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Research article

A comprehensive overview of bovine brucellosis and bovine tuberculosis in Albania: epidemiology and control

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Abstract

Brucellosis and bovine tuberculosis (bTB) are the most significant zoonotic diseases in Albania, largely because they persist endemically in livestock populations, pose occupational risks to animal handlers, and continue to cause sporadic human infections. Despite control measures such as risk-based brucellosis vaccination in small ruminants, slaughterhouse surveillance for bTB, and routine disease testing in cattle, these interventions have not yet achieved effective or sustainable eradication. Between 2021 and 2025, district-level program data for both zoonoses were collected and analyzed. A retrospective review of national surveillance datasets identified 189 seropositive brucellosis cases during the study period. The highest proportions were recorded in Vlorë (61 cases; 32.3%), followed by Elbasan (54; 28.6%), Tiranë (41; 21.7%), and Shkodër (33; 17.5%). Over the same period, the bTB surveillance program detected infections on 52 farms, affecting a total of 89 animals. The mean number of affected animals per farm declined progressively across successive years (2021-2025), from 2.64 to 2.00, 1.67, 1.36, and 1.13, respectively. Key control priorities include strengthening vaccination coverage and animal movement controls for brucellosis, enhancing risk-based testing, ensuring the timely removal of reactors, and reinforcing slaughterhouse surveillance for bTB. Routine reporting of the number of animals tested and the geographic locations of testing would enable time-lag analyses, improve prevalence estimates, and support more targeted risk-based interventions. Enhancing public and occupational awareness of transmission pathways, alongside promoting vaccination, is essential for reducing zoonotic risk.

Keywords: Albania, Bovine tuberculosis, Brucellosis, One Health, Surveillance

Introduction

In Albania, several zoonotic infectious diseases are recognized as public health concerns by national and international assessments. Brucellosis and bovine tuberculosis (bTB) are key zoonotic bacterial infections identified in Albania. Both zoonoses are priorities for surveillance and control in veterinary and public health programs, reflecting animal health risks and potential human health impacts [1, 2, 3]. Brucellosis results from infection with small, Gram-negative coccobacilli of the genus *Brucella* (*B.*), which primarily target the reproductive organs of animals. Key reservoirs include cattle (*B. abortus*), small ruminants (*B. melitensis*), pigs (*B. suis*), sheep (*B. ovis*), and dogs (*B. canis*); other potential hosts are wildlife and marine mammals [3, 4]. In Albania, *B. abortus* and *B. melitensis* are of significant importance [1, 3, 5]. The main sources of infection are infected animals that shed large quantities of bacteria, especially in the placenta, milk, vaginal secretions, and birth fluids [3].

Humans primarily contract brucellosis through consumption of unpasteurized milk and dairy products, or through contact with infected animals or aerosols in slaughterhouses and laboratories [3, 4, 6, 7, 8, 9]. Brucellosis remains a significant endemic zoonosis in Albania, affecting livestock and public health. Human cases dropped from 442 in 2012 to 70 in 2018, reflecting reduced transmission and control efforts [2]. These efforts target reservoir populations, strengthen surveillance, and build control capacity. However, ongoing transmission in some animals suggests that control must adapt to local practices, animal movements, and inconsistent implementation of measures [2, 7, 9, 10].

For sheep and goats, Albania adopted a nationwide strategy based on mass vaccination (2011–2012 and again in 2017), followed by systematic vaccination of replacement animals, reflecting the feasibility of vaccination under endemic conditions [2, 5, 10]. The key operational challenge has been achieving high and consistent coverage, particularly during replacement-only phases, which can leave susceptible subgroups and permit continued circulation.

In cattle, the epidemiological situation is more heterogeneous: test-and-slaughter has performed well in larger dairy herds and should continue, whereas expansion to smaller herds should be guided by statistically robust serological surveys; in contrast, high-prevalence beef herds in parts of the south may require mass vaccination, supported by strict movement restrictions to prevent mixing animals from vaccinated and non-vaccinated systems [10].

Human infection patterns further reinforce the livestock link, as outbreak investigations through 2015 attributed most cases to direct animal contact (~70%) and a smaller proportion to dairy product exposure (~18%), underscoring the importance of sustained animal control and enabling systems such as identification/registration, enforceable movement control, surveillance capacity, and laboratory diagnostics [1, 2, 3, 4, 7, 8]. Diagnosis of brucellosis mainly relies on serology with various assays, combined with molecular detection by PCR. However, isolation and identification are the gold standard for diagnosis [3, 4, 6, 7, 8, 10, 11].

From an economic and policy perspective, brucellosis control also entails substantial costs beyond those associated with animal and human disease outcomes. Peck and Bruce emphasize that brucellosis causes reproductive losses and reduced milk production in livestock and recurrent febrile illness in humans, while generating significant economic consequences through productivity losses and expenditures on surveillance, prevention, and control [9]. They also note that Albania is a complex setting in which both *B. abortus* and *B. melitensis* affect humans and key livestock species, underscoring the need for sustainable, context-specific mitigation policies that account for the distribution of costs and benefits between the public sector and livestock owners [9].

Bovine tuberculosis (bTB) is a persistent, multispecies disease primarily caused by *Mycobacterium* (*M.*) *bovis* and, in some regions, *M. caprae*, both of which are members of the *M. tuberculosis* complex [12, 13, 14, 15, 16]. *M. bovis* is an animal pathogen that has a major impact from a One Health perspective because of its consequences for human health and its innate resistance to pyrazinamide [13, 14, 16]. While cattle are the primary maintenance host, the disease can also spread to other species and persist in wildlife reservoirs, including possums, cervids, and badgers. Consequently, eradication becomes more challenging where cattle and wildlife come into close contact [12, 13, 14, 15, 16, 17]. Aerosols from close contact are the primary mode of transmission in cattle, while ingestion and other routes may also be involved. *M. bovis* can survive for months in cold, moist conditions and on pasture [18, 19]. Although reports of bTB in Albania are typically low, especially in large dairy herds under active surveillance, clustering at the spatial and herd levels suggests that isolated foci may persist despite positive national indicators [12, 13, 17]. According to international guidelines for the control of *M. bovis*, this pattern supports risk-based surveillance [12, 13, 14, 17].

Because no single test identifies all infected animals, bTB diagnosis relies on a combination of methods. The single intradermal cervical tuberculin test (SICTT) and other cell-mediated immunity-based tests remain the backbone of global surveillance and eradication programs. The enzyme-linked immunosorbent assay (ELISA) and other serological tests are increasingly used as supplementary methods, particularly to identify animals missed by skin testing or those in later stages of disease. Despite constraints on cost, time, and infrastructure, bacteriological culture and molecular techniques, such as PCR and more sophisticated genotyping approaches, provide confirmatory diagnosis. An integrated diagnostic framework for successful bTB control is created by combining molecular techniques, serological assays, and skin tests [13, 14, 15, 20]. The limited specificity and positive predictive value of field skin testing in low-prevalence settings necessitate repeat and confirmatory testing, underscoring the importance of enhanced diagnostic capability and integrated surveillance (herd testing, abattoir findings, and trace-back) [13, 14, 17].

Although Albania has established national control programs for major zoonotic diseases, the precision and long-term effectiveness of these programs remain constrained by fragmented animal and human health data systems, inconsistent program support, limited population-level testing coverage, reduced surveillance intensity as disease prevalence declines, and the inherent limitations of diagnostic test performance [2, 12, 17, 18, 20, 21]. This study aimed to analyze active surveillance data from Albanian districts during 2021–2025 to explore the spatiotemporal patterns of bovine brucellosis and tuberculosis and to evaluate how these patterns may influence risk-based control strategies and probabilistic forecasting using Monte Carlo simulation.

Materials and methods

Study design and data sources

A retrospective descriptive study was conducted to assess Albania's national control program for major bacterial zoonoses, with a focus on bovine brucellosis and bovine tuberculosis (bTB). The data originated from several sources, including peer-reviewed literature, gray literature (government reports and policy papers), and aggregated epidemiology and surveillance data from national veterinary authorities. Veterinary operations at the national level are supervised, managed, and coordinated by the National Authority for Veterinary Services and Plant Protection (AKVMBP). Veterinary services have been implemented through four regional structures: Shkodër (northwestern Albania, including Shkodër, Malësi e Madhe, Lezhë, Mirditë, Pukë, Tropojë, Has, and Kukës); Tirana (central-western Albania, including Tiranë, Kavajë, Dibër/Peshkopi, Mat, Bulqizë, Krujë and Durrës); Elbasan (central-eastern Albania, including Elbasan, Berat, Skrapar, Dimal, Pogradec, Ersekë/Kolonjë, Devoll and Korçë); and Vlorë (southwestern Albania, including Fier, Lushnjë, Sarandë, Përmet, Tepelenë and Gjirokastër). The collection of surveillance data from both current regional reporting units and former administrative districts enabled spatial and temporal analyses.

Data management and descriptive analysis

The surveillance data on brucellosis and bovine tuberculosis were imported and standardized using R software (version 4.2) to include the following variables: year (or reporting period), analytical group (species, district, or source), and case counts (non-negative integers). Descriptive analyses included calculating annual totals, absolute and percentage year-over-year (YoY) changes, and cumulative totals for the study period. Proportional distributions for each species and district were also calculated. Epidemiological "hotspots" were identified by determining the highest observed counts (also referred to as "top cells") at the district-year or species-year level.

Predictive modeling and sensitivity analysis

To assess forecast uncertainty and look into potential future trends, a Monte Carlo simulation framework based on negative binomial regression has been used [22]. This probabilistic approach uses repeated random sampling to estimate the range and probability of future events, such as overall case counts and district-level distributions. Sensitivity analyses were carried out to assess how robust the results were under different modeling assumptions, including: (i) forecast horizon variation; (ii) inclusion of nonlinear temporal trends using quadratic terms (poly(Year, 2)), (iii) adjustment for population-at-risk through offset variables when available; and (iv) exclusion of incomplete reporting periods, such as year-to-date (YTD) or aggregated intervals.

Statistical software

R software (version 4.2) was used for all statistical analyses and data visualizations. In addition, the analysis used various libraries, including viridis (color scales), MASS (statistical modeling), and broom (model output processing). It conflicted (package conflict resolution) and required specialized tools for Monte Carlo simulation. The analysis also utilized the functionality of the tidyverse suite of packages (dplyr, tidyr, ggplot2, forcats).

Results

Five-year trends in bovine brucellosis and tuberculosis in Albania (2021–2025)

Findings from the analysis of bovine brucellosis and bovine tuberculosis during the 2021–2025 research period are presented in Tables 1–3 and Figures 1–5. These tables and figures provide a comprehensive view of trends in two major zoonotic diseases in Albanian livestock over five years, detailing temporal patterns, spatial distributions, testing outcomes, and outbreak characteristics for both diseases. In line with enhanced surveillance and targeted testing, brucellosis indicators show variable testing levels. For tuberculosis, there was a significant jump in tuberculin testing in 2024, with the number of positive cattle remaining generally low. Overall, the integrated table 1 provides a comprehensive view of multi-year trends, enabling cross-disease comparisons and risk-based resource allocation within Albania's One Health surveillance framework.

Table 1: Integrated surveillance indicators for bovine brucellosis and bovine tuberculosis in Albania (2021–2025).

Disease	Indicator	2021	2022	2023	2024	2025
Bovine brucellosis	Number of farms tested with the MRT	3,217	2,359	2,220	2,357	4,415
	Number of MRT positive farms	112	38	54	102	27
	Number of cattle tested by the RBPT	1,032	382	1,460	1,113	760
	Number of animals serologically confirmed positive (ELISA test)	61	34	30	31	33
Bovine tuberculosis	Cattle tested with the tuberculin skin test	21,810	21,443	31,114	220,350	72,489
	Number of positive herds	11	9	6	11	15
	Number of positive cattle	29	18	10	15	17

MRT = Milk Ring Test, RBPT = Rose Bengal Plate Test, ELISA = enzyme-linked immunosorbent assay

Bovine brucellosis in Albaina (2021–2025)

The annual trends in bovine brucellosis testing and detection in cattle herds between 2021 and 2025 are presented in Figure 1. Animal-level serological testing was conducted using the Rose Bengal Plate Test (RBPT), while farm-level screening was performed using the Milk Ring Test (MRT). The figure illustrates the number of animals and farms tested, the number of positive results, and the corresponding annual seroprevalence rates. Although the overall decline in national positive cases was not statistically significant, the aggregate number of positive results decreased over the study period. A marked reduction is observed from 2021 to 2022, followed by a relatively stable trend through 2025. Despite year-to-year fluctuations, the regression slope suggests a slight overall downward trend.

Regionally, the distribution of cases was concentrated in Vlorë, Elbasan, Tiranë, and Shkodër, with Vlorë accounting for approximately one-third of all reported cases. At the district level, Vlorë recorded the highest overall burden, with very high numbers in 2021 (25 cases), followed by a rebound during 2024–2025 (15 and 12 cases, respectively). Elbasan started with a high number of cases (23 in 2021) and showed a steady decline to only 2 cases in 2025. Tiranë peaked in 2022 (13 cases) and remained relatively elevated in 2025 (11 cases). Shkodër decreased to zero cases in 2024 but increased again to 8 cases in 2025 (Table 2, Figure 2). Considering that the 2025 data cover only the period from January to May, the observed pattern suggests sustained reductions in Elbasan after 2021, persistence and possible re-emergence in Vlorë, and recent increases in Tiranë and Shkodër. These trends warrant targeted epidemiological follow-up and strengthened control measures, particularly in Tiranë and Shkodër.

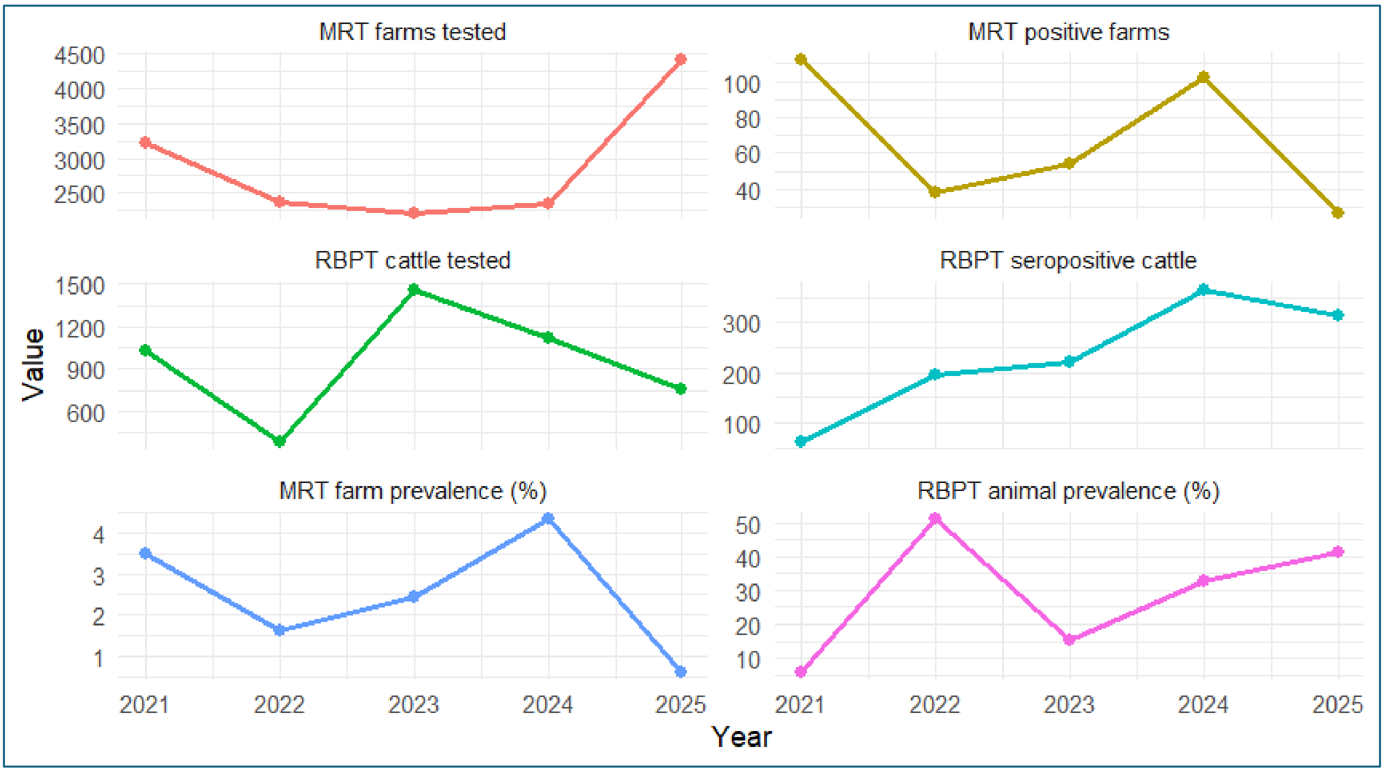

Figure 1: Trends in bovine brucellosis surveillance indicators in cattle and farms (2021–2025), MRT = Milk Ring Test, RBPT = Rose Bengal Plate Test. MRT was used as a herd-level screening test to identify dairy farms potentially infected with brucellosis, while the RBPT was used at the individual animal level among MRT-positive herds. MRT farm prevalence is defined as "farm-level prevalence based on MRT screening," whereas RBPT animal prevalence is defined as "animal-level seroprevalence based on RBPT testing".

Table 2: Distribution of bovine brucellosis cases by district and year in Albania (2021–2025).

Region	2021	2022	2023	2024	2025
Vlorë	25	5	4	15	12
Elbasan	23	12	7	10	2
Tiranë	4	13	7	6	11
Shkodër	9	4	12	0	8
Total	61	34	30	31	33

The trend and Monte Carlo-based forecast of ELISA-confirmed bovine brucellosis cases in cattle for the period 2021–2030 are presented in Figure 3. Observed data indicate a marked decline in reported cases from 61 in 2021 to approximately 30–33 cases during 2023–2025, followed by a period of relative stabilization. Depending on the epidemiological scenario considered, forecasts for 2026–2030 produced using a negative binomial regression model and a Monte Carlo simulation differ significantly. Forecasts under the baseline scenario indicate that reported instances will gradually decrease over time, with relatively short prediction horizons. On the other hand, both the moderate and high-risk scenarios show a steady rise in the number of cases, with the high-risk scenario indicating a clear increasing trend and significantly broader uncertainty ranges. Future disease dynamics are becoming more variable and unclear, as evidenced by these growing prediction intervals. Projections are sensitive to underlying epidemiological assumptions, as demonstrated by the gap between scenarios. The alternative scenarios take into account the impact of rising human brucellosis cases and possible under detection in cattle populations, despite the baseline scenario showing the continuance of existing trends. Specifically, the high-risk scenario indicates that the number of cases may increase significantly by 2030 if increased surveillance and control measures are not implemented.

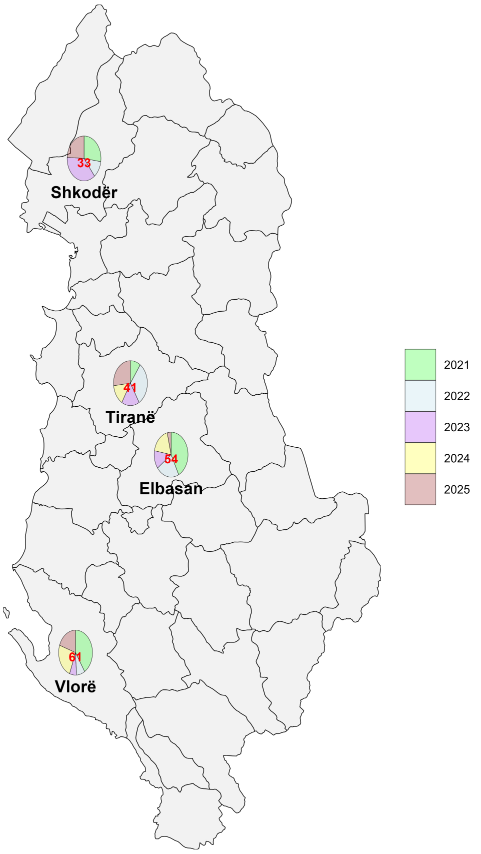

Figure 2: Spatial distribution of bovine brucellosis cases in Albania during 2021–2025 (2025 is YTD January-May). Data are presented across four aggregated regions (Shkodër, Tiranë, Elbasan, Vlorë). Pie charts represent the number of reported cases by year for each region, illustrating temporal variation and regional clustering, with higher case numbers observed in southern and central regions. The explanation for the apparent discrepancy among the data in Table 1 and Figure 2 is that even though the maps and pie charts show the geographic distribution of cases by district and region, the table summarizes the number of cases by year. As a result, there is no direct comparison between these data presentations.

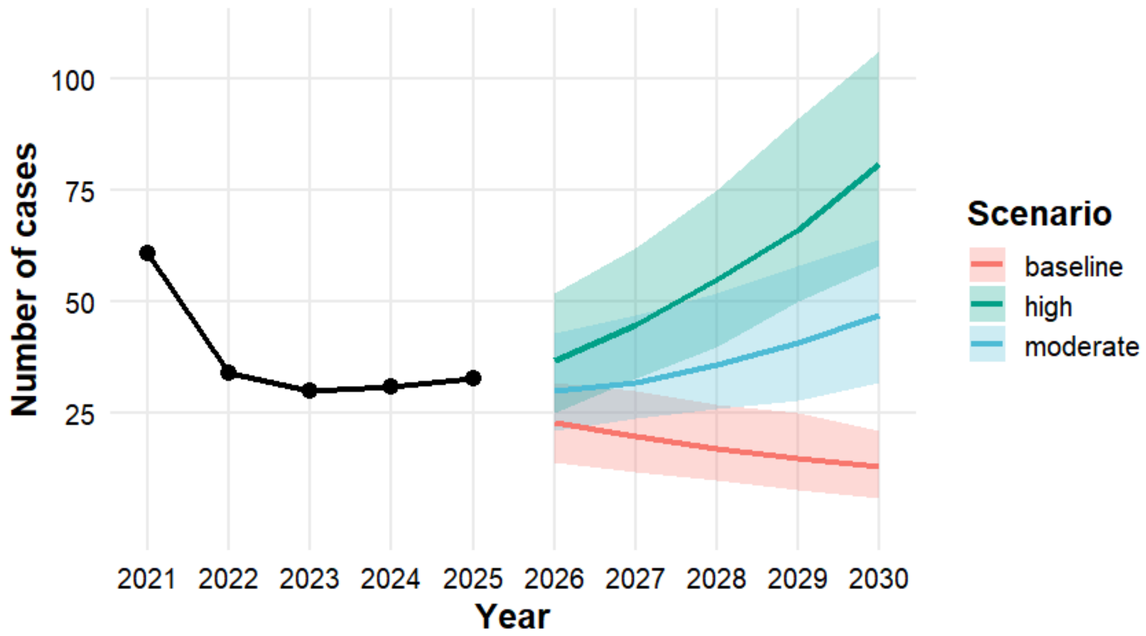

Figure 3: A Monte Carlo simulation based on a negative binomial regression model was used to project future bovine brucellosis cases. Scenario-based forecast of bovine brucellosis cases in cattle in Albania (2021–2030). Observed data (2021–2025) are shown in black, while projections under baseline, moderate, and high-risk scenarios are shown with corresponding 95% prediction intervals. The increasing trend in alternative scenarios suggests that current surveillance may underestimate the true burden of disease.

It is important to interpret these results carefully. The model does not adequately account for variation in testing intensity, reporting procedures, or population structure because it is based on a short time series of ELISA-based surveillance data. Furthermore, despite evidence of high incidence, inconsistent surveillance in beef cattle may significantly overestimate the actual infection burden. Therefore, while the moderate and high-risk scenarios may more closely reflect the underlying transmission dynamics, the decline observed under the baseline scenario is more likely to reflect surveillance limitations rather than a true epidemiological decrease.

Bovine tuberculosis in (bTB) in Albania (2021–2025*)

There has been a clear decline in the number of animals with bovine tuberculosis per positive farm. The trend line shows a steady decrease over time, indicating that fewer animals are infected on affected farms. This suggests improvements in farm-level management and control measures. Although the total number of affected farms is expected to increase in 2024–2025, the reduction in the number of infected animals per farm indicates better within-farm regulation and disease control. Overall, tested cattle have consistently shown low-level bTB detection over the past five years. However, due to incomplete 2025 data, it is not yet possible to confirm a true reduction in infection pressure. Continued full-year surveillance will be necessary to determine whether the lower number of positive detections in 2025 reflects genuine epidemiological progress or is simply the result of incomplete reporting. Following a decrease from 29 positive cases in 2021 to 10 cases in 2023, a total of 32 cases were reported during the 2024–mid-2025 study period, indicating an increase beyond 2023. Comparisons with prior annual data should be assessed with careful consideration because the dataset includes both the first half of 2025 and the entire year of 2024.

It is important to note that 8 out of 36 districts (22.2%) have recorded bTB cases (Table 3). Infected herds by district and period show that Kukës, part of the Shkodër region, has remained a consistent hotspot from 2021 to 2023 (6, 7, and 4 herds, respectively), increasing to 13 positive herds in 2024–2025. Bulqizë, within the Tirana region, shows a clear upward trend, rising from 0–2 cases in earlier years to 8 positive herds in 2024–2025. In contrast, Korçë (Elbasan region) declined to zero cases after 2022. Mat and Dibër, both in the Tirana region, show small increases in the most recent period. Meanwhile, Lushnjë, Fier (Vlorë region), and Tirana remain minimal or sporadic (Figure 4 A). Because the 2024–2025 period spans two years, direct year-over-year comparisons should be avoided. Nevertheless, the map highlights a recent concentration in the northeast, particularly the Kukës–Bulqizë corridor, where intensified testing and contact tracing could have the greatest epidemiological impact.

According to the number of reported cases, Kukës remains a recurrent hotspot, with high numbers recorded in 2021–2023 (11, 11, and 8 cases, respectively), followed by a further increase to 16 cases in 2024–2025. In contrast, Korçë showed an early peak (11 cases in 2021 and 6 in 2022) but has reported no cases since then. Bulqizë has shifted from minimal activity to a notable rise, with cases increasing from 2 in 2023 to 9 in 2024–2025. Meanwhile, Tiranë and Lushnjë have remained low or inactive after 2021. However, new or renewed detections have been reported in Fier (3 cases, 2024), Mat (2 cases), and Dibër (2 cases) during 2025 (Table 3, Figure 4B). Overall, the spatial pattern indicates continued concentration in the northeast, particularly in Kukës, along with an emerging cluster in Bulqizë. However, comparisons with previous single-year periods should be made cautiously, as the final column combines data from 2024 and 2025.

Table 3: Distribution of bovine tuberculosis (bTB) infected cattle (cases) and herds by district and year in Albania (2021–2025).

Region	District	2021 (cases/herds)	2022 (cases/herds)	2023 (cases/herds)	2024 (cases/herds)	2025 (cases/herds)	Total (cases/herds)
Elbasan	Korçë	11/2	6/1	0/0	0/0	0/0	17/3
Shkodër	Kukës	11/6	11/7	8/4	6/6	10/7	46/30
Tiranë	Bulqizë	0/0	1/1	2/2	6/4	3/4	12/11
	Dibër	0/0	0/0	0/0	0/0	2/2	2/2
	Mat	1/1	0/0	0/0	0/0	2/2	3/3
	Tiranë	2/1	0/0	0/0	0/0	0/0	2/1
Vlorë	Lushnjë	4/1	0/0	0/0	0/0	0/0	4/1
	Fier	0/0	0/0	0/0	3/1	0/0	3/1
Total		29/11	18/9	10/6	15/11	17/15	89/52
Ratio of positive animals per herd		2.64	2.00	1.67	1.36	1.13	1.71

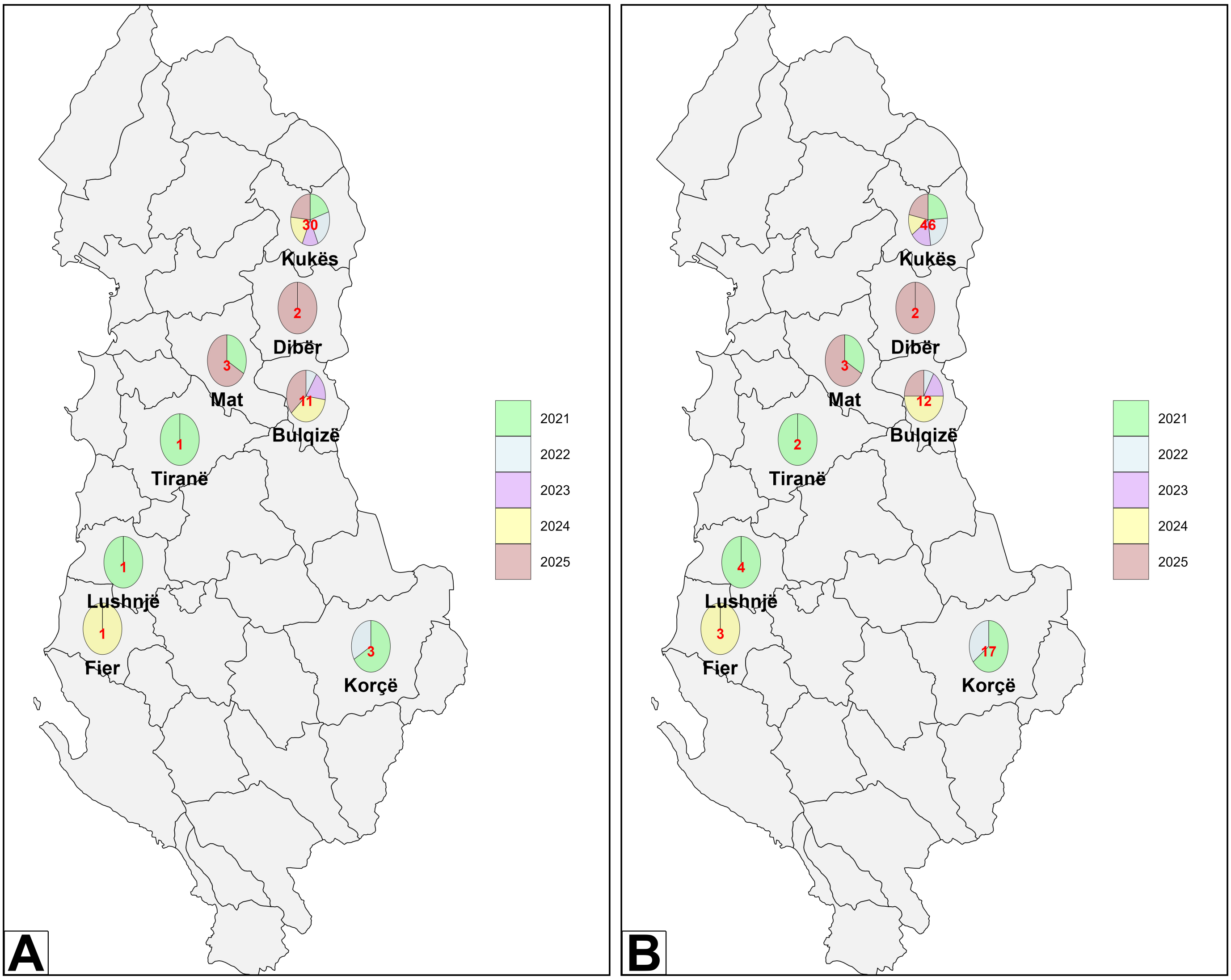

Figure 4: Spatial distribution of bovine tuberculosis (bTB) in Albania during 2021–2025. (A) Distribution of farms/herds affected by bTB; (B) distribution of confirmed bTB cases. Data are aggregated into eight districts (Kukës, Dibër, Mat, Bulqizë, Tiranë, Lushnje, Fier, Korçë). Pie charts represent the number of affected farms or cases by year, highlighting temporal trends and district clustering, with higher concentrations observed in northeastern areas (District of Kukës, Dibër, Mat, Bulqizë, Tiranë, Lushnje, Fier, Korçë).

Although the forecast suggests a slight decline in the median number of infected herds, decreasing from approximately 11 in 2026 to 9 by 2028, interpretation of year-to-year fluctuations should be made cautiously because of the wide 90% prediction intervals (approximately 3–32 herds annually). Given the limited historical dataset and substantial interannual variability, the projections are more consistent with a stable-to-slightly declining epidemiological situation rather than a definitive reduction in herd-level infection. Previous findings identified Kukës (Shkodër region) and Bulqizë (Tirana region) as the principal contributors to the national burden (Table 3), suggesting that continued surveillance and targeted management in these areas would likely have the greatest effect on reducing overall infection levels.

Despite the overall prevalence of bovine tuberculosis remaining low throughout the study period, temporal trends showed an initial decline followed by a modest increase in recent years. In 2021, 29 positive animals were identified among 21,810 tested, corresponding to the highest annual prevalence (0.13%). This may reflect either elevated underlying transmission risk or intensified testing focused on high-risk herds. Subsequently, both the number of positives and prevalence declined in 2022 (0.084%) and 2023 (0.035%), consistent with improved control measures, enhanced herd management, and expansion of surveillance activities. In 2024, only 15 positive animals were detected despite a substantial increase in testing intensity (220,350 animals tested), resulting in the lowest recorded prevalence (0.007%). These findings support the classification of Albania as a low-prevalence setting and indicate effective population-level disease management. In 2025, prevalence increased modestly to 0.023% (17 positives among 72,489 animals tested); however, these data represent only the first half of the year and are therefore not directly comparable with previous full-year estimates.

Overall, the observed epidemiological pattern indicates spatially heterogeneous and clustered infection dynamics, where fluctuations in detected prevalence are more likely associated with changes in surveillance intensity, testing coverage, and risk-based targeting than with widespread transmission. Consequently, short-term increases in detected cases should not necessarily be interpreted as evidence of a failure of control. Rather, the findings emphasize the importance of sustained risk-based surveillance, targeted testing, and focused management of high-risk herds and geographic hotspots that disproportionately contribute to the national burden of bovine tuberculosis.

According to the observed data, individual animal bTB cases declined markedly between 2021 and 2023, followed by a moderate increase during 2024–2025. In contrast, infected herds showed a renewed upward trend after 2023, rising from 6 in 2023 to 15 in 2025. Under the baseline scenario, the model projects a gradual decline in detected animal cases over time, whereas herd-level infection is expected to remain stable or moderately increase. The high-transmission scenario predicts persistence and progressive expansion of bTB, particularly at the herd level, with the number of infected herds potentially exceeding 25 by 2030 (Figure 5). This scenario suggests sustained transmission, spatial clustering, or reemergence under unfavorable epidemiological conditions. Conversely, the low scenario reflects improved control effectiveness and reduced transmission pressure, resulting in a continuous decline in both detected cases and infected herds.

Differences across the scenarios demonstrate the sensitivity of future bTB dynamics to transmission intensity, surveillance coverage, and control measures. The wider prediction intervals in the high scenario indicate greater uncertainty and variability, consistent with heterogeneous disease spread, under detection, and fluctuating transmission pressure.

Because bovine tuberculosis is a chronic and biologically complex disease, estimation of the true burden remains challenging, particularly due to the limited sensitivity of field diagnostic tests and incomplete surveillance coverage. Consequently, strengthening surveillance intensity and expanding population-level testing remain essential for effective disease detection and control.

The projections further suggest that higher forecasted numbers under the high scenario may reflect not only increased incidence but also improved detection resulting from intensified surveillance and testing efforts. These findings emphasize the critical importance of sustained surveillance, herd-level interventions, movement control, and targeted control strategies in high-risk areas to reduce uncertainty and limit long-term persistence of bTB in Albania.

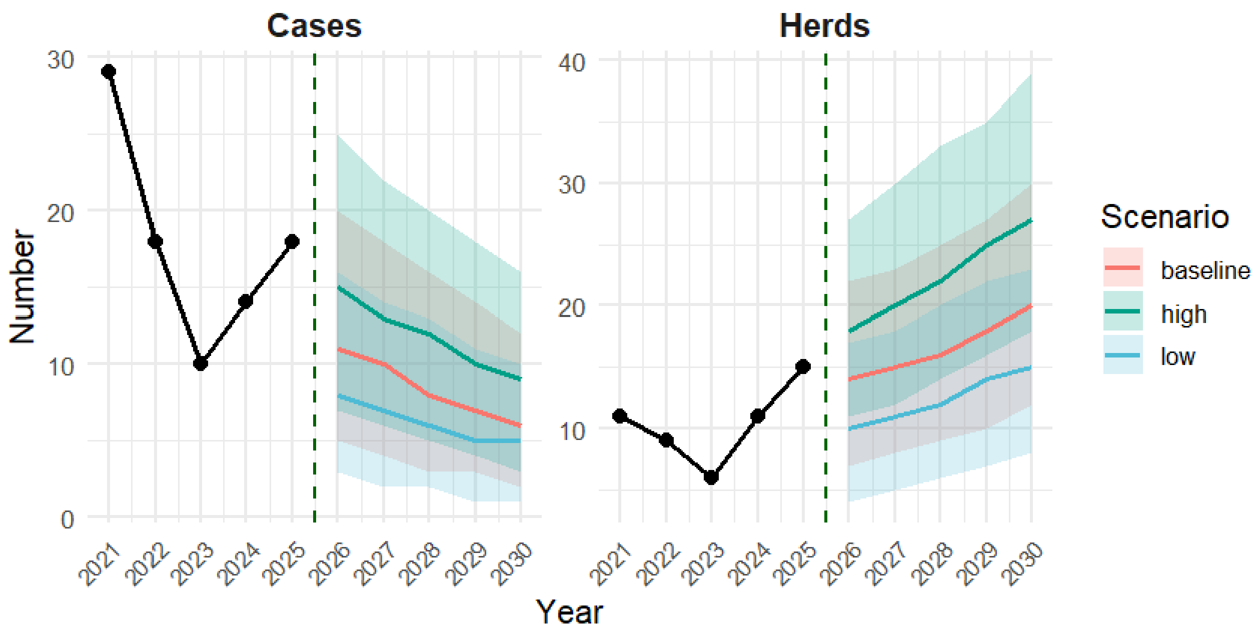

Figure 5: Scenario-based Monte Carlo forecast of bovine tuberculosis cases and infected herds in Albania, 2021–2030. Observed data for 2021–2025 are shown in black, while projections for 2026–2030 are based on negative binomial regression and Monte Carlo simulations under low, baseline, and high scenarios. The dashed vertical line separates the observed and forecast periods. Solid colored lines represent median projected values, and shaded areas indicate the 90% prediction intervals (5th–95th percentiles).

Discussion

This study includes active surveillance of brucellosis and bovine tuberculosis in Albanian districts from 2021 to 2025, with a combined 2024–2025 period. The two target diseases show consistent spatial signals and time-varying dynamics that can inform control programs, despite biological variability. Bovine brucellosis and tuberculosis are considered major zoonoses transmitted from infected animals to humans, causing significant public health and economic burdens [23]. Both are relevant One Health diseases require collaboration among different One Health domains, such as veterinary, medical, and environmental professionals, to mitigate their spread and transmission [24].

The analysis conducted in the current study showed clear spatial differences between different regions. Vlorë had consistently higher burdens; Elbasan declined over time; Tiranë showed elevated levels in 2025 (YTD); and Shkodër reemerged after a year without reported cases. Forecasts suggest a stable-to-slightly declining national trend, though wide prediction intervals reflect uncertainty due to small sample sizes and localized transmission. In higher-incidence areas like Vlorë, strengthening test-and-cull strategies and improving traceback and forward tracing could enhance control. Districts with emerging or reemerging signals, such as Tiranë and Shkodër, may benefit from intensified surveillance of livestock markets and animal movements, especially within dealer networks, transhumance routes, and communal grazing systems.

Following nationwide vaccination of small ruminants, sustained livestock-focused brucellosis management in Albania has been associated with a significant reduction in human cases, underscoring the essential role of animal reservoirs in human risk. This emphasized that human brucellosis is largely associated with the prevalence of the disease in domestic animals [25]. However, vaccination efficacy is limited when coverage is unequal, particularly in replacement-only campaigns, which may leave susceptible regions, as evidenced by ongoing transmission and persistent human infections [1, 2, 3, 7, 8].

Brucellosis vaccination in Albania has been implemented exclusively in small ruminants (sheep and goats) using the *B. melitensis* Rev.1 vaccine strain. A national mass vaccination campaign was conducted in 2012 and 2013 and repeated in 2017. During the intervening period (2014–2016) and continuously since 2018, the control program has focused on vaccinating replacement animals aged 3–6 months to maintain herd immunity and reduce transmission. No brucellosis vaccination program is currently implemented in cattle [1, 2, 5, 10]. Differentiated, risk-based control is supported by cattle's heterogeneous epidemiology: test-and-slaughter is effective in larger, lower-prevalence dairy herds, but broader implementation, particularly in smallholder and extensive beef systems, requires robust serological evidence and stringent movement control. If mixing with unvaccinated herds is avoided, mass vaccination may be the only practical solution in areas with high prevalence, such as some beef herds [2, 7, 8].

High diagnostic specificity is crucial because false-positive results have a greater impact on serological test performance as brucellosis prevalence declines. Validation studies and meta-analyses consistently show that the fluorescence polarization assay (FPA) offers greater specificity and overall accuracy than conventional tests such as the serum agglutination test (SAT) and the complement fixation test (CFT), as well as ELISA-based assays. In low-prevalence settings, where FPA helps prevent misclassification of uninfected animals, minimizes unnecessary culling and financial losses, and enables more dependable decision-making in surveillance and eradication programs, this high specificity is especially crucial [7, 10, 26].

Overall, Albania's experience supports the idea that, because interventions distribute costs and benefits differently among stakeholders, long-term brucellosis control must strike a compromise between epidemiological effectiveness, economic efficiency, and equity. Maintaining high vaccination rates when necessary and bolstering enabling mechanisms (identification and registration, surveillance, laboratory capacity, movement control, and compensation) to ensure long-term control and eventual eradication will be necessary for further success [2, 3, 4, 12].

The control program for bovine tuberculosis in Albania shows a generally low frequency, especially in larger dairy herds under active surveillance. Despite the presence of infected herds in hotspot areas, the ratio of positive animals per infected herd gradually decreased from 2.64 in 2021 to 1.13 in 2025 (overall mean: 1.71), indicating increased containment of infection over time and decreased within-herd transmission (Table 3). However, it also indicates spatial and herd clustering, suggesting that significant bTB local foci may develop regardless of favorable national indicators [12, 13, 14, 15].

A concordant spatial structure is observed in cattle and in affected herds. The ongoing hotspot is Kukës, which increased in 2024 and 2025. Later in the period, Bulqizë becomes a second focus, while Korçë decreases to zero. Compared with 2021–2023, the annual herd totals indicate a recovery in 2024–2025. Nevertheless, Monte Carlo simulations for 2026–2028 indicate stable to mildly declining medians with wide 90% predictive intervals, underscoring the importance of low counts and stochasticity. From a programmatic perspective, the concentration in the northeast suggests local maintenance networks that may be connected to animal movements among small herds, informal trade, or shared winter habitation. Cattle-to-cattle transmission of bTB plays an important role in introducing the infection into healthy herds through the purchase of infected animals or contiguous spread [27].

Mandatory restrictions on animal movement need to be a priority control measure. In particular, before animals are traded or transported between different districts, movement permits supported by confirmed, negative brucellosis and bTB test results should be a prerequisite. Additionally, because combining animals from various herds can facilitate the spread of disease, risk-based testing should be increased at locations with significant livestock concentrations, such as animal markets, assembly facilities, collection points, and trade networks. In the Kukës and Bulqizë regions, which were found to be persistent hotspots over the study period, increased surveillance and follow-up of reactor animals and influenced herds have been particularly crucial. By implementing these measures, the risk of disease transmission through animal movement and trade would be minimized, traceability strengthened, and early detection of diseased animals encouraged. Furthermore, the monitoring and surveillance of both wild and domestic hosts are essential to mitigate the spread of infection and critical for prevention and control strategies of brucellosis and TB in bovines [28, 29]. Future models will improve targeting by including the herd size and cattle population balances whenever possible. A One Health approach should include ongoing monitoring of wildlife interfaces, if accessible locally [16, 24, 28].

The limited specificity and positive predictive value of field bTB skin testing are persistent problems in low-prevalence settings, necessitating repeat visits and confirmatory testing. This highlights the importance of investing in fit-for-purpose diagnostics and integrating multiple surveillance streams (e.g., herd testing, abattoir surveillance, trace-back) [14, 15, 16, 17, 20].

Recent research underscores the need for additional testing approaches and the evaluation of the advantages and disadvantages of current diagnostic techniques. Comparative analyses support parallel use of the IFN-γ assay to increase sensitivity and facilitate early detection, as it identifies a higher proportion of infected animals than SICTT or ELISA alone [15, 17, 18, 20, 21]. Although bTB serological assays are typically less sensitive in early infection, they detect humoral immune responses that skin tests may miss, which explains why test results often do not match, as observed in field studies, including those from Albania [17]. Despite advances in molecular diagnostics and genotyping, particularly whole-genome sequencing, which have greatly improved strain discrimination and our understanding of transmission dynamics, routine application remains limited in many settings [21]. With the potential for quick, sensitive, and field-adaptable diagnostics, emerging nanoparticle-based electrochemical biosensors offer a bright future. Based on our experience and the evidence, we strongly recommend a multi-test approach to bTB diagnosis, including skin tests, serology, and molecular methods, to maximize detection, especially in low-prevalence or end-stage eradication settings.

Two "cross-cutting themes" appeared across data sources and diseases. First, bovine tuberculosis exhibits long-lasting hotspots, whereas brucellosis causes temporary surges in particular locations. This trend suggests a dual approach of ongoing baseline interventions in known areas and rapid surge capacity when new signals emerge. While increases in bTB-positive herds in 2024–2025 may reflect improved case detection, reductions following significant peaks (such as brucellosis in 2023) may indicate increased control efforts rather than a true decline in the epidemic. This underscores the need to regularly link testing volumes to case counts. Second, to support risk-aware interpretation and minimize overemphasis on point estimates, computed median values and 90% prediction intervals have been provided for both diseases. To account for model parameter uncertainty, stochastic process variability, and the small size and heterogeneity of the available surveillance data, comparatively large Monte Carlo intervals were intentionally included. This method facilitates careful analysis of long-term predictions and provides a more accurate representation of possible future epidemiological scenarios.

The findings indicate two main priority actions: 1) targeted brucellosis control, test-and-cull, and movement oversight, in districts exhibiting persistent or recurring signals; 2) risk-based bTB testing and movement control. Future models that incorporate testing volume, vaccination coverage, and animal-movement data will enhance risk prediction and help measure the efficacy of interventions. From a One Health perspective, routine human TB diagnostics frequently fail to differentiate *M. bovis* from *M. tuberculosis*, and intrinsic resistance of *M. bovis* to pyrazinamide has treatment implications, underscoring the significance of coordinated veterinary–public health action and food safety measures [13, 14, 16]. As a result, zoonotic TB may go undetected. In situations where resources and laboratory capacity are limited, emerging techniques such as rapid molecular methods and innovative biosensor platforms may further facilitate rapid identification and targeted treatment [17, 21].

A number of limitations need to be addressed when interpreting these data. A small number of variables, including testing intensity, animal mobility, herd demographics, and, in the case of brucellosis, low vaccination coverage among ruminants, were used in the investigations. Furthermore, relying solely on routine surveillance data may introduce bias because testing effort and confirmation procedures vary across years and regions. Overall, both current trends and model-based estimates are somewhat questionable due to insufficient test sensitivity and specificity, especially in low-prevalence settings.

Conclusion

Brucellosis and bovine tuberculosis in Albania showed clear district-level variance rather than a consistent national trend. Brucellosis was still low in 2023, but it increased sharply before declining. While some districts showed emerging or reestablishing patterns, other places (such as Vlorë) showed permanent or recurrent signals. Overall, the frequency of bTB remained low but spatially confined, with a continuous hotspot in Kukës, secondary cluster cases in Korçë, and additional cases reported in Bulqizë over the study period. Under baseline assumptions, Monte Carlo projections using a negative binomial framework revealed somewhat dropping median trends but comparatively large prediction ranges. The sensitivity of forecasts to underlying epidemiological conditions and monitoring performance was highlighted by various scenarios suggesting probable persistence or a rise, particularly at the herd level. Ongoing transmission within limited foci may be masked by the chronic nature of bTB, low case numbers, and inadequate diagnostic sensitivity. The introduction of risk-based surveillance measures, such as focused testing in hotspot districts, improved testing and slaughter strategies with systematic traceback and forward monitoring, and increased movement control between epidemiologically connected areas, is supported by these findings. Simultaneously, improving detection and reducing uncertainty for both diseases requires expanding testing coverage and using appropriate diagnostic techniques.

Declarations and supplementary information

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