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Spatial and temporal distribution of bovine tuberculosis outbreaks in Türkiye between 2017–2023

Şahin Çakır[1], Mustafa Yakar[2] and Francisco Olea-Popelka[3]

[1]Department of Microbiology, Faculty of Veterinary Medicine, Necmettin Erbakan University, Türkiye; [2]Department of Geography, Faculty of Humanities and Social Sciences, Süleyman Demirel University, Türkiye and [3]Department of Epidemiology and Biostatistics, Schulich School of Medicine & Dentistry, Western University, Canada

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Corresponding author:
Şahin Çakır;
Email: sahin.cakir@erbakan.edu.tr

Abstract

Bovine tuberculosis (bTB) is a zoonotic disease that poses a significant threat to both animal and public health globally, leading to considerable socio-economic losses. Primarily caused by *Mycobacterium bovis*, bTB epidemiology and geographical distribution among cattle herds are complex and multifactorial. This study describes the spatiotemporal distribution of bTB outbreaks among cattle premises in Türkiye from 2017 to 2023 using Geographic Information Systems (GIS) and spatial analyses, including the assessment of distances between bTB outbreak premises and livestock bazaars. The findings indicate that bTB outbreaks occurred in various regions over time but remain particularly concentrated in certain areas. Kernel density analysis provides additional evidence for this high-density area of bTB outbreaks. Furthermore, the finding that 88.1% of bTB outbreaks occurred within 50 km of livestock bazaars highlights an important geographical characteristic of the livestock industry in Türkiye that could play a potential role in the epidemiology of bTB. In conclusion, the study highlights the importance of utilizing spatial epidemiology to understand key aspects of the spatiotemporal distribution of bTB in Türkiye, which is crucial to design strategies to control bTB. It is expected that the study will guide national disease management strategies, contribute to the efficient allocation of resources, and inform future research.

Introduction

Bovine tuberculosis (bTB) is a chronic infectious disease that primarily affects cattle [1, 2]. The main causative agent of this disease, *Mycobacterium bovis* (*M. bovis*), has a global distribution and a wide host range, including wildlife and humans [3–5]. The negative impact of bTB on both animal and public health, combined with the socio-economic losses it causes, raises serious global concerns [6, 7].

Globally, tuberculosis (TB) is the world's leading cause of death from a single infectious agent and among the top ten causes of death, with an estimated 10.7 million people suffering from TB in the year 2024 and 1.23 million people dying from this disease in 2024 [8]. In Türkiye, a total of 9156 TB cases in people were reported in 2021, and 9851 cases in 2022 [9]. While *M. bovis* is estimated to account for approximately 10% of human TB cases in developing countries [6], this rate was found to be 5.3% in Türkiye [10]. The World Health Organization (WHO) estimated approximately 143000 zoonotic TB cases worldwide in 2018, caused by *M. bovis* [11]. Similarly, the European Food Safety Authority reported 111 zoonotic TB cases in the European Union in 2021, caused by *M. bovis* or *M. caprae*, and to date, zoonotic TB still poses a serious threat to public health [12] in countries in which bTB is prevalent and socio-cultural factors facilitate transmission of *Mycobacterium tuberculosis* complex (MTBC) species between cattle and people.

bTB is endemic in cattle populations in many countries, negatively impacting economic development and leading to significant financial burdens for breeders and taxpayers [13–15]. It is estimated that the disease infects over 50 million cattle worldwide, resulting in annual economic losses of approximately US$3 billion [6, 16]. The reported socio-economic loss in Türkiye is estimated to range from approximately US$15 million to US$59 million annually [17]. The total population of cattle in Türkiye is approximately 17 million, and a previous study [18] shows that 0.8% of premises (herds) had a bTB outbreak for the period 2017–2021. The national bTB control programme in Türkiye established in 2024, is based on slaughterhouse surveillance, followed by tuberculin skin testing (TST) of cattle on premises where infected cattle had been identified at slaughter and kept during the previous 6 months. Cattle that test positive are conditionally slaughtered with compensation paid to breeders, and affected premises remain under quarantine until the infection has been cleared. In addition, financial support is provided to premises officially recognised as free from bTB to encourage the maintenance of disease-free status.

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Spatiotemporal epidemiological studies are essential for understanding the distribution and dynamics of bTB, which can subsequently be used to identify potential risk factors and support evidence-based disease control strategies. By integrating geographical data with mapping and spatial analytical methods, spatiotemporal studies provide valuable insights into disease patterns and facilitate the identification of high-density areas [1, 2, 15, 19–21].

Geographic Information Systems (GIS) are an effective tool for spatial epidemiological research to describe distribution, patterns, and to evaluate risk factors of diseases within a population. The collection, organization, and analysis of data from disease-affected areas based on designated spatial epidemiological units are vital [1, 15]. While research on the use of GIS for animal diseases in Türkiye remains limited, it has begun to increase recently. Most studies that have used GIS in Türkiye have primarily focused on visualizing diseases through maps, with a few exceptions involving spatial analyses [22–25]. In the study by Çakır and Yakar [18], which mapped the spatial distribution of bTB in Türkiye for the period 2017–2021, the authors demonstrated the spatial distribution of bTB outbreaks and how this distribution changed over the 5-year period. However, the study by Çakır and Yakar [18] did not include any spatial analyses to determine whether bTB outbreaks exhibited a high-density area tendency, among other aspects of spatial distribution.

Therefore, the aim of this study was to describe the spatial and temporal patterns of bTB outbreaks in Türkiye between 2017 and 2023 using GIS-based spatial analysis methods. In this study, in addition to mapping the spatial distribution of bTB outbreaks in Türkiye between 2017 and 2023 (two additional years of data compared to the spatial distribution), spatial analyses using buffer analysis (BA) were used to determine distances from premises with bTB outbreaks to livestock bazaars for all bTB outbreaks between 2017 and 2023.

Methods

Study area

Türkiye is located in the Northern Hemisphere, consisting of 81 provinces and 973 districts, with an area of 780580 km^2 (Figure 1). The country's diverse climate, altitude, topography, and vegetation support extensive agricultural and livestock production systems. There are approximately 16.6 million head of cattle on 1.1 million cattle premises across the country [26, 27].

Data collection

The data on bTB outbreaks used in this study were obtained from the Veterinary Information System (VIS), a module within the Agricultural Information System (AIS) under the Republic of Türkiye, Ministry of Agriculture and Forestry (MoAF). The data in VIS were entered directly into the system by veterinary officials working in the Provincial and District Directorates of MoAF (https://hbs.tarbil.gov.tr/Main/InternalUser).

The bTB dataset recorded in VIS includes address information and geographic coordinates of the premises identified as having a bTB outbreak across the country. Additionally, the database included field-collected information (Table 1) regarding the source of infection for bTB identified by official veterinarians. These epidemiological data are important for understanding potential risk factors for bTB outbreaks identified by field veterinarians as part of field epidemiological outbreak investigations. Seventeen categories were recorded and include (but are not limited to): (1) Latent/subclinical infection within the premises, (2) purchase of infected animals, (3) local pasture, (4) purchase of contaminated vehicles/equipment, (5) recurrent infection within the premises. These data were used for descriptive purposes in our study after the category 'being investigated' was removed (Table 1).



Figure 1. Map of Türkiye's administrative division.

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Table 1. Sources of bTB infection identified through epidemiological investigations of affected cattle premises in Türkiye (2017–2023)

Number	Epidemiological category/Year	2017	2018	2019	2020	2021	2022	2023	2017–2023	General %	Known %
1	Being investigated	315	373	573	538	728	326	153	3006	23.2	
2	Other	18	232	374	268	251	529	669	2341	18.1	
3	Direct contact with wildlife	1	2	0	0	1	0	0	4	0.0	0.1
4	Indirect contact with wildlife	8	4	1	0	2	3	4	22	0.2	0.3
5	In the transport vehicle	6	3	3	2	1	1	1	17	0.1	0.2
6	Iatrogenic transmission	2	2	7	3	5	6	9	34	0.3	0.4
7	Infected bull	1	0	6	3	10	5	4	29	0.2	0.4
8	Contaminated animal feed	7	6	6	1	2	5	3	30	0.2	0.4
9	Vectorial transmission	5	3	9	6	1	12	4	40	0.3	0.5
10	Animals distributed from the young farmer project	2	9	17	1	1	0	0	30	0.2	0.4
11	In the livestock bazaars	8	8	5	12	3	10	16	62	0.5	0.8
12	Neighbour village/premises	7	14	12	11	11	6	6	67	0.5	0.9
13	Recurrent infection within the premises	16	29	39	38	37	41	31	231	1.8	3.0
14	Purchase of contaminated vehicles/equipment	65	50	80	53	43	43	14	348	2.7	4.6
15	Local pasture	93	121	133	123	125	94	114	803	6.2	10.5
16	Purchase of infected animals	197	224	222	184	203	282	182	1494	11.5	19.6
17	Latent/subclinical infection within the premises	469	549	761	634	628	736	635	4412	34.0	57.9
Total		1220	1629	2248	1877	2052	2099	1845	12970		

Source: [26].

In addition, the number of animals sent to conditional slaughter or culled from premises with outbreaks between 2017 and 2023 due to the disease and the compensation amounts paid for these animals were also obtained from VIS.

This study covered the period 2017–2023, with data for each year. This study used the exact coordinates of the affected premises for point-based mapping. Thus, the spatial pattern of the disease was mapped at the highest possible precision, and descriptive spatial analyses were performed accordingly.

The geographic coordinates of livestock bazaars in Türkiye were obtained from MoAF with the necessary permits and incorporated into the study. These data enabled the analysis of the distance between livestock bazaars and the location of premises with bTB outbreaks. The coordinate data for both bTB outbreaks and livestock bazaars were verified, and any missing or erroneous records identified were corrected using Google Maps searches based on the addresses of the relevant premises. Duplicate notification reports were also removed from the dataset after reviewing the disease notification number, record, and approval dates.

Finally, since bTB is a notifiable disease in Türkiye, the necessary legal permissions for data access and publication of the results were obtained from the MoAF. This descriptive study only included data on affected premises with a bTB outbreak during 2017–2023, and data on unaffected premises were not available.

Data analysis

Kernel density analysis

Kernel Density Analysis (KDA) was performed using the Spatial Analyst tool in ArcGIS Pro version 3.6 on thematic maps of the outbreaks [28].

KDA was used to visualize and evaluate spatial data. This analysis shows the density of the data points, identifies hotspot and coldspot areas, and highlights locations where bTB outbreaks occur more frequently.

Buffer analysis

BA creates zones around a specified point, line, or polygon at defined distances. This analysis is used to identify the impact area or regions within a certain distance of a particular location. In this study, livestock bazaars were used as reference points in the BA to assess spatial proximity of bTB outbreaks to these locations. The distribution of bTB outbreaks was determined within buffer zones of <25, <50, <75, <100, and <125 km from livestock bazaars. The distribution of bTB outbreaks within each buffer zone was then determined using the Buffer tool in ArcGIS Pro version 3.6 [29].

Results

Temporal distribution of bTB outbreaks

From a population of approximately 1.1 million cattle premises in Türkiye, a total of 12970 bTB outbreaks were identified during the study period (2017–2023), and 107929 cattle were sent for conditional slaughter or were culled due to the disease. The total compensation paid to breeders amounted to ₺1052824716.48 (approximately US$24.2 million) during the study period (Table 2).

Epidemiological investigation of bTB outbreaks

Official veterinarians who detected outbreaks of bTB in the field also investigated the most likely epidemiological transmission route

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Table 2. Total number of cattle and bTB disease data in Türkiye (2017–2023)

Year	Number of bTB outbreaks	Number of cattle (head)	Number of cases (head)	Incidence[a] (Per 100000)	Number of cattle compensated (head)	Amount of compensation paid (₺)
2017	1220	16105025	11763	73.0	10553	42080777.19
2018	1629	17220903	11035	64.1	11412	56163211.90
2019	2248	17872331	16781	93.9	23567	121083274.08
2020	1877	18157971	19471	107.2	17991	114029486.83
2021	2052	18036117	18579	103.0	17312	136565536.10
2022	2099	17023791	17206	101.1	14884	190818833.06
2023	1845	16583005	13040	78.6	12210	392083597.32
Total	12970	–	107875	–	107929	1052824716.48

Source: [26, 27], [US$1 = ₺(Turkish Lira)43.5].
[a]Incidence: (Number of cases/Number of cattle) × 100000).

of the disease and entered their findings into VIS. The data obtained from this epidemiological investigation were collected at the national level and were important for understanding the dynamics of bTB disease.

In the epidemiological investigation on 12970 premises with a bTB outbreak (Table 1), 3006 (23.2%) were excluded from this analysis since no findings were identified, and these premises were recorded as 'being investigated', leaving 9964 premises with completed epidemiological investigations. Among those with a completed epidemiological investigation, for 2341 (18.1%) premises the source of infection was classified in the 'other' category, with the remaining 7623 premises classified in one of 15 categories (Table 1) with a 'known' source of infection. Five of these 15 categories accounted for nearly the entirety, 7288 (95.6%), of the premises (7623) with a 'known' source of infection. The top five categories were: (1) latent/subclinical infection within the premises 4412 (57.9%), (2) purchase of infected animals 1494 (19.6%), (3) local pasture 803 (10.5%), (4) purchase of contaminated vehicles/equipment 348 (4.6%), and (5) recurrent infection within the premises 231 (3.0%). The remaining ten categories accounted for 335 (4.4%) premises with completed epidemiological investigations and a 'known' source of infection (Table 1).

Spatial distribution of bTB outbreaks

Maps showing the spatial distribution of bTB outbreaks between 2017 and 2021 were previously published by Çakır and Yakar [18]. However, they are updated here to illustrate the temporal distribution of outbreaks, adding new data for the years 2022 and 2023 and to serve as a basis for the KDA and BA, which were not previously conducted. Although there are variations in the distribution pattern by year, the main provinces where higher numbers of bTB outbreaks were observed in 2022–2023 are Erzurum, Elazığ, Sivas, Çorum, Tokat, Samsun, Çankırı, Kastamonu, Bolu, Bartın, Düzce, Kütahya, Aydın, Denizli, Burdur, and Edirne (Figure 2).

Kernel density analysis

Figure 3 shows the KDA results for 2017–2023. The maps in Figure 3 show the spatial distribution of bTB outbreaks and illustrates temporal changes in high-density outbreak areas of across different regions of Türkiye.

The density of bTB outbreaks in zones surrounding these high-density areas varies over time. A prominent high-density area identified in this analysis includes a group of premises in the Thrace region, encompassing the provinces of Edirne, Kırklareli, and Tekirdağ. Another high-density area, occasionally expanding, was detected in the Aegean and Mediterranean regions, covering the provinces of Aydın, Denizli, and Burdur. A crescent-shaped high-density region was identified to the east and south of the Gulf of İzmit, including the provinces of Kocaeli, Sakarya, Düzce, Bolu, Bartın, Kütahya, and Bursa. Provinces with increasing outbreak densities over the years are primarily located in Central Anatolia, including Kayseri, Sivas, Yozgat, Çankırı, Aksaray, Niğde, and Konya, and in the Black Sea region, including Tokat, Amasya, Çorum, Kastamonu, and Samsun. Additionally, bTB outbreak concentration is observed in Erzurum, Erzincan, and Elazığ, extending to Adıyaman and Adana.

Buffer analysis

The thematic maps in Figure 4 show the distribution of bTB outbreaks overlaid with livestock bazaar variable as an additional layer. The BA was applied for each year separately between 2017 and 2023 to investigate the relationship between livestock bazaars and bTB outbreaks. The number of bTB outbreaks within each specified distance range/zone from each livestock bazaar was calculated and mapped (Figure 4). Of the total 12970 bTB outbreaks reported between 2017 and 2023, 7604 (58.6%) were found within <25 km, 11428 (88.1%) within <50 km, 12596 (97.1%) within <75 km, 12887 (99.4%) within <100 km, and 12926 (99.7%) within <125 km distance from livestock bazaars. An examination of the maps showing the distribution of bTB outbreaks in relation to livestock bazaars indicates that livestock bazaars are located in close proximity to areas with a high density of bTB outbreaks (Figure 4 and Table 3).

Discussion

The increasing use of advanced tools in veterinary epidemiology and the digital recording of geographically referenced data in Türkiye have enabled the application of various GIS-based analyses to different animal diseases [21]. The spatiotemporal analyses and maps of bTB outbreaks generated in this study were made possible by the recording of geographic coordinates by the

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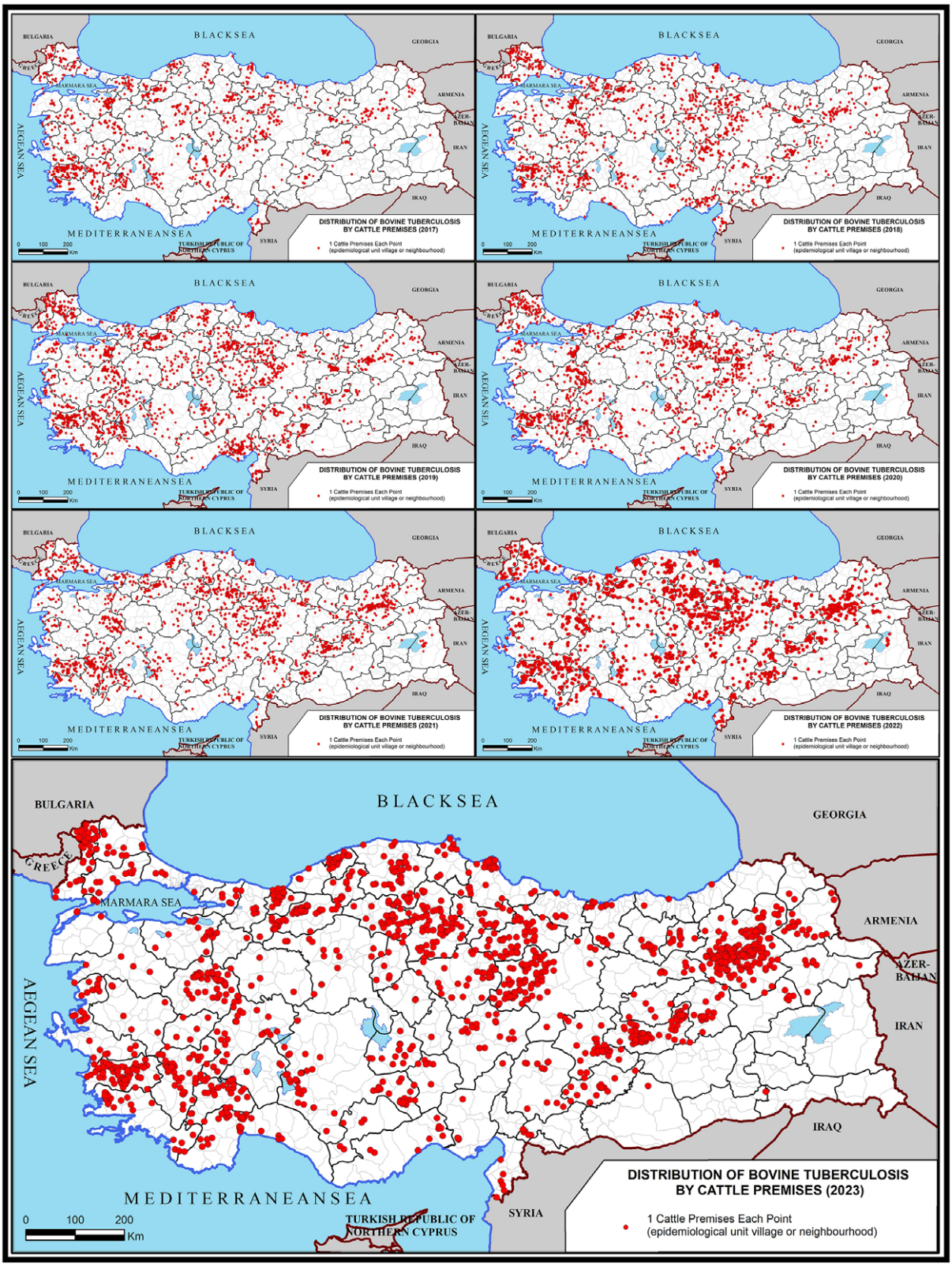


Figure 2. Spatial and temporal distribution of bTB outbreaks (2017–2023).

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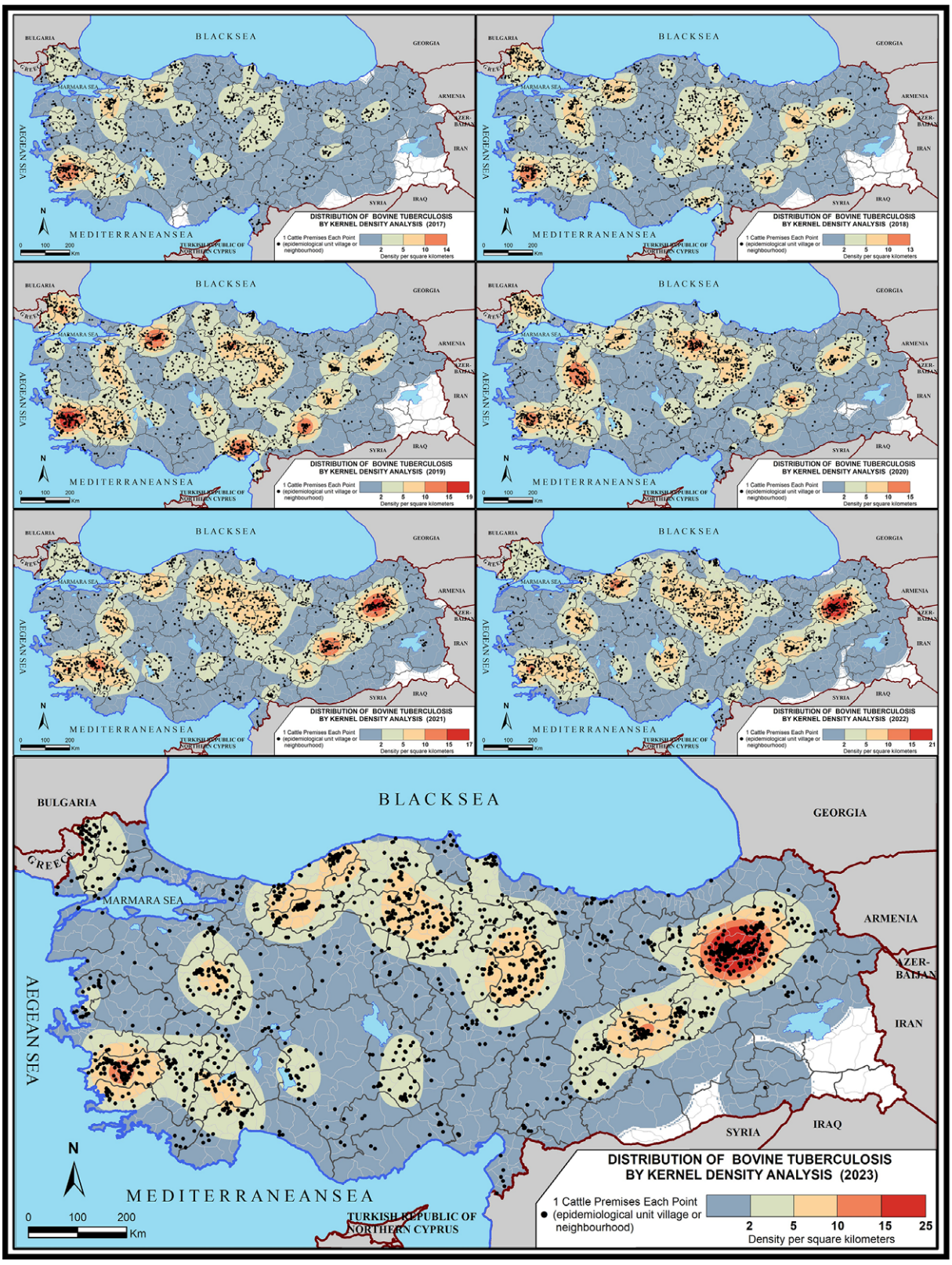


Figure 3. Distribution of bTB outbreaks according to KDA (2017–2023).

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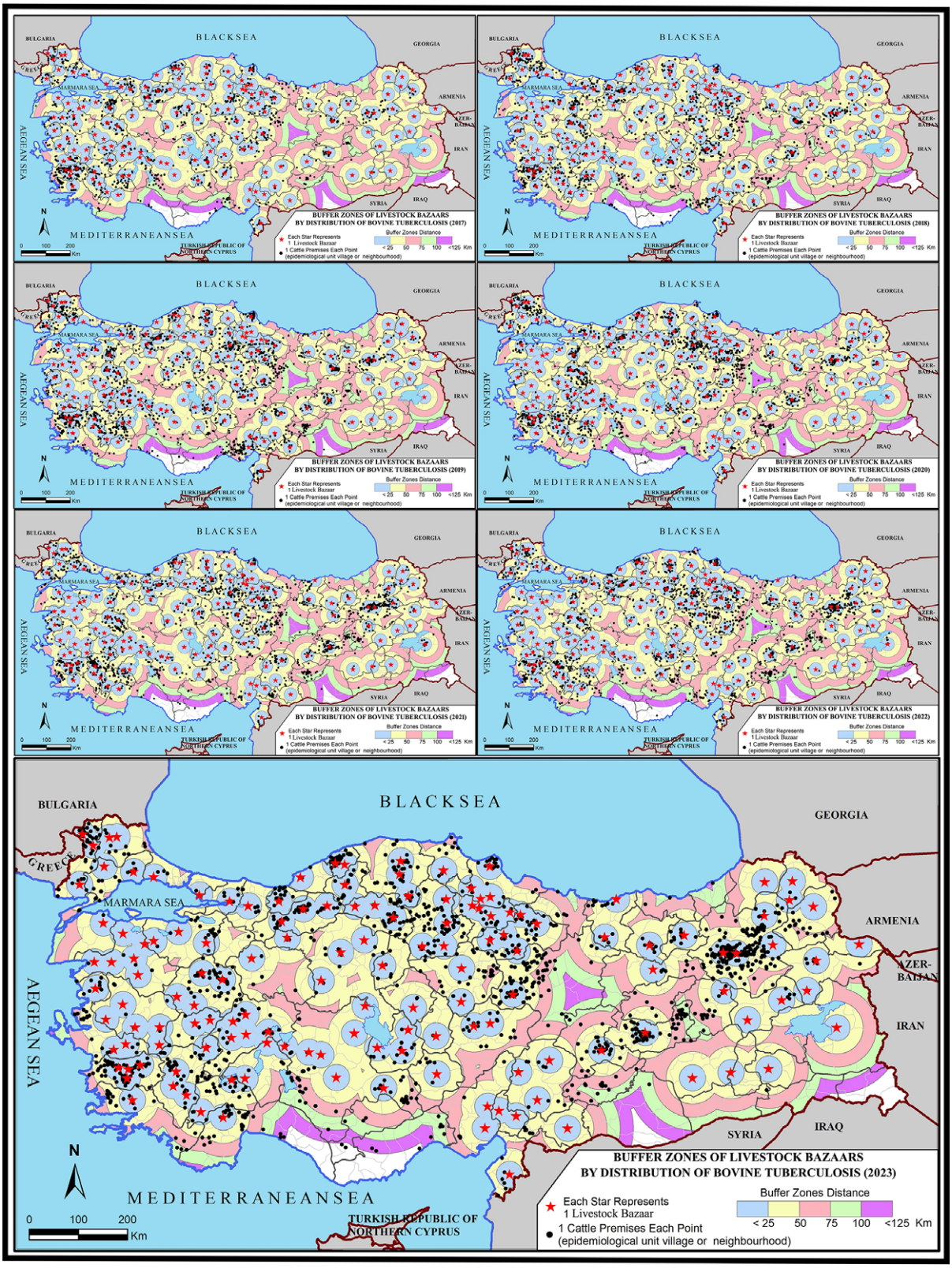


Figure 4. Distribution of bTB outbreaks by livestock bazaars buffer zones (2017–2023).

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Table 3. Distribution of bTB outbreaks by livestock bazaar buffer zones (2017–2023)

Year	<25 km	%	<50 km	%	<75 km	%	<100 km	%	<125 km	%	Total
2017	738	60.5	1089	89.3	1173	96.1	1209	99.1	1212	99.3	1220
2018	996	61.1	1447	88.8	1583	97.2	1615	99.1	1622	99.6	1629
2019	1361	60.5	1965	87.4	2184	97.2	2233	99.3	2239	99.6	2248
2020	1090	58.1	1647	87.7	1815	96.7	1863	99.3	1873	99.8	1877
2021	1150	56.0	1812	88.3	2002	97.6	2042	99.5	2044	99.6	2052
2022	1185	56.5	1825	86.9	2043	97.3	2090	99.6	2095	99.8	2099
2023	1084	58.8	1643	89.1	1796	97.3	1835	99.5	1841	99.8	1845
Total	7604	58.6	11428	88.1	12596	97.1	12887	99.4	12926	99.7	12970

MoAF, specifically for premises with confirmed bTB outbreaks, together with the integration of veterinary epidemiology and geographical expertise.

The use of GIS has made it possible to produce thematic disease maps showing temporal changes in bTB, identify disease patterns and dynamics, detect areas with a high density of bTB outbreaks, visualize spatial relationships to facilitate the interpretation of epidemiological data, and evaluate the stability of infection risk [1]. Analysing the spatial distribution of disease across multiple scales is essential for understanding disease distribution, temporal changes, and transmission dynamics within the population [21]. This highlights the importance of prioritizing areas exhibiting spatial clustering in disease control efforts. Geographically targeted disease management and control programmes can contribute to reducing the overall disease burden (prevalence) and minimizing contact between at-risk animals in these areas and the broader cattle population [4].

Previous studies on the spatial distribution of bTB in Türkiye covering the period 2005–2021 showed that the identification of bTB outbreaks was not evenly distributed across the country. These studies also indicated an increasing trend in the identified number of bTB outbreaks in Türkiye [18, 30]. Our findings in this study suggest that this increasing trend persisted in 2022 and 2023. Furthermore, a recent study published in 2023 mapped the distribution of cattle population at the district level alongside the national distribution of bTB outbreaks in 2021. The correlation analysis conducted in this study revealed a weak positive association between cattle population density and the number of bTB outbreaks [18].

There is a growing recognition that a better understanding of spatial patterns, the identification of high-density bTB outbreak areas, and the analysis of their relationships with other variables are essential for improving disease control. In this study, two additional years (2022 and 2023) of data were incorporated, allowing the analysis of bTB outbreaks over the 2017–2023 period. Furthermore, spatial and temporal changes in bTB outbreaks were evaluated using KDA and BA for the first time in Türkiye.

The number of identified bTB outbreaks is influenced by the characteristics of the slaughterhouse surveillance system, including the frequency of testing, the diagnostic performance of the TSTs, and the effectiveness of local veterinary authority activities. Under the national bTB control programme, the detection of a positive case during slaughterhouse surveillance is legally followed by epidemiological investigation and tuberculin testing of epidemiologically linked premises. The imperfect sensitivity and specificity of TSTs (single intradermal test: 68.1% sensitivity and 96.7% specificity [31]; comparative intradermal tuberculin test: 69.8% sensitivity and 98.0% specificity [32]), together with the persistence of *M. bovis* in manure and slurry for up to 6 months and environmental contamination, are likely to contribute to the persistence of bTB on affected premises [13, 33]. Furthermore, Çakır et al. reported that at least 45.1% of infected premises had another bTB-affected premise within the same settlement [34]. Consistent with this finding, 'latent/subclinical infection within the premises' was the most frequently identified category in the field epidemiological investigations in the present study (57.9%), suggesting that infection may contribute to the persistence of high-density bTB outbreak areas.

The KDA results showed that the spatial distribution of bTB outbreaks in Türkiye varied across the seven-year study period (2017–2023), while high-density outbreak areas persisted in several provinces across western, central, and eastern Türkiye (Figure 3). The persistence of high-density areas across successive years indicates that, despite temporal changes in the overall distribution of outbreaks, their spatial concentration remained relatively stable in certain regions. These findings suggest that KDA can help identify areas that may warrant greater attention in bTB control programmes and support the prioritization of geographically targeted surveillance and control measures.

Given the role of livestock bazaars as hubs for animal movement and the potential for infected animals to facilitate disease transmission between premises, examining the spatial proximity of bTB outbreaks to these locations is epidemiologically relevant [34]. In the present study, 88.1% of bTB outbreaks were located within 50 km of livestock bazaars (Table 3). This finding, together with the epidemiological investigation results showing that the 'purchase of infected animals' was the second most frequently reported source of infection (19.6%) (Table 1), highlights the potential importance of livestock trade in bTB transmission. Premises proximity to livestock bazaars should be further investigated as a potential factor impacting the spatial distribution of bTB outbreaks in Türkiye, as the location, distance, and role of bazaars play a role not only in animal movements but also in other forms of contact with bazaar environments. For example, frequent visits to livestock bazaars by livestock owners may provide opportunities for indirect transmission through contaminated clothing, equipment, vehicles, or other fomites, even in the absence of direct animal purchase or movement [34]. Therefore, strengthening biosecurity measures at livestock bazaars, including controls on animal entry and exit, regular cleaning and disinfection, and measures to minimise direct contact during animal trading, may contribute to

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reducing the risk of bTB transmission. Additional measures, such as pre-sale testing, verification of negative TST status, online or premises-to-premises sales, and quarantine of newly purchased animals, may further reduce transmission risks associated with livestock trade.

Overall, integrating the spatial distribution of bTB outbreaks with the identification of high-density areas, temporal changes in outbreak identification, and epidemiological investigation findings provides an important evidence base for developing more targeted bTB control strategies in Türkiye. The identification of persistent spatial areas, particularly in regions with a high concentration of bTB outbreaks, highlights the value of incorporating spatial epidemiological information into routine surveillance and control planning. In this context, prioritising surveillance and biosecurity measures at livestock bazaars, strengthening the monitoring of undocumented animal movements, and improving the traceability of cattle movements may help reduce opportunities for disease transmission. Spatially targeted interventions could also facilitate more efficient allocation of limited veterinary resources by directing surveillance and control activities towards areas where the risk of disease persistence and distribution is greatest.

Future research should incorporate complementary datasets and multidisciplinary approaches to improve understanding of bTB transmission and inform control strategies in Türkiye. Nationally and regionally representative surveys are needed to update estimates of infection prevalence and to assess its current epidemiological and socio-economic burden. More comprehensive analyses incorporating detailed animal movement data would also help clarify the contribution of animal movements and livestock bazaars to disease spread. Further research should evaluate the performance of existing diagnostic tests and explore the potential value of complementary diagnostic approaches. Finally, involving relevant stakeholders and breeders' organisations in future research and control programmes, together with targeted training and awareness activities, may facilitate stakeholder engagement and improve the implementation of bTB control measures.

This descriptive study has several limitations. First, the limited number of previous studies on the epidemiology of bTB in Türkiye, together with the lack of recent data on the national prevalence and socio-economic burden of the disease, limited our ability to incorporate these aspects into the present analysis. Second, comprehensive spatial data on all cattle premises in Türkiye (approximately 1.1 million premises) were not available [26]. Consequently, we could not conduct spatial 'clustering' analyses that accounted for the population at risk, including premises without reported bTB outbreaks. This limitation is particularly relevant when interpreting the spatial distribution of bTB outbreaks, as the observed distribution may partly reflect the underlying distribution and density of cattle premises, rather than the risk of bTB outbreaks. Furthermore, detailed animal movement data were not available, limiting our ability to directly assess transmission pathways and to distinguish the contribution of livestock bazaars from other movement-related factors. Therefore, the spatial associations identified in this study should not be interpreted as evidence of causal relationships (or risk) for a given area, nor between proximity to livestock bazaars and bTB transmission.

Conclusion

Beyond describing the spatiotemporal distribution of bTB outbreaks, the spatial analyses performed in this study, including mapping, KDA, and BA, identified areas with a high density of outbreaks and demonstrated the distance between bTB outbreaks and livestock bazaars. These findings were interpreted alongside epidemiological investigation data and evidence from the existing literature, providing a broader perspective on the spatial epidemiology of bTB in Türkiye. In addition, the economic burden of bTB during the study period was characterised based on compensation payments associated with animals subjected to conditional slaughter or culling.

The findings of this study highlight the need for a coordinated and effective national bTB control strategy to further evaluate and reduce the risk of continued disease transmission and spread among susceptible cattle and premises. Beyond its impact on cattle health and production, bTB remains a public health concern because of the potential zoonotic transmission of *M. bovis* and other members of the MTBC, particularly in rural settings where cattle infection is prevalent and socio-cultural practices that increase the risk of zoonotic transmission of MTBC, such as the consumption of unpasteurized dairy products, may occur. Effective control of bTB is therefore important not only for reducing disease transmission but also for mitigating the associated socio-economic and operational burdens, particularly in rural communities.

The findings of this study provide important evidence to inform decision-making and policy development for national bTB control strategies, support the efficient allocation of public resources, identify areas for further work, and guide the management and monitoring of disease control efforts. By integrating spatial analysis with epidemiological investigation data at the national level, this study also provides a basis for future spatial epidemiological research on bTB in Türkiye and may contribute to a better understanding of the spatial epidemiology of the disease at the international level.

Data availability statement. The data that support the findings of this study are available from the corresponding author upon request.

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References

[1] **Garcia-Saenz A**, et al. (2014) Spatio-temporal variability of bovine tuberculosis eradication in Spain (2006–2011). *Spatial and Spatio-temporal Epidemiology* **10**, 1–10. https://doi.org/10.1016/j.sste.2014.06.002.

[2] **Moustakas A and Evans MR** (2016) Regional and temporal characteristics of bovine tuberculosis of cattle in Great Britain. *Stochastic Environmental Research and Risk Assessment* **30**(3), 989–1003. https://doi.org/10.1007/s00477-015-1140-3.

[3] **Alvarez J**, et al. (2012) Eradication of bovine tuberculosis at a herd-level in Madrid, Spain: Study of within-herd transmission dynamics over a 12-year period. *BMC Veterinary Research* **8**(1), 100. https://doi.org/10.1186/1746-6148-8-100.

[4] **Pereira AC**, et al. (2020) Animal tuberculosis: Impact of disease heterogeneity in transmission, diagnosis and control. *Transboundary and Emerging Diseases* **67**(5), 1828–1846. https://doi.org/10.1111/tbed.13539.

[5] **Reis AC**, et al. (2021) Global trends of epidemiological research in livestock tuberculosis for the last four decades. *Transboundary and Emerging Diseases* **68**(2), 333–346. https://doi.org/10.1111/tbed.13763.

[6] **Chang Y**, et al. (2023) Inferring bovine tuberculosis transmission between cattle and badgers via the environment and risk mapping. *Frontiers in Veterinary Science* **10**, 1233173. https://doi.org/10.3389/fvets.2023.1233173.

[7] **Ciaravino G**, et al. (2023) Improving the communication between farmers and veterinarians to enhance the acceptability of bovine tuberculosis eradication programmes. *Preventive Veterinary Medicine* **220**, 106046. https://doi.org/10.1016/j.prevetmed.2023.106046.

[8] **World Health Organization** (2025) Tuberculosis Fact Sheet. https://www.who.int/news-room/fact-sheets/detail/tuberculosis (accessed 1 February 2026).

[9] **Ministry of Health** (2025) Tuberculosis Combat in Türkiye 2023 Report. Ministry of Health Publication No: 1274, Ankara, Türkiye. https://hsgm.saglik.gov.tr/depo/birimler/tuberkuloz-db/Dokumanlar/Raporlar/Turkiyede_Verem_Savasi_2023_Raporu.pdf (accessed 5 February 2026).

[10] **Bayraktar B**, et al. (2011) Species distribution of the *Mycobacterium tuberculosis* complex in clinical isolates from 2007 to 2010 in Turkey: A prospective study. *Journal of Clinical Microbiology* **49**(11), 3837–3841. https://doi.org/10.1128/JCM.01172-11.

[11] **World Health Organization** (2019) Global Tuberculosis Report 2019 https://www.who.int/publications/i/item/global-tuberculosis-report-2019 (accessed 1 February 2026).

[12] **Bezos J**, et al. (2023) Bovine tuberculosis in Spain, is it really the final countdown? *Irish Veterinary Journal* **76**(S1), 13. https://doi.org/10.1186/s13620-023-00241-0.

[13] **Allen AR**, **Ford T and Skuce RA** (2021) Does *Mycobacterium tuberculosis* var. *bovis* survival in the environment confound bovine tuberculosis control and eradication? A literature review. *Veterinary Medicine International* **2021**, 8812898. https://doi.org/10.1155/2021/8812898.

[14] **Gong Q-L**, et al. (2021) Prevalence of bovine tuberculosis in dairy cattle in China during 2010–2019: A systematic review and meta-analysis. *PLoS Neglected Tropical Diseases* **15**(6), e0009502. https://doi.org/10.1371/journal.pntd.0009502.

[15] **Madden JM**, et al. (2021) Spatio-temporal models of bovine tuberculosis in the Irish cattle population, 2012–2019. *Spatial and Spatio-temporal Epidemiology* **39**, 100441. https://doi.org/10.1016/j.sste.2021.100441.

[16] **Buddle BM**, et al. (2018) Efficacy and safety of BCG vaccine for control of tuberculosis in domestic livestock and wildlife. *Frontiers in Veterinary Science* **5**, 259. https://doi.org/10.3389/fvets.2018.00259.

[17] **Cosivi O**, et al. (1998) Zoonotic tuberculosis due to *Mycobacterium bovis* in developing countries. *Emerging Infectious Diseases* **4**(1), 59–70. https://doi.org/10.3201/eid0401.980108.

[18] **Çakır Ş and Yakar M** (2023) Mapping and filiation of bovine tuberculosis outbreaks in Türkiye (2017–2021). *Etlik Veteriner Mikrobiyoloji Dergisi* **34**(1), 46–58. https://doi.org/10.35864/evmd.1196112.

[19] **Allepuz A**, et al. (2011) Analysis of the spatial variation of bovine tuberculosis disease risk in Spain (2006–2009). *Preventive Veterinary Medicine* **100**(1), 44–52. https://doi.org/10.1016/j.prevetmed.2011.02.012.

[20] **Carneiro PAM**, et al. (2019) Epidemiological study of *Mycobacterium bovis* infection in buffalo and cattle in Amazonas, Brazil. *Frontiers in Veterinary Science* **6**, 434. https://doi.org/10.3389/fvets.2019.00434.

[21] **Conteddu K**, et al. (2024) A scoping review on bovine tuberculosis highlights the need for novel data streams and analytical approaches to curb zoonotic diseases. *Veterinary Research* **55**(1), 64. https://doi.org/10.1186/s13567-024-01314-w.

[22] **Çiçek H**, et al. (2008) Use of geographical information systems in parasitic diseases and the importance of animal health economics. *Türkiye Parazitoloji Dergisi* **32**, 288–294.

[23] **Arıkan F** (2009) *Web GIS Based Animal Diseases Surveillance System* (Dissertation). Ankara, Türkiye: Middle East Technical University, p. 119.

[24] **Çağlar O** (2019) *Spatial Analysis of a Viral Agent First Time Appeared in Turkey by Geographic Information System: Cattle Nodular Exanthem (Lumpy Skin Disease-LSD)* (Dissertation). Ankara, Türkiye: Hacettepe University, p.120.

[25] **Bayir T** (2023) Seasonal variation and spatial-temporal pattern analysis of anthrax among livestock in Türkiye, 2005–2019. *Pakistan Veterinary Journal* **43**, 523–530. https://doi.org/10.29261/pakvetj/2023.059.

[26] **Ministry of Agriculture and Forestry** (2024) Agricultural Information System. https://hbs.tarbil.gov.tr/Main/InternalUser (accessed 20 February 2024).

[27] **Turkish Statistical Institute** (2024) Livestock Statistics Database. https://biruni.tuik.gov.tr/medas/?kn=101&locale=tr (accessed 13 September 2024).

[28] **ESRI** (2025a) Kernel Density Analysis (Spatial Analyst Toolbox), ArcGIS Pro Documentation. https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/how-kernel-density-works.htm (accessed 15 September 2025).

[29] **ESRI** (2025b) Buffer Analysis (Geoprocessing Analyst Toolbox), ArcGIS Pro Documentation. https://pro.arcgis.com/en/pro-app/latest/tool-reference/analysis/how-buffer-analysis-works.htm (accessed 15 September 2025).

[30] **Çakır Ş**, **Yakar M and Keskin İ** (2021) Temporal and spatial distribution of bovine tuberculosis outbreaks in Turkey (2005–2020). *Etlik Veteriner Mikrobiyoloji Dergisi* **32**(2), 130–139. https://doi.org/10.35864/evmd.997098.

[31] **Akçay E** (2000) *The Comparison of the ELISA and the Gamma-Interferon Assay for Diagnosis of Bovine Tuberculosis* (Dissertation). Ankara, Türkiye: Ankara University, p. 60.

[32] **Sayın Z** (2010) *Comparative Diagnosis of Cattles Tuberculosis by Different Methods* (Dissertation). Konya, Türkiye: Selçuk University, p. 126.

[33] **Fielding HR**, et al. (2021) Characterization of potential superspreader farms for bovine tuberculosis: A review. *Veterinary Medicine and Science* **7**(2), 310–321. https://doi.org/10.1002/vms3.358.

[34] **Çakır Ş**, et al. (2022) Epidemiological investigation of bovine tuberculosis infection dynamics in Turkey. *Turkish Journal of Veterinary and Animal Sciences* **46**, 147–156. https://doi.org/10.3906/vet-2107-23.

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