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Geographical factors and air raid alarms influence leptospirosis epidemiology in Ukraine (2018–2023)

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ABSTRACT

Leptospirosis, a widespread zoonotic disease caused by *Leptospira* spp., affects approximately 1 million people annually and causes about 58,000 deaths worldwide. This study examines the epidemiology of leptospirosis in Ukraine from 2018 to 2023, focusing on the impact of weather and geographical factors on disease transmission. Data from the Ukrainian Centre for Disease Prevention and Control, the Ukrainian Hydrometeorological Center, and the State Agency of Water Resources of Ukraine were analyzed. The country was divided into five regions: North, East, Center, South, and West. For the visualization, but not the quantitative analyses, the notification rate (NR) of leptospirosis was classified into three categories: low, moderate, and high.

The highest NR were in Zakarpattia, Ivano-Frankivsk, Khmelnytskyi, Mykolaiv, and Kherson regions, with Zakarpattia having the highest rate. We analyzed whether various weather parameters—such as average annual temperature, precipitation, days with precipitation $\geq$1 mm, and relative humidity—were associated with the notification rate (NR) of leptospirosis, but no significant correlations were detected.

However, a significant positive correlation was observed between higher density of the river network and NR (Kendall's rank correlation, $r = 0.65$, $p = 0.0005$), indicating that geographical factors may play an important role in *Leptospira* transmission. Additionally, we found a significant correlation between monthly air raid alarm frequency and the NR of leptospirosis cases in 2023. Case reports of individuals contracting leptospirosis in bomb shelters further support the hypothesis that air raid evacuations impact leptospirosis epidemiology. Further investigation is needed to fully understand this relationship and its implications.

1. Introduction

Leptospirosis is a zoonotic disease and one of the most widespread worldwide, affecting approximately 1 million people annually and causing about 58,000 deaths [1]. The disease is caused by bacteria from the genus Leptospira, and its symptoms range from asymptomatic to mild fever to severe acute infection, which can result in organ failure and death [2–5].

Infection occurs through direct or indirect contact with infected reservoir host animals that carry the bacteria in their renal tubules and excrete them in their urine. While many wild and domestic animals can serve as reservoir hosts, the brown rat (*Rattus norvegicus*) is the primary reservoir of *Leptospira* associated with human infections [6].

This zoonotic disease is especially prevalent in many countries of Latin America and South-East Asia. While vaccines against human leptospirosis are available in some countries, such as Japan, China, Cuba, and France, prevention primarily relies on sanitation measures, which can be challenging to implement in developing countries [7]. The annual incidence rate typically ranges from 0.1 to 1 per 100,000 people in temperate climates, rising to over 10 per 100,000 in tropical regions [8].

In 2023, Ukraine reported leptospirosis rates significantly higher than those in EU and European Economic Area countries, with 1.06 cases per 100,000 people (433 confirmed cases) (Fig. 1). For instance, Slovenia and France had the highest total notification rates of 0.82 and 0.76 per 100,000 population, respectively, both substantially lower than those we determined for Ukraine [8]. Ukraine, the largest country in Europe, with its diverse climates, mountains, landscapes, and forests, faces unique epidemiological challenges [9,10]. Additionally, the ongoing war in Ukraine presents a unique occupational risk to military

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personnel, who have an increased risk of infection due to exposure to contaminated water sources and potential reservoir hosts such as rodents [11]. Studying the incidence of leptospirosis among servicepeople of the Armed Forces of Ukraine in 2022, Ogorodniychuk et al. reported that 6 contract servicepeople and 40 mobilized military personnel contracted leptospirosis, accounting for 32 % of all leptospirosis cases registered in Ukraine that year [9,12].

The civilian population is also at risk, particularly following the destruction of the Kakhovka Dam in 2023, which led to a threefold increase in notification rates compared to the previous year [13,14].

Extreme weather events, such as heavy rainfall and flooding, are consistently associated with increased incidence of urban leptospirosis [15]. Alongside these large sporadic events, seasonal leptospirosis patterns linked to cyclic rainfall have been observed in several tropical developing countries. Previous studies suggest that, in addition to rainfall, other climatic factors like temperature and humidity may also independently contribute to the transmission of leptospirosis [16,17]. This is why we aim to investigate whether weather conditions affect the epidemiology of leptospirosis in Ukraine.

2. Material and methods

The study area for our investigation encompassed all regions of Ukraine except for the temporarily occupied territories of Crimea, Luhansk, and Donetsk. The study period spanned from 2018 to 2023. Data on the incidence of leptospirosis were extracted from the database of the Ukrainian Centre for Disease Prevention and Control (UCDC), as reporting leptospirosis is mandatory. The leptospirosis notification rate (NR) was calculated per 100,000 population for each region and year by dividing the total number of reported cases by the regional population size and multiplying the result by 100,000

Per Ministry of Health Order No. 905(December 28, 2015), the clinical criteria for leptospirosis include the presence of fever or at least two of the following symptoms: chills, headache, myalgia, conjunctival suffusion, hemorrhagic manifestations on the skin or mucous membranes, rash, jaundice, myocarditis, meningitis, renal failure, or respiratory complications (such as hemoptysis). Diagnosis requires laboratory confirmation via PCR or microscopic agglutination test (MAT).

We investigated weather parameters such as average annual temperature, average annual precipitation, the annual number of days with precipitation ≥1 mm, and annual average relative humidity, officially obtained from the Ukrainian Hydrometeorological Center [18] (Supplementary File 1). Additionally, we used geographical data that we believe could affect *Leptospira* transmission, such as the average density of the river network (km/km^2). This parameter was calculated as the mean of the total river length divided by the area for each studied region, based on data from the State Agency of Water Resources of Ukraine.

Given the higher risk of *Leptospira* transmission in cellars and shelters due to the war, we also aimed to investigate how air alarms affect the NR of leptospiral infections. We obtained data on the duration of air alarms in each region from an official website (https://alerts.in.ua/) and used this information to explore potential associations with leptospiral NR.

To facilitate analysis, Ukraine was divided into: North (Zhytomyr, Kyiv, Chernihiv, Sumy), East (Kharkiv), Center (Dnipropetrovsk, Kirovohrad, Poltava, Cherkasy), South (Zaporizhzhia, Kherson, Odesa, Mykolaiv), and West (Lviv, Ivano-Frankivsk, Zakarpattia, Ternopil, Chernivtsi, Volyn, Rivne, Khmelnytskyi).

All data were divided into percentiles for map visualization and visualized as follows: light blue for less than the 25th percentile, blue for between the 25th and 75th percentiles, and dark blue for greater than the 75th percentile. Additionally, we used correlation analysis to examine the relationships between the variables. Numerical summaries are expressed as mean ± standard deviation (SD). We conducted data analysis using the R statistical software, employing the following packages: dplyr for data manipulation, tidyr for data tidying, ggplot2 for data visualization, and ggrepel for enhanced labeling in plots.

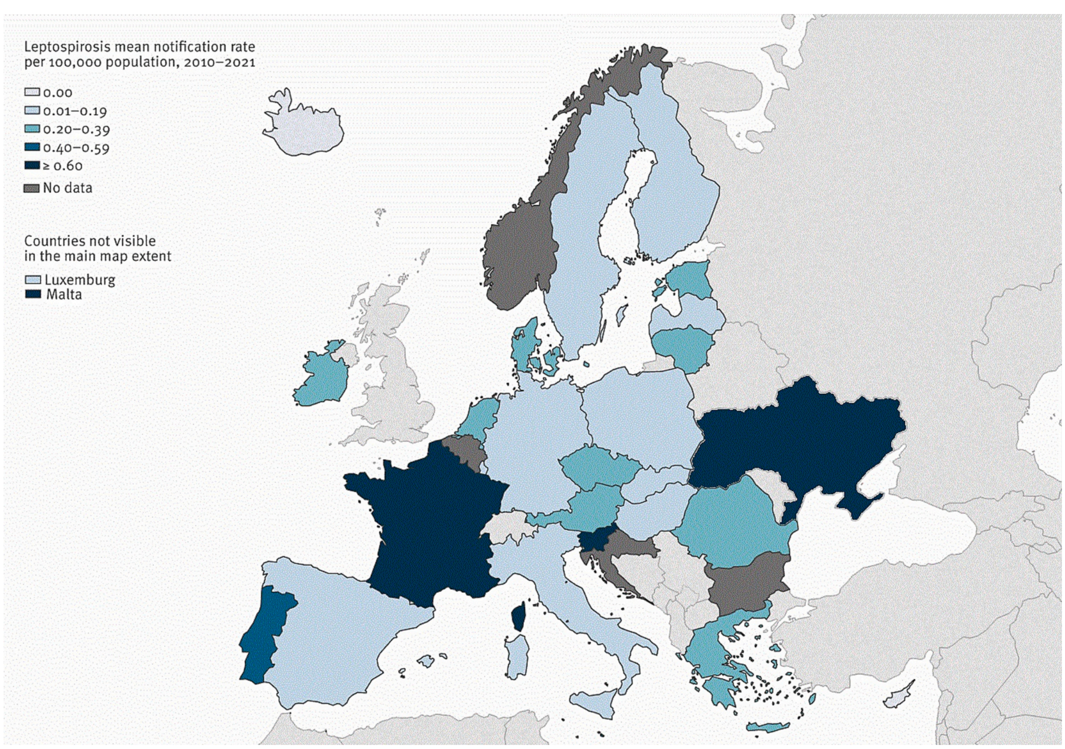

Fig. 1. Average annual rate of confirmed leptospirosis cases per 100,000 population, European Union/European Economic Area, 2010–2021. Adapted from ECDC. The average number of leptospirosis cases in Ukraine is one of the highest in Europe, amounting to 0.73 per 100,000 people for the period 2010–2021. For comparison, in neighboring countries, the rate is 0.1 in Poland, 0.15 in Slovakia, and 0.34 in Romania.

3. Results

3.1. Weather-geographical factors in Ukraine

We investigated average annual temperature, average annual precipitation, the annual number of days with precipitation ≥1 mm, and annual average relative humidity from 2018 to 2023.

Average annual temperature was higher in Zakarpattia and in the central-southern part of Ukraine (Fig. 2, A), with the highest recorded in Kherson (12.1 ± 0.5 °*C*) and Odesa (11.7 ± 0.7°*C*). Average annual precipitation was higher in the western part of Ukraine (Fig. 2, B), with the highest in Ivano-Frankivsk (806.1 ± 116.4 mm) and Zakarpattia (780.3 ± 116.8 mm). The annual number of days with precipitation ≥1 mm was also higher in the western part of Ukraine, particularly in Zakarpattia (134.0 ± 7.6 days) and Lviv (124.0 ± 6.2 days) (Fig. 2, C). Annual average relative humidity followed a similar pattern, being higher in the western part of Ukraine, with peaks in Volyn and Lviv regions (Fig. 2, D).

Additionally, we investigated the Average Density of River Network, which was highest in the western part of Ukraine, particularly in Zakarpattia (1.25km/km^2) and Ivano-Frankivsk (1 km/km^2) (Fig. 2, E).

Correlation analysis did not find any significant effect of weather factors. However, a significant positive correlation was found between higher density of river network and NR of leptospirosis (r = 0.65, p = 0.0005), indicating a moderate association between these variables (Supplementary File 2).

3.2. Effect of air alarms on Leptospiral epidemiology

We examined the duration of air alarms, which was highest in Kharkiv (4295.15 h) and Zaporizhzhia (4067.38 h) (Fig. 2, F). We also analyzed the number of alarms announced in relation to weather conditions (weather data provided by Visual Crossing: https://www.visualcrossing.com/). Most of the alarm cases (13,364) were announced during cloudy weather without precipitation. We also analyzed whether the number of alarms per month is related to the number of recorded cases of leptospirosis. There was a statistically significant correlation (r = 0.7, p = 0.01) (Fig. 3).

3.3. Seasonality and geographic concentration of leptospirosis cases in Zakarpattia, 2023

Due to the high NR of Leptospira in this region, we examined monthly changes in NR and weather patterns for 2023. In 2023, the majority of leptospirosis cases in Zakarpattia were concentrated towards late summer and early autumn, with 25 out of 150 (16.6 %) cases reported in August and 47 (31.3 %) in September. The highest rainfall was recorded in June and July, which can be connected to the leptospirosis cases because it takes time for water to wash away animal excretions, enter water supply distribution centers, and reach humans. Additionally, the incubation period for leptospirosis ranges from 2 to 30 days, which further explains the separation between the peaks of rainfall and leptospirosis cases. Most cases of leptospirosis were reported in one district of Zakarpattia - Perechynskyi, with 46 cases (Fig. 4).

4. Discussion

We have explored the influence of weather-geographical factors and air alerts on the epidemiology of leptospirosis in Ukraine.

Warm and humid conditions favor the survival of leptospires in the environment, leading to a higher incidence of human leptospirosis cases in tropical and subtropical regions [19,20]. Moreover, outbreaks have been linked to floods and hurricanes following heavy rainfall [3].

Research by Chadsuthi et al. suggests that flooding significantly contributes to disease transmission, with severe flooding resulting in a greater number of infected individuals in Thailand [21]. Various weather parameters, including rainfall, the number of wet days per week, days with rainfall exceeding 100 mm per week, minimum temperature, average temperature, and average humidity, are correlated with local leptospirosis incidence. The climate in Kandy, Sri Lanka, for example, is favorable for leptospirosis transmission [22]. Cunha et al. found that an increase in leptospirosis cases is associated with higher than usual rainfall, lower than expected temperatures, and higher than expected humidity [16].

But why did our analysis show that weather did not affect leptospiral epidemiology? One possible explanation is the construction of reservoirs during the Union of Soviet Socialist Republics (USSR) period—Dniester, Kyiv, Kaniv, Kremenchuk, Dniprodzerzhynsk, Dnipro, and Kakhovka [23]. This led to changes in the landscape and the formation of new leptospirosis hotspots in densely populated areas of Ukraine.

Domestic researchers of leptospirosis identify two regions with a high incidence of the disease: the first covers the Ukrainian Carpathians, and the second runs from north to south along the Dnipro River. Scientists have found that the incidence along the Dnipro has increased relatively recently, starting in the second half of the 20th century [23]. It is interesting to note that in the western regions, where rainfall is higher, the dominant *Leptospira* serogroups during this period were Grippotyphosa and Pomona, primarily spread by moisture-loving wild rodents. In contrast, in the southern and central regions, synanthropic rodents, the main carriers of the *Leptospira* serogroups Icterohaemorrhagiae and Hebdomadis, played a significant role [12].

Due to drainage reclamation in the forest zone and intensive hydrotechnical construction on the Dnipro and Dniester rivers, the patterns of leptospirosis spread in Ukraine have significantly changed, leading to the emergence of new epidemic risk zones. The destruction of the Kakhovka dam in 2023 is also expected to have a significant impact, potentially leading to an increase in zoonotic diseases in Kherson.

A recently published systematic review by Baharom et al. found that water-related risk factors, such as using natural water as the primary water source, engaging in water-related recreational activities, flood exposure, and contact with mud and stagnant water, were associated with an increased risk of leptospirosis [24]. Based on this, the destruction of the Kakhovka dam and the resulting flood are among the factors that may contribute to leptospirosis infections in this affected region.

Confirmation of the hypothesis that geographical factors such as reservoirs, rivers, and lakes play a greater role than weather factors (e.g., humidity, precipitation) is supported by the correlation we found between the density of the river network and the NR of leptospirosis. Zakarpattia has the highest notification rate in Ukraine and the highest river network density, at 1.5–1.7 km/km^2.

The military importance of leptospirosis was first acknowledged during World War I, when epidemic outbreaks of Weil's disease, characterized by jaundice, were reported among soldiers engaged in trench warfare [25]. British, German, French, and Belgian troops experienced significant morbidity due to leptospirosis, with similar reports from Italian and Canadian forces. The causative agent, Leptospira, was identified through concurrent research efforts by military medical services in Germany, France, and Britain, as well as by Japanese researchers who had described the disease earlier. Research has indicated that doxycycline may serve as a chemoprophylactic agent, a post-exposure preventive measure, or an empirical treatment, though evidence supporting its effectiveness is somewhat limited [26].

Not only are military personnel at risk of leptospirosis infection, but the risk to civilian populations is also a serious concern. During heavy bombings, particularly in frontline regions, there is an increased risk of infection in basements and bomb shelters [27,28]. While basements themselves are not specifically mentioned as a risk factor, if they are prone to flooding, have poor sanitation, or are infested with rodents, they could potentially contribute to the risk of leptospirosis.

We found one case report describing a 70-year-old man with leptospirosis. During the Russo-Ukrainian War, the patient only left his house during air alarms and went to the bomb shelter located in the basement

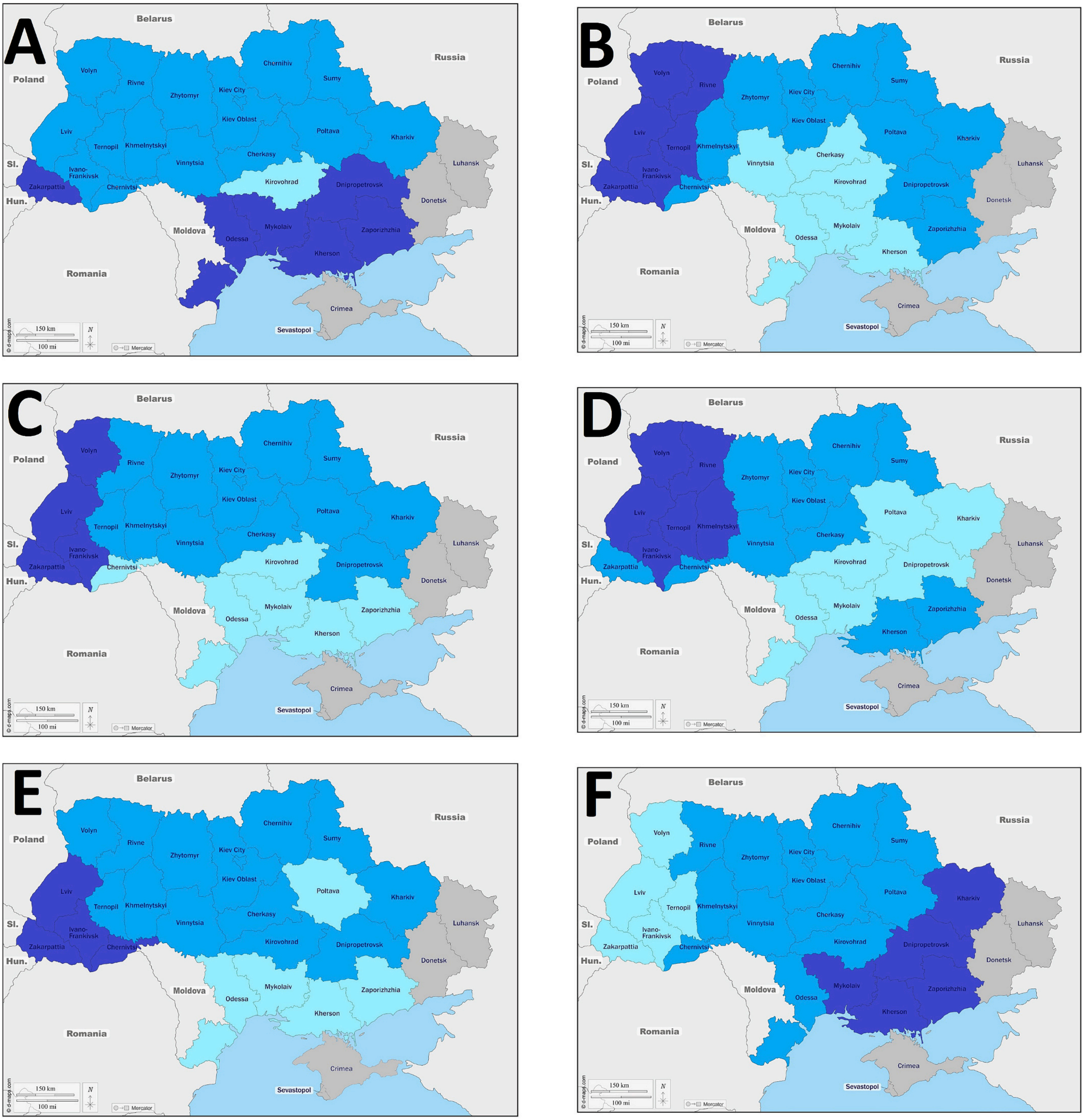

Fig. 2. **A** - Average Annual Temperature in the period 2018–2023 (light blue: less than 9.5 °C; blue: 9.5 to 10.5 °C; dark blue: greater than 10.5 °C). The average annual temperature was higher in Zakarpattia and the central-southern part of Ukraine. **B** - Average Annual Precipitation in the period 2018–2023 (light blue: less than 539 mm; blue: 539 to 608 mm; dark blue: greater than 608 mm). The average annual precipitation was higher in the western part of Ukraine. **C** - Annual Number of Days with Precipitation ≥1 mm in the period 2018–2023 (light blue: less than 93.2 days; blue: 93.2 to 113 days; dark blue: greater than 113 days). The number of days with precipitation was higher in the western part of Ukraine. **D** - Annual Average Relative Humidity in the period 2018–2023 (light blue: less than 73.00 %; blue: 73.00 to 75.8 %; dark blue: greater than 75.8 %). Relative humidity was higher in the western part of Ukraine, with peaks in the Volyn and Lviv regions. **E** - Average Density of River Network (km/km^2) (light blue: less than 0.3; blue: 0.3 to 0.5; dark blue: greater than 0.5). The highest river network density was in the western part of Ukraine – Zakarpattia, Lviv, Ivano-Frankivsk, and Chernivtsi regions. **F** - Air Alarm Duration (light blue: less than 714.17 h; blue: 714.17 to 2254.9 h; dark blue: greater than 2254.9 h). The longest durations of air alarms were in Kharkiv (4295.15 h) and Zaporizhzhia (4067.38 h).
The grey zone represents occupied territories with NA (Not Available) data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

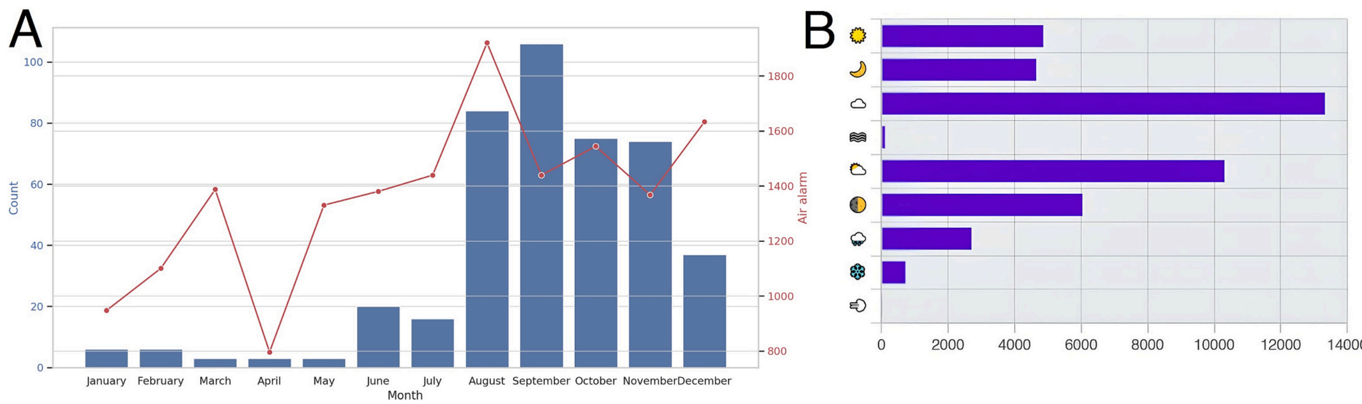

Fig. 3. A - Monthly Leptospirosis Infections and Air Alarms (Blue bars represent the count of people infected with leptospirosis each month. Red line with markers represents the corresponding air alarm values for each month); B- Number of alarms announced depending on the weather: Sun – sunny weather, Moon – nighttime weather, Cloud – cloudy weather, Fog (wavy lines) – foggy weather, Partly Cloudy (sun partially covered by a cloud) – partly cloudy weather, Cloudy Night (moon with cloud) – cloudy night weather, Rain – rainy weather, Snow – snowy weather. The highest number of alarms was announced during cloudy weather, while the lowest was during foggy weather. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

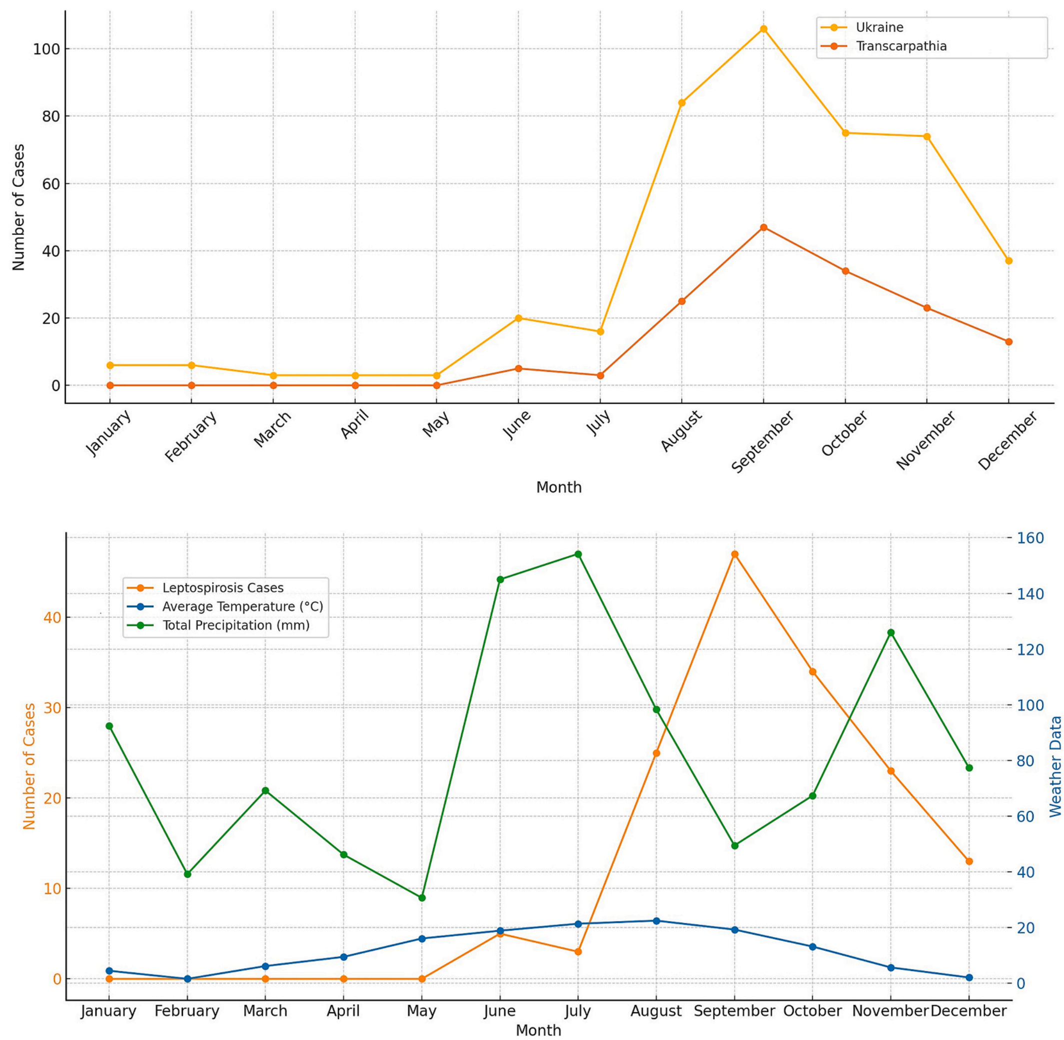

Fig. 4. Seasonal and Weather Distribution in 2023 in Zakarpattia Region.
The top chart shows that in 2023, the majority of leptospirosis cases in Zakarpattia were concentrated in late summer and early autumn, with 25 out of 150 cases reported in August and 47 in September.
The bottom chart illustrates the changes in average temperature and total monthly precipitation in 2023, alongside leptospirosis cases. The highest rainfall was recorded in June and July.

of his apartment complex. The main reason, as the authors assert, is unsuitable living conditions in bomb shelters and direct contact with dried remains of rodent excrement in the shelters [29].

5. Conclusions

Leptospirosis shows significant regional variability in Ukraine, with high notification rates in Zakarpattia, Ivano-Frankivsk, Khmelnytskyi, Mykolaiv, and Kherson. We did not detect a significant effect of weather conditions such as temperature, precipitation, and humidity on NR of leptospirosis in our data. On the other hand, we did find indication of roles for geographical factors in Leptospira transmission, in particular, we found a positive correlation between density of the river network and NR of leptospirosis. Additionally, we found a statistically significant correlation between the number of alarms per month and the number of recorded cases of leptospirosis in 2023. This, together with case reports of individuals contracting leptospirosis in bomb shelters, points to the possibility that air raid alarms affect the epidemiology of leptospirosis. Further investigation is important to understand this relationship and its implications fully.

6. Limitations

This study has several notable limitations. The increase in leptospirosis notification rates observed in 2023 requires cautious interpretation. Significant migration, displacement, and population loss during the conflict may have impacted per capita notification rates, meaning they may not fully reflect leptospirosis trends within the shifting population base. Another key limitation is the lack of access to comprehensive national data on NR changes over time. Without this data, the analysis may not capture the full scope of leptospirosis incidence fluctuations across Ukraine, potentially limiting insights into broader epidemiological trends. Additionally, while the study explores correlations between air raid alarm frequency and leptospirosis incidence, the mechanisms underlying this association remain speculative and warrant further investigation.

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CRediT authorship contribution statement

Pavlo Petakh: Writing – original draft, Validation, Supervision, Investigation, Formal analysis, Conceptualization. **Wolfgang Huber:** Writing – review & editing, Data curation. **Oleksandr Kamyshnyi:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.onehlt.2024.100944.

Data availability

Data will be made available on request.

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