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Spatiotemporal Clustering of Animal Rabies in Kazakhstan: Insights from ArcGIS Pro-Based Analysis

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Abstract

Background and Aim. Rabies is a zoonotic viral disease that continues to pose a major public health threat worldwide, particularly in regions with limited access to vaccination and disease monitoring. Kazakhstan remains endemic for animal rabies, with variable patterns across geography and species. The objective of this study is to identify spatial and temporal clusters of rabies outbreaks among animals in Kazakhstan from 2013 to May 2025, using GIS-based methods to inform regional control and prevention strategies.

Materials and Methods. This study applied three geospatial tools within ArcGIS ProHot Spot Analysis using Getis-Ord Gi*, Kernel Density Estimation (KDE), and Space-Time Kernel Density to a national dataset of confirmed rabies cases among animals. The database included geographic coordinates, species type, dates of confirmation, and number of infected animals. KDE and Getis-Ord Gi* were used to detect spatial clusters and density gradients, while Space-Time Kernel Density enabled tracking of outbreak patterns over time.

Results. Hot Spot Analysis identified high-risk zones in northeastern (North Kazakhstan, Pavlodar oblasts) and western regions (Aktobe oblast), potentially linked to wild animal migration and insufficient vaccination coverage. KDE revealed additional high-density areas in southern and eastern regions. Space-time analysis showed persistent clusters in Zhambyl, Kostanay oblasts, and western Kazakhstan, while central regions exhibited low density likely due to geographic and demographic isolation.

Conclusion. Spatial and spatiotemporal analyses demonstrated that rabies outbreaks in Kazakhstan are not randomly distributed but form distinct species- and region-specific clusters. These insights support the need for differentiated veterinary approaches. Timely and geographically targeted vaccination programs particularly in identified hot spots are critical to reducing the incidence of rabies.

Keywords: animal rabies; ArcGIS Pro; epidemiology; Kazakhstan; spatial analysis; vaccination.

Introduction

Rabies is a fatal zoonotic disease caused by lyssaviruses that affects the central nervous system of mammals, including humans. Once clinical symptoms emerge, the disease is almost invariably lethal. Despite the long-standing availability of effective vaccines and post-exposure prophylaxis, rabies continues to cause tens of thousands of human deaths globally each year, with a disproportionate impact on rural communities in low- and middle-income countries [1, 2].

In Kazakhstan, rabies remains a significant public and veterinary health concern, with confirmed outbreaks recorded annually in both domestic and wild animal populations. Between 2013 and 2023, hundreds of cases were reported across the country, with notable fluctuations in intensity by season, region, and species involved [3]. The persistence of rabies in Kazakhstan is driven by several interrelated factors, including low vaccination coverage among stray and rural domestic animals, the ecological dynamics of wildlife reservoirs such as foxes and wolves, and limited surveillance infrastructure in sparsely populated areas [4, 5].

Recent studies have also highlighted the role of transboundary dynamics, particularly in northern and western regions bordering Russia, which may facilitate the reintroduction and circulation of rabies virus strains across administrative boundaries [6]. These challenges were tragically underscored in May 2025, when a fatal human case of rabies was reported in Lisakovsk, Kostanay Region. The case involved a woman who was bitten by a domestic cat and did not receive timely post-exposure prophylaxis, pointing to ongoing systemic weaknesses in rabies awareness and response mechanisms [7].

To improve disease control and allocate limited resources effectively, spatial epidemiology offers a valuable approach. Geographic Information Systems (GIS) enable the visualization, modeling, and interpretation of complex epidemiological data. Recent advances in GIS platforms, such as ArcGIS Pro, allow for high-resolution analysis of disease patterns by incorporating multiple data layers, including case locations, host species distribution, demographic and environmental factors [8, 9].

The present study applies a suite of spatial and spatiotemporal analytical tools within ArcGIS Pro specifically Getis-Ord Gi* Hot Spot Analysis, Kernel Density Estimation, and Space-Time Kernel Density to identify high-risk zones of animal rabies in Kazakhstan. By integrating geographic, temporal, and biological dimensions, the research aims to support the development of regionally adapted and evidence-based rabies control measures.

Beyond its direct public health implications, rabies also exerts a considerable socio-economic burden, particularly in agrarian economies such as Kazakhstan. Livestock losses due to rabies outbreaks reduce household income in rural areas and create barriers to food security, while costs associated with post-exposure prophylaxis place additional strain on healthcare systems. Moreover, the persistence of rabies undermines international trade in animal products, as importing countries impose strict sanitary regulations. These factors underscore the urgent need for evidence-based spatial risk assessments that can guide targeted interventions, optimize vaccination strategies, and enhance cross-sectoral collaboration under the One Health framework [10, 11].

Materials and Methods

This study utilized confirmed rabies case data collected from veterinary surveillance reports in Kazakhstan between 2013 and May 2025 [3, 4]. Each record included spatial coordinates, date of confirmation, species involved, and number of infected animals [3, 6]. All spatial analyses were performed using ArcGIS Pro (Esri, Redlands, CA), which provided integrated tools for geostatistical evaluation [8, 9].

To identify spatial clusters of rabies cases, Hot Spot Analysis was performed using the Getis-Ord Gi* statistic, a standard method for detecting areas of significantly high or low values in spatial data [3, 8]. This method identifies spatial clusters with elevated (hot spots) or diminished (cold spots) rabies incidence based on Z-scores and P-values [9]. A high positive Z-score and low P-value indicate statistically significant clustering of high values (hot spots), while a high negative Z-score and low P-value suggest clustering of low values (cold spots) [6, 9]. Interpretation of the outputs included Z-score-based classification: areas with values above 1.96 ($p<0.05$) were classified as statistically significant [3, 9]. The analysis was applied to point data from the 2013–2025 rabies case database using the number of infected animals as the population field [3, 8].

Kernel Density Estimation (KDE) was used to assess the spatial intensity of outbreaks by generating a continuous raster surface where each cell value reflected the density of rabies cases in its vicinity [3, 9]. The KDE parameters included: input points (rabies cases), a defined search radius based on average inter-case distances, and a population field representing infected animal counts [4, 9]. Outputs were visualized as heatmaps where areas of higher density were indicated by more intense coloration [3, 9].

For spatiotemporal analysis, the Space-Time Kernel Density method was applied [3, 9]. This technique expands traditional KDE by integrating the temporal dimension, allowing for detection of outbreak clusters that persist or evolve over time [3, 9]. Inputs included the same point dataset, with daily time intervals and distance measured in meters [3, 6]. The outputs were rendered in three-dimensional space-time cubes, where purple dots represented individual rabies cases across time, and darker areas within the color gradient reflected higher densities of outbreaks [3, 9]. Dashed boundary lines indicated administrative divisions of Kazakhstan [3, 4].

All analyses adhered to established methodological standards and were designed to be fully reproducible using documented workflows in ArcGIS Pro [8, 9]. Data processing and visual interpretation were performed consistently using heatmap and cluster detection outputs to facilitate accurate and actionable conclusions [3, 9].

Results and Discussion

Between 2013 and May 2025, a total of 1,010 confirmed rabies outbreaks were reported across Kazakhstan, involving 1,243 infected animals. These outbreaks affected more than ten animal species, including companion, agricultural, and wild animals. Approximately 58% of outbreaks occurred in rural and urban settlements, with repeated cases documented in major cities such as Semey (35 cases), Taraz (29), and Shymkent (28).

The highest cumulative outbreak numbers were recorded in the northeastern (n = 236) and western (n = 219) regions, followed by the southern (n = 196) and northern (n = 130) zones (Figure 1). Annual data revealed consistent case reporting throughout the entire period, with seasonal peaks observed in spring and late autumn, and a noticeable contribution from agricultural and companion animal populations.

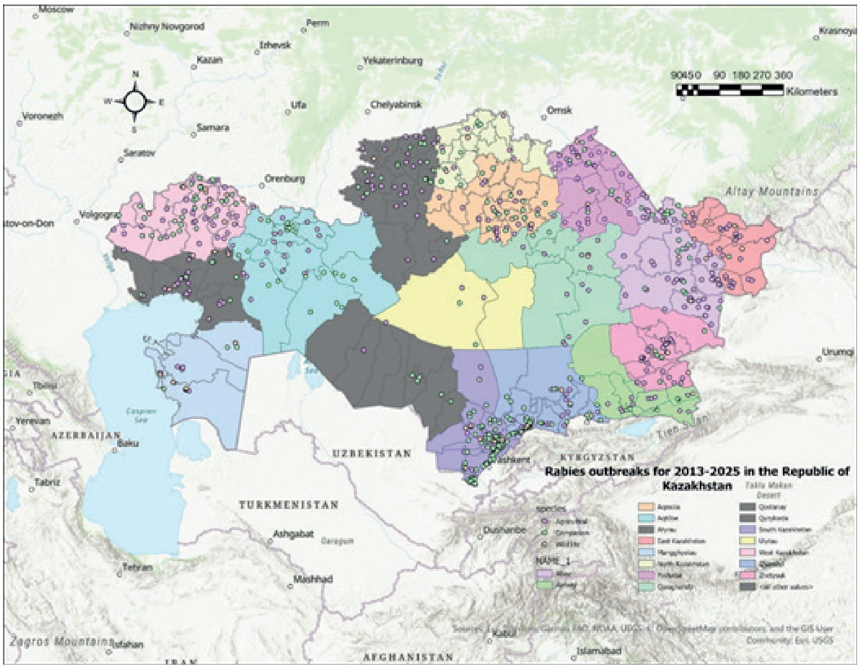

Figure 1 – Spatial Distribution of Rabies Foci in the Republic of Kazakhstan, 2013-2025 (may)

This long-term pattern reflects a persistent endemic status of rabies in Kazakhstan, with clear regional clustering and repeated emergence in certain high-risk areas. These findings emphasize the importance of spatially focused control measures, especially in endemic zones with recurrent activity.

The Hot Spot Analysis (Getis-Ord Gi) revealed statistically significant spatial clustering of rabies outbreaks in Kazakhstan from 2013 to 2024 (Figure 2). Hot spots areas with significantly elevated rabies incidence were predominantly located in northeastern Kazakhstan (North Kazakhstan and Pavlodar oblast) and western Kazakhstan (Aktobe oblast). These clusters are likely associated with active wildlife migration or insufficient effectiveness of vaccination programs. In particular, western regions demonstrated high animal density and low vaccination coverage only 26% of total vaccinations targeted livestock and 8.8% domestic animals. Moreover, no oral vaccination of wild carnivores is carried out in western Kazakhstan, as bait distribution polygons for wildlife immunization are absent in this region, which likely contributes to sustained transmission among wildlife reservoirs and cross-species spillover.

In contrast, cold spots zones with significantly low incidence were detected in the southern regions of the country, specifically in Almaty and Zhambyl oblasts. According to the methodological framework of Hot Spot Analysis (Getis-Ord Gi*), such cold spots represent statistically significant clustering of low values, which may indicate suppression or control of disease transmission in those areas. In the context of rabies, this suggests a likely impact of effective prevention efforts. As supported by previous cluster and outlier analyses, these areas may reflect the positive outcomes of consistent domestic animal vaccination campaigns and elevated levels of oral immunization of wildlife conducted during 2015-2017 and 2022-2023. The spatial concentration of low-incidence values in these regions may thus reflect a measurable containment of the epizootic process through targeted immunoprophylaxis.

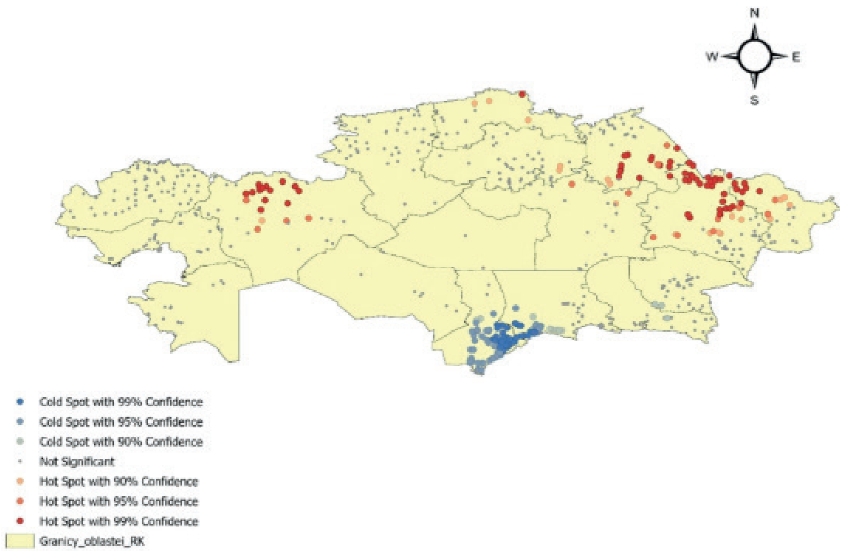

Figure 2 – Hot Spot Analysis of Rabies Cases in Kazakhstan

Kernel Density Estimation illustrated the spatial distribution of rabies cases across Kazakhstan, revealing high-density outbreak zones in Western (West Kazakhstan and Aktobe), Northern and Eastern (North Kazakhstan, Pavlodar, East Kazakhstan), and Southern (Zhambyl and Almaty) oblasts. Central Kazakhstan (Karaganda oblasts) showed relatively low case density, potentially due to sparse human and livestock populations or improved control and vaccination measures in certain southern districts (Figure 3).

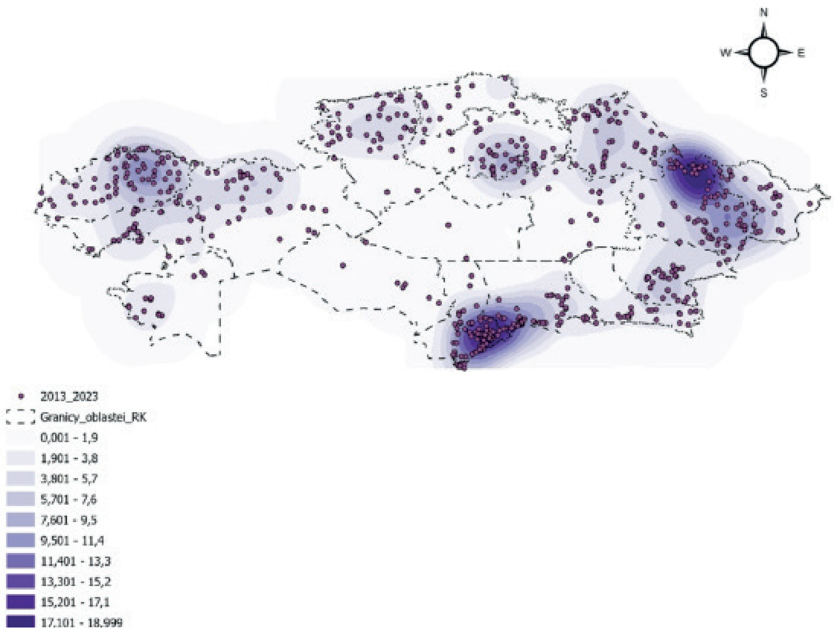

Figure 3 – Kernel Density Estimation of Rabies Case Distribution

Spatiotemporal analysis using Space-Time Kernel Density demonstrated dynamic clustering patterns over time. Medium-density clusters (represented as shaded purple regions) were prominent in West Kazakhstan, North Kazakhstan (Kostanay oblast), and most notably in the South (Zhambyl oblast). Central Kazakhstan remained less affected, possibly due to lower population densities, limited livestock activity, and geographic isolation (Figure 4).

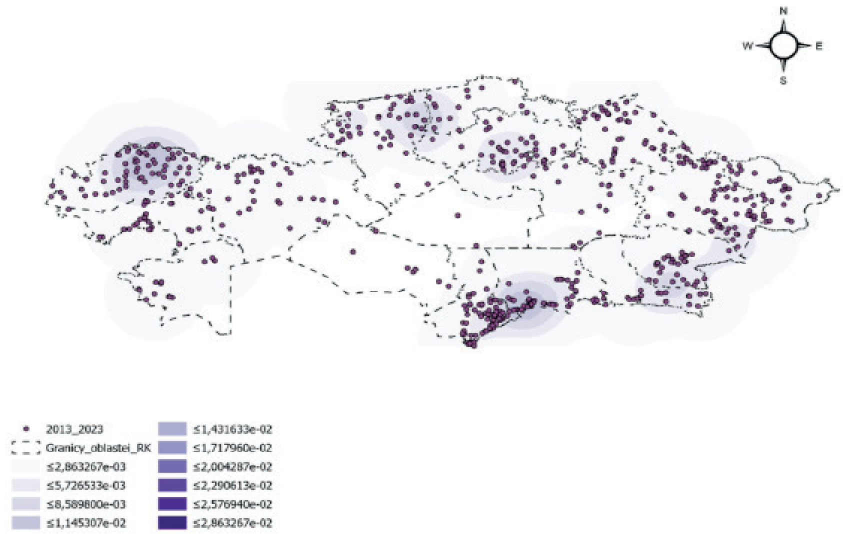

Figure 4 – Space-Time Kernel Density Map of Rabies Outbreaks 2013-2024

Conclusion

The applied spatial and spatiotemporal analysis methods (Getis-Ord Gi* Hot Spot Analysis, Kernel Density, and Space-Time Kernel Density) successfully identified distinct clusters and high-risk territories for rabies outbreaks in Kazakhstan, which correspond with species-specific distributions of infected animals [8, 9, 12]. Companion animals formed clusters predominantly in southern Kazakhstan, agricultural livestock were concentrated in eastern and western regions, and wild animals were most prevalent in western, southern, and northeastern parts of the country [3, 4]. Rabies emergence appears to be strongly influenced by environmental conditions that affect wildlife reservoirs, a factor that should be integrated into the planning of veterinary interventions [5, 6, 13].

These findings support the development of differential control and surveillance strategies and provide baseline analytical and visual tools essential for evaluating the efficacy of rabies prevention programs [1, 2, 14]. Specific clusters identified in eastern and western regions (livestock), southern regions (domestic animals), and northeastern and western territories (wildlife) indicate the need for tailored preventive approaches. For instance, the domestic animal cluster in southern Kazakhstan represents a restrained epizootic scenario influenced by veterinary measures, as supported by Anselin Local Moran's I and cold spot detection [8, 12]. However, despite the planned 70% vaccination coverage, challenges persist due to large populations of pets and the unaccounted stray animal population [14, 15, 16]. This suggests the need for stronger state veterinary oversight and measures to control both owned and stray animal populations.

Vaccination in southern regions should align with seasonal declines in rabies cases ideally between July and September. In eastern Kazakhstan, where low-infection livestock clusters are surrounded by high-risk zones, early and simultaneous vaccination efforts should be scheduled between October and January, coinciding with the housing season for livestock [3, 14]. In western Kazakhstan, the resumption of oral vaccination is advised due to climatic changes affecting wildlife populations and migration patterns [4, 6, 13]. Rising average annual temperatures (+0.38 °C) driven by warm air masses from the Caspian Sea may increase wildlife activity and interspecies contact during winter–spring months [6, 13]. Wildlife migration from bordering regions of the Russian Federation and milder winters, combined with anomalously warm spring and autumn periods, have contributed to sustained rabies activity in North Kazakhstan and Pavlodar regions [3, 5, 12]. These areas confirmed as high-incidence zones by hot and cold spot analyses require enhanced preventive efforts through adjusted timing and expanded coverage from September to November.

Authors' Contributions

AK: Conducted laboratory research and wrote the first draft of the manuscript. AK, MY: Developed the aims, objectives, and methodology of the work; AA: prepared the article per the publication requirements. SA: Performed statistical analysis and reviewed the manuscript. All authors read, reviewed, and approved the final version of the manuscript.

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