10
Crimea	0.10	0.00	0.15	0.00	0.81	1.02	0.87	1.33	1.18	1.38	2.15									
UKRAINE	0.43	0.30	0.48	0.66	0.99	1.34	2.12	2.77	3.49	3.61	4.25	3.77	7.96	6.45	9.29	12.77	10.62	6.56	5.85	9.36

Fig. 1. Dynamics of human incidence of LB over 20 years (2003–2022) in the regions of Ukraine (0/0000)

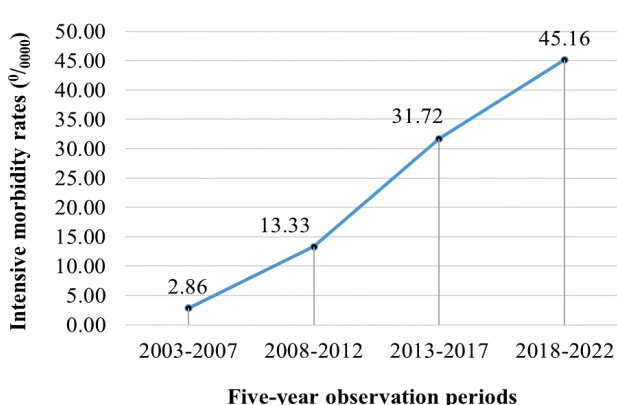


Fig. 2. Dynamics of growth in the incidence of LB in Ukraine

After analyzing the data on the incidence of humans with LB for each month of epidemiological surveillance from 2017 to 2022, it was found that the incidence rate fluctuates throughout the year and has seasonal dynamics (Fig. 3). The seasonal incidence index in June (2.1), July (2.8), August (2.5) and September (1.6) exceeds one, indicating that in these months the incidence of LB is usually higher compared to the overall average incidence of 0.75 cases per 100,000 population. In other months of the year, the average incidence of LB has a seasonal index of less than one. In particular, in November, the seasonal index is 0.8, in May – 0.7, in December – 0.5, in January and April – 0.2, in February and March – 0.1. Statistical analysis confirms the difference in morbidity rates between months during the year ($P < 0.001$). The analysis of seasonal dynamics shows that the highest incidence of LB is observed in the summer months (1.85 ‰), which is 2.2 times higher than in autumn (0.84 ‰, $P = 0.0825$), 5.4 times higher than in winter (0.34 ‰, $P = 0.0002$), and 8.0 times higher than in spring (0.23 ‰, $P = 0.0006$).

An analysis of data over the past decade (2013–2022) on the incidence of LB in humans and domestic dogs revealed a strong positive correlation between the incidence rates in the regions of Ukraine ($R = 0.89$; $P < 0.001$). In particular, the highest incidence rates of LB were

observed in Cherkasy region (207.97 ‰ – humans; 33.31 ‰ – dogs), Kyiv city (201.06 ‰ – humans; 23.54 ‰ – dogs), Kyiv region (187.92 ‰ – humans; 31.14 ‰ – dogs), Sumy (153.13 ‰ – humans; 20.24 ‰ – dogs), Vinnitsia (134.13 ‰ – humans; 13.63 ‰ – dogs), and Ternopil (133.13 ‰ – humans; 15.81 ‰ – dogs) regions for both humans and domestic dogs ($R = 0.89$; $P = 0.0436$). Conversely, the lowest incidence rates of LB among humans and domestic dogs were recorded in Zakarpattia (37.71 ‰ – humans; 5.28 ‰ – dogs), Volyn (28.53 ‰ – humans; 4.63 ‰ – dogs), Zaporizhzhia (18.41 ‰ – humans; 3.59 ‰ – dogs), Mykolaiv (11.31 ‰ – humans; 7.03 ‰ – dogs), Odesa (7.34 ‰ – humans; 1.34 ‰ – dogs) and Kherson (4.14 ‰ – humans; 2.19 ‰ – dogs) regions ($R = 0.83$; $P = 0.042$) (Table 1, Fig. 4).

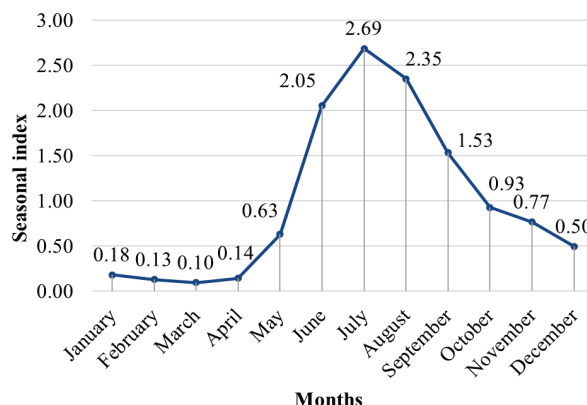


Fig. 3. Dynamics of the incidence of LB during the year in Ukraine (data are presented in the form of seasonal indices for 2017–2022)

Luhansk and Donetsk oblasts and the Autonomous Republic of Crimea were excluded from the correlation analysis due to the lack of information on the number of cases of LB in domestic dogs from these regions. In addition, given that Luhansk and Donetsk oblasts belong to the Eastern geographic region, we did not estimate the prevalence of LB in domestic

dogs in this area and did not compare it with other geographic regions. It should be noted that in Luhansk region, the average value of the intensity index of human incidence of LB over the past 10 years was 17.72 ‰ , and for Donetsk region over the same period was 37.05 ‰ . But in 2022, the level of data on the infectious disease incidence of the population from these two regions of Ukraine is almost absent due to the aggression of the Russian Federation. Statistical reports of the Public Health Center of the Ministry of Health of Ukraine show that in Donetsk region in 2022, 0.37 ‰ cases were registered, which is 91.38% less than in 2021, and in Luhansk region – 0.09 ‰ , which is 96.72% less, respectively.

The analysis of the data on the incidence of LB by geographical regions shows a similar epidemiological situation among the populations of humans and domestic dogs and a similar geographical distribution of the disease. The highest incidence rates of LB are observed in the Northern regions, both among domestic dogs (22.83 ‰) and humans (144.61 ‰). The Central region has slightly lower incidence rates – 17.27 ‰ among domestic

dogs and 126.88 ‰ among humans. A relatively low incidence of LB is observed in the Western region (12.38 ‰ for domestic dogs and 77.15 ‰ for humans), and the lowest in the Southern region, except for the Autonomous Republic of Crimea (5.57 ‰ for domestic dogs and 20.15 ‰ for humans). The similarity of the geographical distribution of LB in the Northern, Central, Western and Southern regions among humans and domestic dogs is confirmed by a strong positive correlation between the intensity of the disease ($R = 0.9859$; $P = 0.0141$). In addition, it was found that in the Eastern region, the prevalence of LB among humans is 39.62 ‰ . The prevalence of LB among dogs in the Eastern geographic region was not determined due to the lack of data from Luhansk and Donetsk oblasts. We did not compare the prevalence of LB in domestic dogs from the Eastern region with other geographic regions and included them in the correlation analysis. The difference in the prevalence of LB between different geographic regions is statistically significant for both the domestic dogs population ($P = 0.0003$) and the human population ($P = 0.0016$).

Table 1

The incidence of human and domestic dogs with LB in different regions of Ukraine over the past 10 years (2013–2022)

Regions	Average population in the regions	Approximate number of domestic dogs*	Total number of cases of LB		Intensive morbidity rates, ‰	
			domestic dogs**	humans	domestic dogs	humans
Cherkasy	1 214 571	534 411	178	2 526	33.31	207.97
city Kyiv	2 896 188	1 274 323	300	5 823	23.54	201.06
Kyiv	1 758 722	773 838	241	3 305	31.14	187.92
Sumy	1 089 265	479 277	97	1 668	20.24	153.13
Vinnitsia	1 567 889	689 871	94	2 103	13.63	134.13
Temopil	1 049 322	461 702	73	1 397	15.81	133.13
Poltava	1 409 544	620 200	81	1 760	13.06	124.86
Chemihiv	1 018 246	448 028	98	1 000	21.87	98.21
Zhytomyr	1 223 497	538 339	85	1 012	15.79	82.71
Lviv	2 508 620	1 103 793	132	2 030	11.96	80.92
Rivne	1 148 933	505 531	51	810	10.09	70.50
Kharkiv	2 669 846	1 174 732	120	1 711	10.22	64.09
Khmelnysky	1 271 146	559 304	56	802	10.01	63.09
Dnipropetrovsk	3 201 060	1 408 466	123	1 907	8.73	59.57
Chemivtsi	898 530	395 353	45	418	11.38	46.52
Kirovograd	949 115	417 611	38	385	9.10	40.56
Ivano-Frankivsk	1 365 892	600 993	63	549	10.48	40.19
Zakarpattia	1 249 058	549 586	29	471	5.28	37.71
Donetsk	4 043 520	1 779 148	no data	1 580	no data	37.05
Volyn	1 030 426	453 388	21	294	4.63	28.53
Zaporizhzhya	1 711 088	752 879	27	315	3.59	18.41
Luhansk	2 097 056	922 704	no data	389	no data	17.72
Mykolaiv	1 132 131	498 138	35	128	7.03	11.31
Odesa	2 371 798	1 043 591	14	174	1.34	7.34
Kherson	1 039 582	457 416	10	43	2.19	4.14

Note: * the number of domestic dogs was calculated by extrapolating data based on the assumption that about 44% of the Ukrainian population owns dogs; ** the number of cases of LB in domestic dogs is based on a survey of veterinarians.

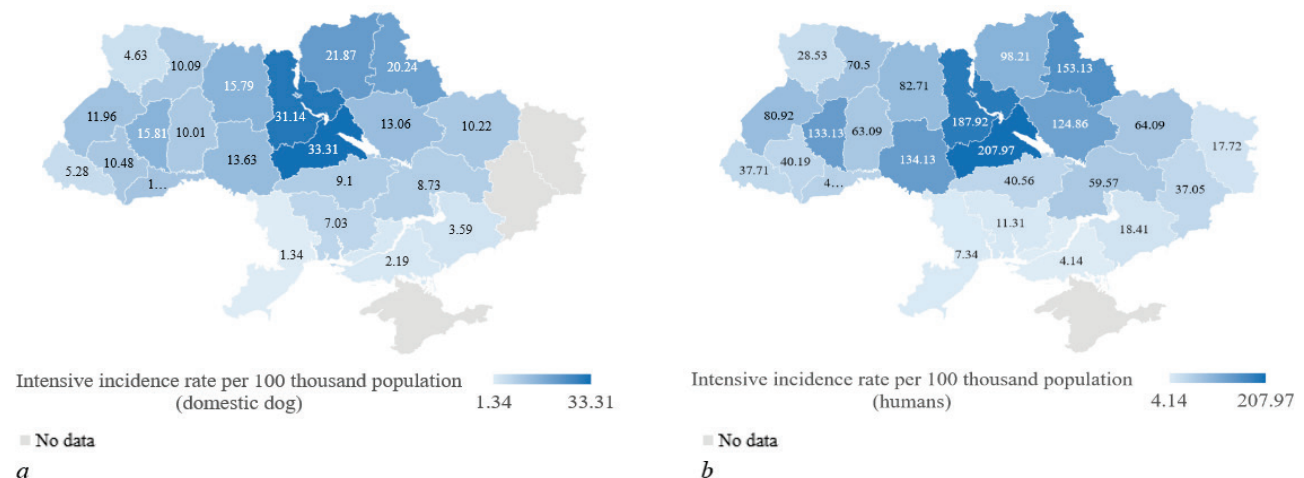


Fig. 4. The epidemiological situation with LB among domestic dogs (a) and humans (b) over the past 10 years (2013–2022), Ukraine

Discussion

The study analyzes the epidemiological landscape of LB in humans and domestic dogs in Ukraine. Its main objectives were to study the trends

in the incidence of LB in humans, analyze the seasonal dynamics of the disease, and compare regional prevalence in human and dog populations. After analyzing the data on the incidence of LB in Ukraine, it was found that in 2003 the incidence rate was 0.43 ‰ , in 2022 – 9.36 ‰ , and the

highest rates were recorded in 2018 – 12.77 ‰. Although over the past 20 years there have been some fluctuations in incidence rates, the analysis of data for 5-year periods of epidemiological surveillance shows an upward trend in the incidence of LB and is confirmed statistically ($R = 0.87$; $P < 0.001$; $\beta = 0.56$). In particular, in the first 5 years of LB case registration, 2003–2007, the intensity rate was 2.86 ‰, and in the last 5 years, 2018–2022, the intensity rate was recorded at 45.16 ‰. In general, the results of this study are consistent with the previous findings of the analy-

sis of the incidence of LB in Ukraine (Rogovskyy et al., 2020). Similar incidence rates of LB were observed in Poland, where 49.3 ‰ were registered in 2015–2019 (Paradowska-Stankiewicz et al., 2023). In contrast, other countries bordering Ukraine, such as Slovakia, Russia, and Belarus, have much lower rates of LB incidence – below 20 ‰. In European countries such as Belgium, Finland, the Netherlands, and Switzerland, the incidence of LB has exceeded 100 ‰ in different periods (2005 to 2020) (Voyiatzaki et al., 2022; Burn et al., 2023).

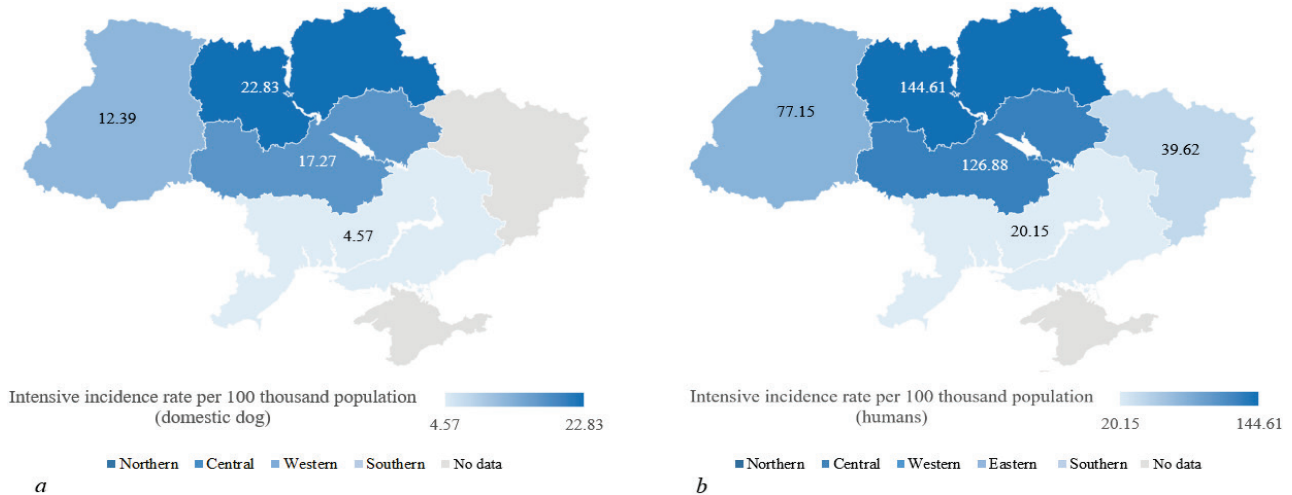


Fig. 5. Prevalence of LB in different geographical regions in the domestic dog population (a) and in the human population (b) in Ukraine over the past 10 years (2013–2022)

It has been established that LB in Ukraine has a pronounced seasonality and is characterized by significant fluctuations in the intensity of the disease throughout the year. High incidence rates are consistently observed in the warm period, mainly in the summer months and early autumn, in September, while in other seasons significantly lower incidence rates are recorded. Our results are consistent with a previous study that described the seasonal trends of LB in 2017–2019 in Ukraine (Nebogatkin & Shulhan, 2020). This distinct seasonality is inextricably linked to the behavior of ixodid ticks, which are the main vectors of *B. burgdorferi* s. l. The onset and cessation of host-seeking activity of ixodid ticks are closely related to temperature thresholds. In particular, *I. ricinus*, the key vector of *B. burgdorferi* s. l., requires relative humidity above 45% and a stable average daily temperature of 7–8 °C to start searching for a host. In particular, observations in Central Europe have shown that *I. ricinus* ticks remain largely inactive during the winter months, typically from November to February. In contrast, from March to October, they are more active in search of a host. With the onset of the autumn season, nymphs and adult *I. ricinus* ticks become more sensitive to lower temperatures, often entering a state of behavioral diapause. Importantly, during the feeding process, infected ticks can transmit *B. burgdorferi* s. l. to susceptible hosts, including humans and dogs. Various environmental factors such as temperature, humidity and precipitation are reliable predictors of the spatial and temporal distribution of ticks (Hubálek et al., 2003; Daniel et al., 2015; Voyiatzaki et al., 2022).

Sentinel animal surveillance is not a new practice in the study of zoonotic diseases, and the use of dogs as sentinels to detect the risk of human exposure to LB has been previously described (Skotarczak et al., 2005; Miró et al., 2013; Milich et al., 2022). The data of our study indicate a similar epidemiologic picture of LB in the human population and in the dog population over the past ten years (2013–2022) in Ukraine. High incidence rates of LB in humans and domestic dogs were observed in the North of Ukraine, with the highest values in Kyiv, Sumy, and Chernihiv regions. The combined incidence rate of LB in the Northern regions for 2013–2022 for the human population was 144.61 ‰, and for domestic dogs – 22.83 ‰. The incidence rate was somewhat lower in the Central part of Ukraine, in particular in Cherkasy, Vinnytsia and Poltava, and the combined incidence rate of LB for the human population was 126.88 ‰ and for domestic dogs – 17.27 ‰. The incidence of LB was significantly lower in the Southern regions of Ukraine (20.15 ‰ – humans;

5.57 ‰ – domestic dogs). The difference in the incidence of LB in humans and domestic dogs in different regions can be explained by the indirect influence of climatic features for these geographical areas. In particular, the more arid climate of the South of Ukraine may prevent the spread of vector-competent *I. ricinus* ticks, while the temperate climate and forested areas of the Northern and Central regions facilitate the circulation of the LB pathogen (Panteleienko et al., 2022). In addition, our study found a strong correlation and linear relationship between the prevalence of LB among humans and domestic dogs in Ukraine ($R = 0.83$; $P = 0.042$). This similarity in the prevalence of LB in humans and domestic dogs is not unique and is consistent with previous studies. For example, in the United States, a positive correlation was found between LB-seropositive dogs and the incidence of LB in humans ($R^2 = 0.75$; $P < 0.001$) (Mead et al., 2011). Moreover, there are studies that confirm the link between humans and domestic dogs based on quantitative assessments, which ultimately supports the role of domestic dogs as an early warning system for human LB (Liu et al., 2019).

This study, when viewed within the framework of One Health, emphasizes the complex interrelationship between human, animal and environmental health. Lyme borreliosis is not confined to one area; it affects both humans and animals and is influenced by environmental factors. The growing prevalence of LB in Ukraine highlights not only the threat to public health but also the impact on animal populations, especially dogs. This complexity underscores the need for a holistic approach to understanding and managing LB, as it requires collaboration between human and animal health and environmental and climate sciences. By studying the disease from this multifaceted perspective, this study aimed to improve our understanding of its epidemiology and regional distribution, which will allow us to develop more effective and evidence-based prevention and control strategies. The study is consistent with the principles of One Health, recognizing the complex interactions between humans, wildlife, domestic animals, ticks and the environment in the spread of LB (Ellwanger et al., 2022; Ghai et al., 2022). The results of the study add to the knowledge of the role of domestic dogs in the epidemiology of LB. The strong positive correlation between the incidence rates in humans and domestic dogs emphasizes the importance of including veterinary data in disease surveillance activities. Integration of veterinary data into human disease surveillance will help to assess the risks of LB infection and warn of its dynamics. Given that dogs are also at high risk of *B. burgdorferi* s. l.

infection, the study emphasizes the importance of considering LB prevention strategies for domestic dogs. Currently, only one vaccine for dogs against LB is registered on the Ukrainian veterinary market – Borrelym 3 (Bioveta, Czech Republic). However, in Ukraine, vaccination against LB is not integrated into vaccination protocols. Efforts to promote vaccination and preventive measures could significantly reduce the incidence of LB in the pet dog population.

Thus, the impact of LB goes beyond public health and encompasses various aspects of environmental and climate sciences, veterinary medicine and animal health. Adding to the knowledge of LB through scientifically based independent research can contribute to improved LB control strategies. Such an approach would not only protect public health, but also protect the welfare of pets, particularly dogs, which are an integral part of many households in Ukraine.

Conclusions

Over the past two decades, there has been an upward trend in the incidence of LB in humans in Ukraine ($R = 0.87$; $P < 0.001$; $\beta = 0.56$). The highest incidence rates of LB occur in the summer months, in June, July, August and the first month of autumn – September. There are geographical differences in the prevalence of LB in Ukraine. The Northern and Central regions, including Kyiv, Sumy, Chernihiv, Cherkasy, Vinnytsia, and Poltava oblasts, have consistently higher rates of LB among both humans and domestic dogs compared to the Southern regions of Ukraine, in particular Odesa, Mykolaiv, and Kherson oblasts, where the incidence of LB is much lower. There was a strong correlation ($R = 0.9859$, $P = 0.0141$) between the geographical distribution of LB among humans and domestic dogs, as well as a difference in the prevalence of LB between different geographical regions for both the domestic dog population ($P = 0.0003$) and the human population ($P = 0.0016$). The strong positive correlation between the incidence of LB among humans and domestic dogs in Ukraine emphasizes the potential of using dogs as sentinels for early warning systems in disease monitoring and management. Integration of veterinary data into human disease surveillance activities can help assess the risk of infection with LB and provide insight into its dynamics. It is important to consider prevention strategies for domestic dogs, including vaccination of domestic dogs against LB, especially in high-risk regions. Understanding LB from a One Health perspective can help to develop more effective, evidence-based prevention and control strategies, protecting both public health and the welfare of domestic dogs, which are also at risk of LB infection.

The research was conducted within the framework of the scientific topic of the Department of Epizootology and Infectious Diseases, Faculty of Veterinary Medicine of Belotserkiv National University "Study of epizootology, diagnosis, treatment and prevention of transmissible animal diseases" (state registration number 0121U110292).

The authors declare that they have no conflict of interest.

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