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Assessment and risk mapping of ruminant diseases in the Black Sea basin

Margarida de Castro Arede

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PhD Thesis

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Tesi doctoral presentada per la ***Margarida de Castro Arede*** per accedir al grau de Doctor en Veterinària dins del programa de Doctorat en Medicina i Sanitat Animals de la Facultat de Veterinària de la Universitat Autònoma de Barcelona, sota la direcció del **Alberto Allepuz** Palau i el **Jordi Casal Fàbrega**.

Bellaterra, 2024

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Declaren:

Que la memória titulada **"Assessment and risk mapping of ruminant diseases in the Black Sea basin"** presentada per la Margarida de Castro Arede per a l'obtenció del grau de doctor en Veterinària, s'ha realizat sota la seva direcció en el programa de doctorat de Medicina i Sanitat Animals, del Departament de Sanitat i d'Anatomia Animals, opció Sanitat Animal.

I per a que consti als efectes oportuns, signen la present declaració a Bellaterra, 14 Juny de 2024:

Alberto Allepuz Palau	**Jordi Casal Fabrega**	**Margarida de Castro Arede**
Director i tutor	Director	Doctoranda

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List of abbreviations and acronyms

AHP	Analytical Hierarchy Process
AFSA	Azerbaijan Food Safety Authority
AIC	Akaike Information Criterion
AICc	Akaike Information Criterion (with correction for small sample size)
AUC	Area Under the Curve
BAM	Biotic, abiotic, and movement
CARD	Center for Agribusiness and Rural Development
CCHF	Crimean Congo Haemorrhagic Fever
CCHFV	Crimean Congo Haemorrhagic Fever virus
CIS	Commonwealth of Independent States
CR	Consistency Ratio
DTRA	Defense Threat Reduction Agency
DT	Decision Tree
EE	Expert elicitation
EMPRES-i	Animal Disease Information System
ENM	Ecological Niche Modelling
EPSG	European Petroleum Survey Group
ETRS	European Terrestrial Reference System
EU	European Union
EuFMD	European Commission for the Control of Foot-and-Mouth Disease
EVI	Enhanced Vegetation Index
FAO	Food and Agriculture Organization
FAO-REU	FAO Regional Office for Europe and Central Asia
FMD	Foot-and-Mouth Disease
FMDV	Foot-and-Mouth Disease Virus
FSU	Former Soviet Union
GAM	Generalized Additive Model
GARP	Genetic Algorithm for Rule-set Production

GBIF	Global Biodiversity Information Facility
GIS	Geographic Information System
GIS-MCDA	Geographic Information System - Multi-Criteria Decision Analysis
GLM	Generalized Linear Model
GLW4	Gridded Livestock of the World, Version 4
LCC	Lambert Conformal Conic (projection)
LMICs	Low and Middle-Income Countries
LR	Large ruminants
LSD	Lumpy Skin Disease
LSDV	Lumpy Skin Disease Virus
MACR	Mean of the Absolute Change Rate
MODIS	Moderate Resolution Imaging Spectroradiometer
NAITS	National Animal Identification and Traceability System
NATO	North Atlantic Treaty Organization
NDVI	Normalized Difference Vegetation Index
NSPs	Non-structural Proteins
OAT	One-at-a-Time
OIE	Office International des Epizooties
OR	Omission Rate
PCA	Principal Component Analysis
PCP-FMD	Progressive Control Pathway for Foot-and-Mouth Disease
PC	Principal Component
PPR	Peste des Petits Ruminants
PPR-GREN	PPR Global Research and Expertise Network
PPRV	Peste des Petits Ruminants Virus
pROC	Partial Area Under the Curve of the Receiver Operating Characteristic
PVS	Performance of Veterinary Services
ROC	Receiver Operating Characteristic
ROC AUC	Receiver Operating Characteristic Area Under the Curve
RM	Regularization Multiplier

SP	Structural Proteins
TRACES	Trade Control and Expert System
USSR	Union of Soviet Socialist Republics
VSP	Veterinary Surveillance Points
WAHIS	World Animal Health Information System
WHO	World Health Organization
WOAH	World Organisation for Animal Health
WLC	Weighted Linear Combination

Abstract

Ruminant production in the Black Sea basin is deeply rooted in ancient shepherding traditions, shaped by transient populations, and influenced by evolving geographical and political landscapes. This sector, primarily consisting of smallholders and family farms, is vital for national economies and the livelihoods of rural populations. However, it faces the emergence and spread of transboundary animal diseases and zoonoses that threaten national economies, food security, and public health.

This dissertation aims to provide a review of ruminant production and the priority diseases affecting ruminants in the Black Sea region. This research comprises nine countries: region, namely Armenia, Azerbaijan, Belarus, Bulgaria, Georgia, Moldova, Romania, Türkiye, and Ukraine. It focuses on six diseases: anthrax, brucellosis, Crimean Congo haemorrhagic fever (CCHF), foot-and-mouth disease (FMD), lumpy skin disease (LSD), and peste des petits ruminants (PPR). Additionally, we employ relevant methods to spatially quantify the suitability of PPR and anthrax in the study region.

Study 1 sought to identify the factors influencing the risk of incursion and spread of selected ruminant diseases in the region. Examined factors included historical and geographical contexts, types of production, demographics, rural practices, socio-economic factors, animal trade, and veterinary service capacity. The findings suggested that post-Soviet reforms, the high proportion of smallholdings and family farms, and the practice of pastoralism influenced disease risk. Furthermore, the allocation of resources to veterinary services, the countries' political affiliations (e.g. European Union, Commonwealth of Independent States), the existence of national animal information and traceability systems, and armed conflicts also significantly impacted disease risk.

Despite advancements in veterinary infrastructure and substantial international support, there is still a need to improve animal health, especially in rural and remote areas. Effective disease management strategies require an understanding of the primary challenges and needs of smallholders in each country. The establishment of priorities with farmers, national

stakeholders, and international agencies will help identify opportunities for better disease management and the prevention of future outbreaks. These efforts are tied to incentives for rural development, requiring financial aid, efficient resource allocation, and sustainable strategies.

Study 2 employed spatial multicriteria decision analysis (GIS-MCDA) to generate a risk map for PPR spread in the study region. The results indicated that there were high-risk areas in Türkiye, the Bulgaria-Türkiye border, and southern-central Georgia, while there were lower-risk areas in Belarus, Ukraine, and parts of Bulgaria and Armenia. Despite its limitations, this knowledge-driven method represents a rapid and cost-effective tool for providing preliminary estimates of disease spread risk, which can inform control planning in resource-limited settings.

Study 3 employed the Maxent algorithm to model the suitability of anthrax in the study region, considering environmental factors such as soil composition, climate, and vegetation. The study also assessed the importance of host abundance in the distribution of this disease in the region. The findings indicated that there was a high suitability for anthrax in areas across central and eastern Türkiye, Armenia, southern Georgia, southern Russia, Bulgaria, southern and eastern Romania, Hungary, Moldova, and southern Ukraine. The abundance of ruminants was identified as a significant factor in the occurrence of anthrax in the Black Sea basin. These insights are critical for the development of targeted interventions to mitigate the risk of anthrax in livestock and prevent public health impacts.

Resumen

La producción de rumiantes en los países del Mar Negro se encuentra profundamente arraigada en antiguas tradiciones de pastoreo y ha sido moldeada por poblaciones nómadas, así como por un contexto político y geográfico en constante evolución. Este sector, formado mayoritariamente por pequeños ganaderos y explotaciones familiares, es crucial en las economías nacionales y en los medios de vida de la población rural. Sin embargo, esta producción se enfrenta a la emergencia y propagación de zoonosis y enfermedades animales transfronterizas que representan una amenaza para las economías nacionales, la seguridad alimentaria y la salud pública.

El objetivo de esta tesis es realizar una revisión bibliográfica sobre la producción y las enfermedades prioritarias que afectan a los rumiantes en la región del Mar Negro. La investigación abarca nueve países de la región: Armenia, Azerbaiyán, Bielorrusia, Bulgaria, Georgia, Moldavia, Rumanía, Turquía y Ucrania. Se centra en seis enfermedades: carbunco bacteridiano, brucelosis, fiebre hemorrágica de Crimea-Congo, fiebre aftosa, dermatosis nodular contagiosa y peste de pequeños rumiantes (PPR). Además, empleamos métodos para cuantificar espacialmente la idoneidad de la PPR y el carbunco en la región.

El estudio 1 identificó los factores que afectan el riesgo de entrada y propagación de enfermedades en rumiantes en la región. Se examinaron el contexto histórico-geográfico, tipos de producción, censos, prácticas ganaderas, factores socioeconómicos, comercio de animales y la capacidad de los servicios veterinarios. Los resultados revelaron que las reformas post-soviéticas, la proporción de granjas pequeñas y las prácticas de pastoreo influyeron en el riesgo de las enfermedades estudiadas. También se observó que la asignación de recursos a los servicios veterinarios, las afiliaciones políticas de los países (por ejemplo, la Unión Europea y la Comunidad de Estados Independientes), la existencia de sistemas nacionales de información y trazabilidad animal y los conflictos armados influyeron significativamente en el riesgo.

A pesar de los avances y el apoyo internacional, es imperativo mejorar la salud animal, especialmente en áreas rurales y remotas. Para que las estrategias de gestión de enfermedades sean eficaces, la colaboración entre ganaderos, instituciones nacionales y agencias internacionales es fundamental para identificar oportunidades de mejora y prevenir futuros brotes. Estos esfuerzos están relacionados con los incentivos para el desarrollo rural, que requieren ayuda financiera, una asignación eficiente de recursos y estrategias sostenibles.

En el estudio 2, se aplicó un GIS-MCDA para producir un mapa que identificara zonas de riesgo de propagación de la PPR en la región. Los resultados mostraron zonas de alto riesgo en Turquía, en la frontera entre Bulgaria y Turquía, e en el centro-sur de Georgia. En contraste, se identificaron áreas de menor riesgo en Bielorrusia, Ucrania y en partes de Bulgaria y Armenia. A pesar de sus limitaciones, esta metodología, basada en el conocimiento, es una herramienta rápida y económica para estimar el riesgo de propagación de enfermedades, útil para la planificación sanitaria en entornos con recursos limitados.

El estudio 3 empleó el algoritmo de Maxent para identificar zonas de alto riesgo para la transmisión del ántrax, considerando factores ambientales como la composición del suelo, el clima y la vegetación. También se evaluó la relevancia de la abundancia de hospedadores en la distribución de esta enfermedad. Los hallazgos destacaron una marcada idoneidad para el ántrax en áreas del centro y este de Turquía, Armenia, sur de Georgia, sur de Rusia, Bulgaria, sur y este de Rumanía, Hungría, Moldavia y sur de Ucrania. La abundancia de rumiantes fue un factor determinante en la incidencia de ántrax en la cuenca del Mar Negro. Estos hallazgos son fundamentales para diseñar intervenciones que mitiguen el riesgo de ántrax y prevengan impactos adversos en la salud pública.

Resum

La producció de remugants dels països que envolten el Mar Negre està profundament arrelada en antigues tradicions de pasturatge i ha estat modelada per poblacions nòmades i un context polític i geogràfic en constant evolució. Aquest sector, format majoritàriament per petits ramaders i explotacions familiars, té un paper fonamental en les economies nacionals i els mitjans de vida de la població rural. No obstant això, s'enfronta a la propagació de zoonosis i malalties animals transfrontereres, que representen una amenaça per a les economies nacionals, la seguretat alimentària i la salut pública.

L'objectiu d'aquesta tesi és revisar la producció ramadera i les malalties que afecten els remugants a la regió del Mar Negre, incloent Armènia, Azerbaidjan, Bielorússia, Bulgària, Geòrgia, Moldàvia, Romania, Turquia i Ucraïna. Es centra en sis malalties: àntrax, brucel·losi, febre hemorràgica de Crimea-Congo, febre aftosa, dermatosi nodular contagiosa i pesta dels petits remugants (PPR). A més, s'empren mètodes per quantificar espacialment la idoneïtat de la PPR i l'àntrax a la regió.

El primer estudi es va enfocar en identificar els factors que afecten el risc d'entrada i propagació de malalties en remugants a la regió. Es van examinar elements com el context històric i geogràfic, tipus de producció, demografia, pràctiques ramaderes, factors socioeconòmics, comerç d'animals i la capacitat dels serveis veterinaris. Els resultats van mostrar que factors com les reformes posteriors al període soviètic, la proporció de granges petites i les pràctiques de pasturatge van influir en el risc de malalties. També es va observar que l'assignació de recursos als serveis veterinaris, les afiliacions polítiques dels països, l'existència de sistemes d'informació i traçabilitat animal i els conflictes armats influïen significativament en el risc.

Malgrat els avenços en la infraestructura veterinària i el suport internacional, és crucial millorar la salut animal, especialment en àrees rurals i remotes. El disseny d'estratègies efectives de control de malalties requereix conèixer els desafiaments i necessitats dels petits ramaders a cada país. La col·laboració entre ramaders, institucions nacionals i agències

internacionals és clau per identificar oportunitats de millora i prevenir futurs brots. Aquests esforços estan relacionats amb els incentius per al desenvolupament rural, que requereixen suport financer, una assignació eficient de recursos i estratègies sostenibles.

A l'estudi 2, es va aplicar un GIS-MCDA per produir un mapa de risc que identifiqui les zones més adequades per a la propagació de la PPR als països de la regió. Els resultats van mostrar zones d'alt risc a Turquia, a la frontera entre Bulgària i Turquia, i al centre-sud de Geòrgia, mentre que es van identificar àrees de menor risc a Bielorússia, Ucraïna i parts de Bulgària i Armènia. Tot i les limitacions d'aquesta metodologia, aquest enfocament és una eina ràpida i econòmica per proporcionar estimacions preliminars sobre el risc de propagació de malalties, útil per planificar accions de control en entorns amb recursos limitats.

Finalment, l'estudi 3 va fer servir l'algorisme de Maxent per identificar zones d'alt risc per a la transmissió del carboncle, considerant factors ambientals com la composició del sòl, el clima i la vegetació. També es va avaluar la rellevància de l'abundància d'hostes en la distribució de la malaltia. Els resultats van mostrar una idoneïtat per al carboncle en àrees del centre i est de Turquia, Armènia, sud de Geòrgia, sud de Rússia, Bulgària, sud i est de Romania, Hongria, Moldàvia i sud d'Ucraïna. També es va identificar l'abundància de remugants com un factor determinant en la incidència de carboncle a la conca del Mar Negre. Aquestes troballes són essencials per dissenyar intervencions que mitiguen el risc de carboncle i prevenen el seu impacte en la salut pública.

Introduction

Chapter I

1.1 The study region

The Black Sea region (Figure 1), located between Eastern Europe and Western Asia, exhibits a rich history, complex geopolitics, and great cultural diversity. In this region, countries present socio-economic disparities and structural differences in their agricultural and veterinary sectors. Many countries of the extended region including the disputed territories of Nagorno-Karabakh, Transnistria, and South Ossetia were once part of the former Soviet Union (i.e. Union of Soviet Socialist Republics (USSR)). The dissolution of the USSR in 1991 marked a significant shift in the region's history, leading to the dissolution of the Warsaw Pact—an alliance between the USSR and other eastern European countries—of which Romania and Bulgaria were members. Subsequently, both countries became members of the European Union (EU) in 2007. In contrast, Türkiye has been a member of the North Atlantic Treaty Organization (NATO) since 1952 [1].

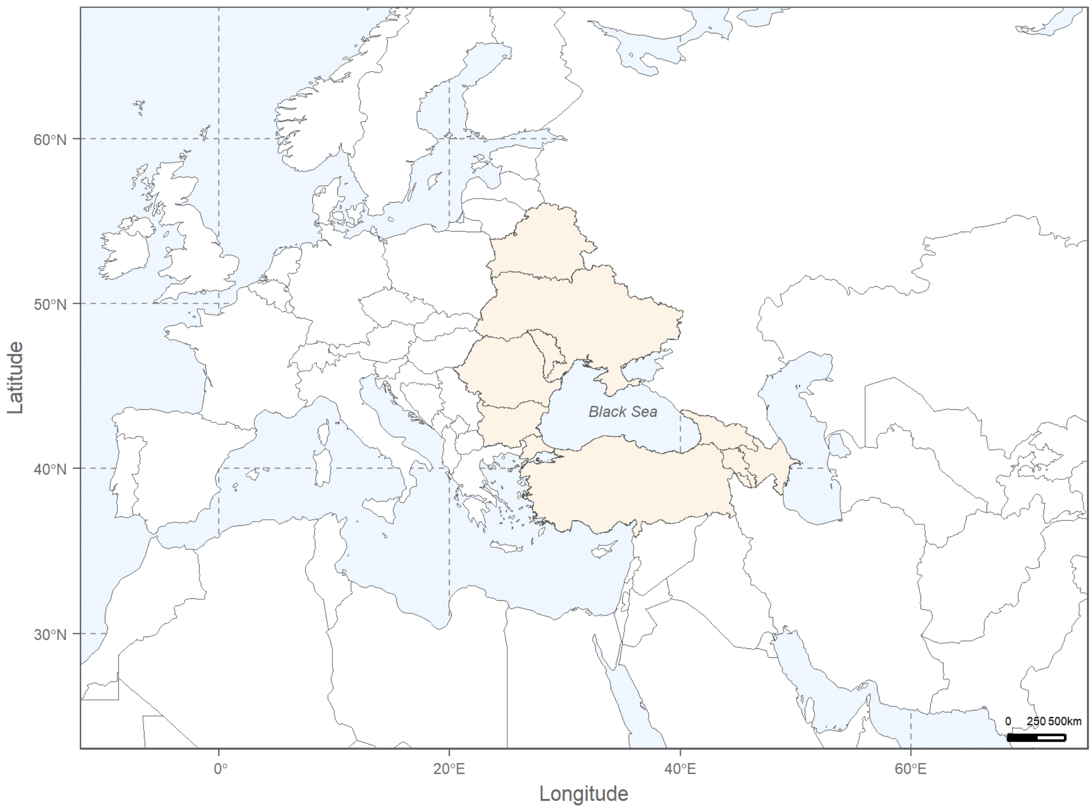


Figure 1: Map of the study region (light orange) and surrounding countries.

This thesis included data from Armenia, Azerbaijan, Belarus, Bulgaria, Georgia, Moldova, Romania, Türkiye, and Ukraine (Figure 2). Data analysed in subsequent chapters spans from 2010 to 2021. The timeline of studied countries' political affiliations is illustrated in Chapter 3, Figure 1. Throughout this study, the term *Black Sea basin* (*BSB*) refers to all included countries. *Caucasus* is used when referring collectively to Armenia, Azerbaijan, and Georgia, while *Thrace* and *Anatolia* differentiate the two main regions of Türkiye.

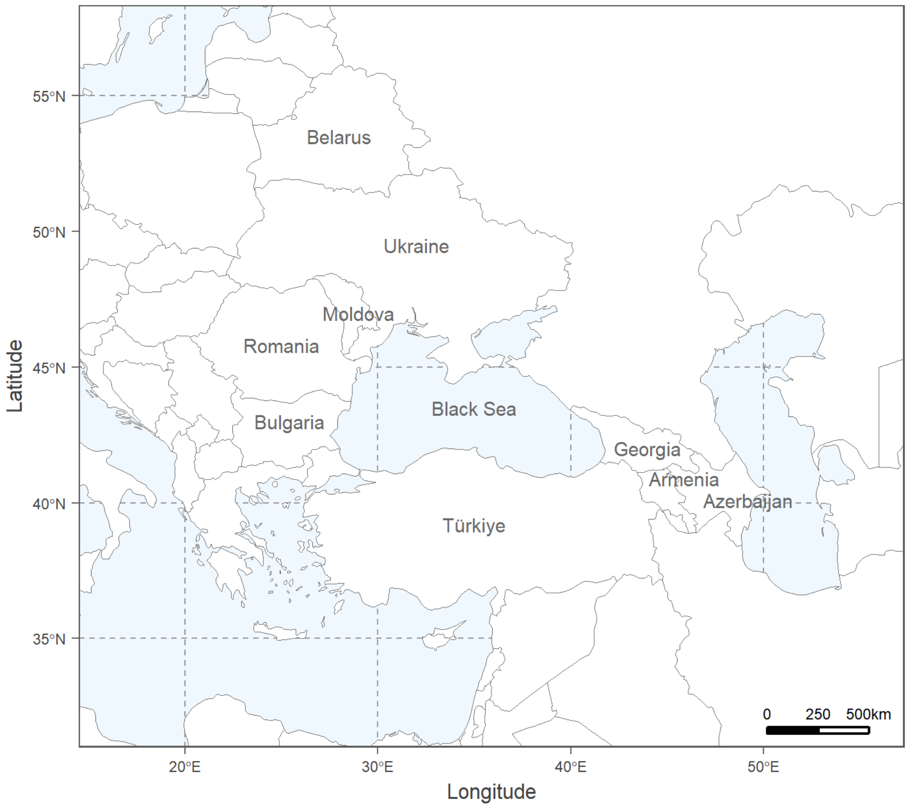


Figure 2: Zoomed in map of the study region.

1.2 Ruminant production in the Black Sea basin

1.2.1 The Black Sea basin and the origins of ruminant production

The domestication of species is closely linked to the development of human culture and gave rise to a new interspecies relationship between humans and animals characterized by mutual adaptation and symbiosis [2]. Sheep are believed as the earliest livestock species to be domesticated by humans, a process estimated to have occurred between 9,000 to 8,000 BC, preceding the domestication of goats, cattle, and swine. This period coincides with the earliest evidence of animal farming in the Middle East region [3], and of pastoralism in Southwest Asia and Anatolia [4,5]. By the third and second century BC, animal husbandry had become a major occupation in the lower Black Sea region, a significant role that continues in this region today [5].

1.2.2 Land reforms following the dissolution of the USSR

Following the dissolution of the USSR, the agricultural and livestock sectors in most countries of the former Soviet Union (FSU) and the former Warsaw pact underwent substantial restructuring. This process was driven by land reforms and farm restructuring that accompanied the transition from a centralised planned economy to a market-oriented economy. Across the entire study region, except for Belarus, it led to a gradual fragmentation of large cooperative farms into small land plots that were allocated to private owners [6–8]. This transition varied in extent and timing, beginning at different points after 1991, depending on the country (Table 1).

The scale and temporal constraints of land reform and farm restructuring in the FSU presented significant challenges. This process aimed to transfer ownership of 120 million hectares within just ten years (1990-2000), a considerably more ambitious effort than comparable initiatives in other countries. For example, Mexico transferred 100 million hectares over 75 years, Brazil 11 million hectares over 30 years, and Japan approximately 2 million hectares in a shorter period [8,11].

The objective of land reform and farm restructuring was to increase farm efficiency and provide land access for impoverished rural communities. However, after 1991, numerous countries in the region experienced a significant decline in agricultural production, yields, and rural employment. The removal of governmental subsidies, rising prices of goods, and high inflation further exacerbated the situation [16]. Other constraints included limited access to credit, low agricultural product prices, inadequate investment in livestock farming, and underdeveloped logistics and infrastructure for product collection, storage, and distribution. Poor feed production and pasture management further contributed to these challenges. This resulted in increased poverty rates, particularly in rural areas [11,17], and a significant decline in rural public services [18].

Table 1: Overview of land reform initiatives in the former Soviet Union (FSU) and former Warsaw Pact countries.

Country		Beginning of land reform	Description
Caucasus	Armenia	1992	Implemented comprehensive land reforms characterized by rapid high fragmentation of land, divided among rural households on equal terms based on family size, to ensure the population could meet their basic foodstuff needs [9]. In Armenia [10] and Azerbaijan [11]. there was a thorough individualization of farms and a complete dismantlement of the state-ordered system and a prohibition of the establishment of new cooperatives/corporate farms. In Georgia [12] There was a combination of privatization and land leasing for commercial purposes.
	Azerbaijan	1996	
	Georgia	1992	
Belarus		*	The only FSU European country where agricultural land remained state-owned and non-transferable, it was still impacted by the market changes following the dissolution of the USSR [13].
Bulgaria		1991	Lands were predominantly granted to the older population, who could use the land, lease, or sell it to newly formed corporate farms or private individuals [14].
Moldova		1998	The individualization was followed by a period of land share entitlement, marked by barriers to de-collectivization [9,11].
Romania		1991	Land reform was marked by quick privatization, in which land parcels were restituted to former owners or their heirs, and the closedown of state-owned farms [14].
Ukraine		2000	Similar to Moldova, land was distributed to the rural population as entitlement paper certificates ('land shares'); which were later converted into physical plots of land for rural households. Marked by strict government restrictions, including bans on land sales [9,15].

The decentralisation resulting from the dissolution of the USSR had a significant impact on veterinary services. Due to limited funding, surveillance programmes collapsed, leading to an increase in infectious diseases including anthrax, brucellosis, foot-and-mouth disease, and tuberculosis [19–21]. Additionally, the decline in artificial insemination practices caused by the abandonment of centralized breeding farms and inexperienced management of core breeding stock deteriorated cattle genetics [18].

Despite signs of partial recovery in the agricultural sector, numerous constraints persist. Land reform, although important, has not fully delivered its intended benefits in most countries by the 2020s [22].

1.2.3 The ruminant production in the Black Sea basin by 2021

Domestic ruminants (cattle, sheep, and goats) are the main subject of the studies included in this thesis. Hereafter, sheep and goats are referred to as small ruminants, when a statement is true for both species and cattle may be referred to as large ruminants.

The ruminant production sector, further explored in this thesis, plays an important role in national economies and/or in the subsistence of rural communities across the Black Sea region today [6,7,23–30].

In **Armenia**, farmlands cover over one-third of the land area, contributing to the preservation of the landscape. Between 2017 and 2021, both cattle and small ruminant populations experienced a slight decline, with recent years showing a tendency to stabilise. As of 2021, livestock farming constituted over 40% of the country's agricultural output, with smallholders being responsible for 95% of its milk and nearly 55% of its meat production. The livestock sector is characterized by an even distribution between cattle and small ruminants, operating within traditional systems, with small herd sizes and a prevalence of mixed animal species. There is a preference for the Brown Caucasian cattle breed, which is raised for both milk and beef production, due to its suitability to local climate conditions [31]. Traditional practices are critical for livelihoods, savings, and risk mitigation strategies of rural communities [32]. Despite a rising trend in national production, Armenia continues to mostly rely on imports of animal products [32,33].

In **Azerbaijan**, livestock production accounted for 50.8% of agricultural output in 2021, with cattle and sheep being the most important livestock sectors. This production is primarily represented by subsistence farming of smallholders and backyard farms, often including mixed production and mixed species. Similar to Armenia, the Caucasian cattle breed is the most prevalent in Azerbaijan due to its resilience to local landscape conditions and available fodder resources. Ruminant production is a traditional rural practice, with households keeping mixed species for subsistence needs such as food, cash, and wealth storage. The livestock farming system is often rudimentary, characterized by minimal inputs and limited use of advanced technology. However, a small percentage of commercially oriented farms (8%) manage larger herd sizes that comprise approximately 45% of the sheep population. From 2015 to 2020, ruminant populations in Azerbaijan remained stable with a slight increasing trend. Despite the observed increasing trend in the ruminant sector productivity, the surge in consumer demand for ruminant products has led to higher imports, resulting in a negative trade balance [24,34,35].

The agricultural system in **Belarus** has largely remained unchanged since the dissolution of the USSR, characterized by state-owned cooperative farms with few private holdings. Cattle breeding is the most important livestock production sector, primarily comprising commercial farms. In contrast, small ruminant production, as of 2021, accounted for only 4.5% of the total ruminant population in Belarus and is primarily extensive. Dairy cattle breeding is characterized by high productivity, with milk and cheese being among the country's top exported products. Moreover, beef cattle breeding is an equally important sector, with a strong emphasis on beef exports, involving the crossbreeding of dairy and beef breeds [36](Morozov, D. pers. comm).

In **Bulgaria**, dairy cattle production has been the leading livestock subsector. However, between 2016 and 2021, there has been a gradual shift from dairy production to beef production. This shift has been influenced by dairy industry reforms and targeted subsidies, which have incentivized non-profitable dairy farmers to transition to beef production. As a result, exports of dairy products, especially cheese, have declined. During this period, the number of cattle and production levels in the country stabilized or increased, reversing the decline observed after 1991. These changes were also linked to shifts in farm size, with a decrease in the number of small farms and an increase in larger ones. Pastoralism is widely practiced during the summer months for both large and small ruminants. Sheep keeping is a longstanding tradition in Bulgaria, particularly well-established in plain and mountainous regions and associated with pastoral practices; it plays a key role in the subsistence of rural populations [29,37,38].

In **Georgia,** as of 2019, animal production comprised 50% of the total agricultural output. The majority of households engaged in animal production for subsistence or semi-subsistence purposes, representing 95% of the ruminant farms. This sector contributed significantly to the country's beef, sheep and goat meat, milk, and wool production. Farms typically keep mixed species and practice dualistic production, where beef is a byproduct of the dairy sector. Sheep farming is deeply rooted in traditional pastoral practices, characterized by seasonal migrations of flocks from lowland winter pastures to mountainous regions in the summer. Sheep graze freely in unfenced villages and mountain pastures, and these practices are self-regulated among local and nomadic users. Between 2015 and 2019, the cattle population exhibited a declining trend of approximately 12%, while the sheep and goat population showed an increase due to the demand for mutton and live animals from neighbouring countries. However, the rise in imports of ruminant products is leading to a trade deficit in these subsectors [6](Chaligava, T. *pers. comm*).

In **Moldova**, as of 2019, cattle and small ruminant production accounted for 36% and 5% of the total animal output, respectively. Smallholders contributed to over 60% of this production [7]. Dairy cattle breeding is the predominant sector in the country, with beef cattle as its byproduct. Sheep breeding remains an important traditional indigenous occupation, providing meat, milk, wool, and skins, and ensuring food security for rural communities (Starciuc, N. *pers. comm*). Between 2015 to 2020, the cattle and sheep population declined by 28% and 2%, respectively, while the goat population increased by 12% nationwide [7].

In 2019, **Romania** ranked as the third largest producer of small ruminants and among the top ten producers of large ruminants within the EU [39]. The country was also a major exporter of live beef cattle, sheep and goats, and the top exporter of sheep and goat meat to third markets from the EU in 2019. Despite the sector being dominated by very small holdings, there is a noticeable trend towards increasing farm sizes. Between 2015 and 2021, the cattle population decreased by about 6%, influenced by low milk prices, limited milk quality, insufficient forage due to drought, a lack of personnel, and low government subsidies. In contrast, the small ruminant sector saw a 10% increase in population, likely driven by incentives supporting this sector and providing stable incomes for farmers. These measures also aim to preserve the country's cultural heritage, particularly pastoralism, promoting high-quality livestock products, food security, and environmental and landscape preservation. In fact, sheep shepherding is a symbol of Romania's folk, with deep-rooted traditions. Across many regions, autochthonous sheep and goat breeds are preserved due to their good adaptation to local fodder resources and terrain conditions [23,39–41].

Türkiye exhibits significant variation in topography, climate, and livestock management practices. Cattle and small ruminant production were the most important livestock sectors, providing not only economic benefits but also food security, income, and risk management for rural communities. These sectors were characterized by small-scale farms that rely on communal grazing, often including mixed species and local breeds, which are better adapted to climatic and landscape conditions but exhibit relatively low productivity. Moreover, these sectors experienced an upward growth trend, with the populations of both large ruminants and small ruminants increasing by 22% and 29%, respectively, between 2015 and 2020 [25,42].

In **Ukraine**, dairy cattle production and beef cattle production, as a byproduct of the former, were the most significant livestock sectors, with smallholders contributing to over two-thirds of the production nationwide. Conversely, the small ruminant sector had little importance and was mostly associated with rural backyard farms. Between 2015 to 2020, the populations of both large and small ruminants decreased by 23% and 14%, respectively. Despite this decline, increased productivity in the cattle production sector has helped to partially maintain overall production levels. While Ukraine has historically been a major global exporter of milk and dairy products, challenges such as market prices, declining animal populations, and limited product quality have led to a trend of reduced exports and increased imports of these products [28,43,44]. The impact of the armed conflict that began in 2022 has had repercussions on the country's ruminant sector, which are briefly mentioned in the discussion section of study 1 (chapter III).

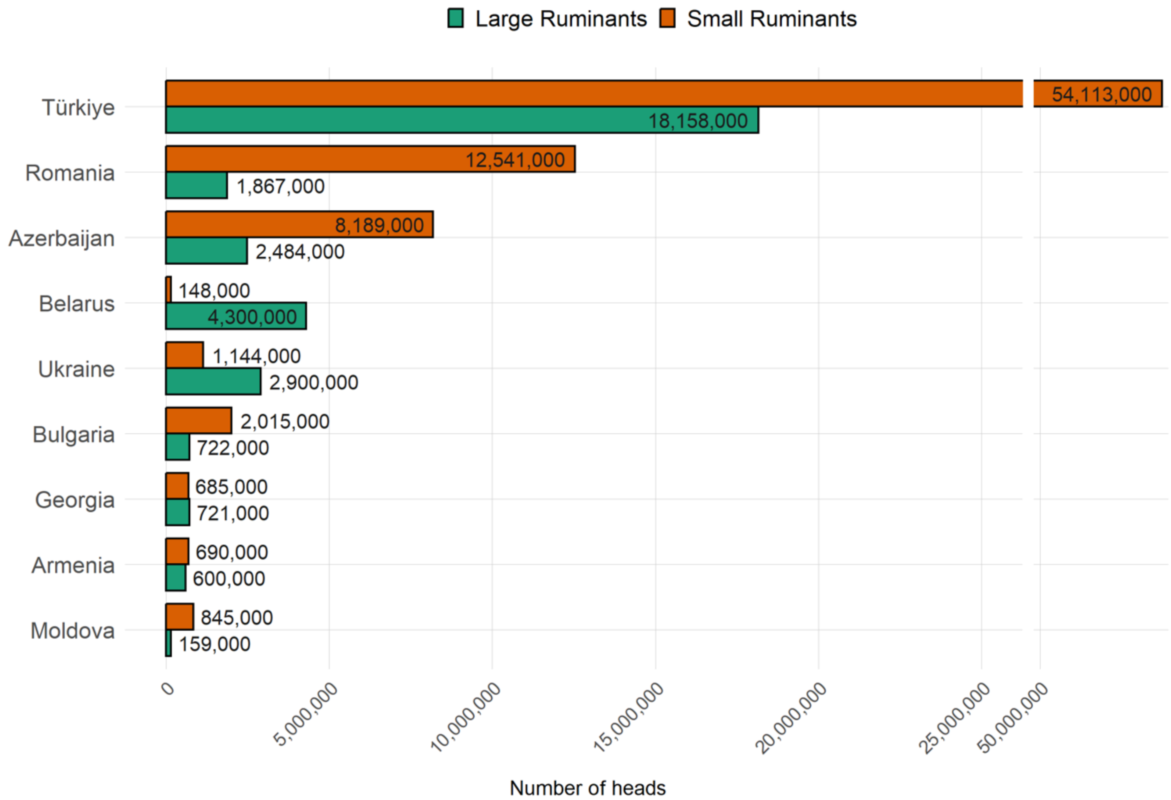


Figure 3: Number of large ruminants and small ruminants in each country of the region in 2021.

1.3 Studied diseases

Study 1 of this thesis focuses on six diseases affecting or threatening ruminants in the Black Sea basin, including anthrax, brucellosis, Crimean Congo haemorrhagic fever, foot and mouth disease, lumpy skin disease, and peste des petits ruminants. Chapters four (study 2) and five (study 3) explore the spatial suitability of peste des petits ruminants and anthrax in the study region, respectively. These diseases are defined as "listed diseases" by the World Organisation for Animal Health (WOAH) Terrestrial Code, making them notifiable to this organization [45].

The following section provides key details about each disease, including the causative agent, epidemiology, infection in domestic ruminants, and humans (in case of zoonoses), as well as strategies for prevention and control.

1.3.1 Anthrax

1.3.1.1 The agent and its epidemiology

Anthrax is a zoonotic bacterial disease caused by *Bacillus anthracis*, a Gram-positive, spore-forming, rod-shaped bacterium that affects all mammals and some bird species [46]. Microbiologically, *B. anthracis* exists in two main forms: the vegetative form and the spore. Vegetative bacilli require specific nutrient and physiological conditions for survival and are not resistant outside the host. Therefore, when shed into the environment through haemorrhagic exudates of a dead infected animal, they encounter nutrient-depleted conditions that are unsuitable for growth. As a result, they either die or undergo sporulation[1], forming inactive spores [47,48]. *B. anthracis* spores are the infective form of anthrax. These spores resist extreme environmental conditions, such as desiccation, extreme temperature, pH, and radiation, for decades until they infect a new host. Upon infecting a host, the spores germinate to produce the vegetative form of the bacilli, which multiply during the infection process, eventually leading to the hosts' death [49,50]. Chapter 5 of this thesis (study 3) explores the influence of environmental conditions, soil, and vegetation characteristics on the suitability of *B. anthracis* in the study region.

Due to its spore-forming nature, *B. anthracis* can be aerosolised for deliberate disease spread and has been considered a potential bioweapon [51]. This concern materialised as a bioterrorist attack in 2001 in the United States, resulting in 10 human deaths [52].

1.3.1.1.1 In ruminants

Anthrax primarily affects herbivores, including domestic and wild ruminants, which are its most susceptible hosts. These species become infected by ingesting or inhaling *B. anthracis* spores in contaminated feed or soil while grazing or eating fodder [46,48,50]. Following an incubation period of three to five days, the disease typically progresses as peracute septicaemia, leading to death within 24 hours of the onset of clinical signs [48]. When an

[1] Sporulation is a dormant state that serves as a protective mechanism for the bacteria until conditions become favorable for growth [47].

infected animal dies, if its carcass is opened by human activities or attacked by scavengers, haemorrhagic exudates are released into the environment, creating the opportunity for the generation of new spores [46].

1.3.1.1.2 In humans

Humans are considered accidental and dead-end hosts of anthrax, becoming infected through direct contact with infected animals, their carcasses or infected animal products. As a result, the disease is primarily associated with occupational exposure, affecting professionals who have direct contact with livestock and their carcasses, such as farmers, butchers, slaughterhouse workers, and veterinarians, as well as employees in the processing industries for bones, hides, and wool. The prognosis of human anthrax is highly correlated with the route of infection that characterises the three respective disease forms in humans—cutaneous, gastrointestinal, or respiratory. Cutaneous anthrax is the most common and it is usually curable, while the other two forms lead to high mortality [50,53].

1.3.1.2 Prevention and control

The effective control of anthrax in livestock has significantly reduced its incidence in humans [19]. This correlation became evident with the development and widespread adoption of the first effective anthrax vaccine for livestock, created by Sterne in 1937 [54,55], followed by the introduction of penicillin as a treatment for the disease [56]. However, the decline in anthrax incidence has also resulted in reduced concern among veterinary and public health authorities towards the disease, as well as a lower recognition of its importance in political and economic contexts. Consequently, there has been a decrease resource allocation for anthrax management, leading to poor disease awareness, underreporting, and failure to implement appropriate measures for disposal and disinfection upon the death of an animal [48].

In regions where anthrax is endemic, effective prevention and control rely on a strict, risk-based vaccination programme for all susceptible animals. Vaccination is recommended once a year before livestock are moved to summer pastures, with an additional dose advised in higher-risk areas [57].

Furthermore, in the event of an outbreak or suspected case, an effective disease management programme is essential to facilitate early disease detection and rapid response, thus reducing environmental contamination and public health risks [58]. An anthrax outbreak response should include trade restrictions and quarantines on animals and animal products, bans on animal slaughtering and carcass opening, and the control of insects, rodents, and scavengers. Additionally, it is crucial to eliminate infection sources through proper disposal and incineration of contaminated carcasses, destruction and disinfection of animal faeces, and disinfection, decontamination and disposal of contaminated surfaces and equipment. Further actions involve antibiotic treatment and vaccination of exposed susceptible animals [50,59]. In the past, burial was the preferred procedure for disposal of anthrax-infected livestock carcasses. However, it has later been deemed unreliable for long-term disease control due to the association of anthrax outbreaks with old burial sites [50].

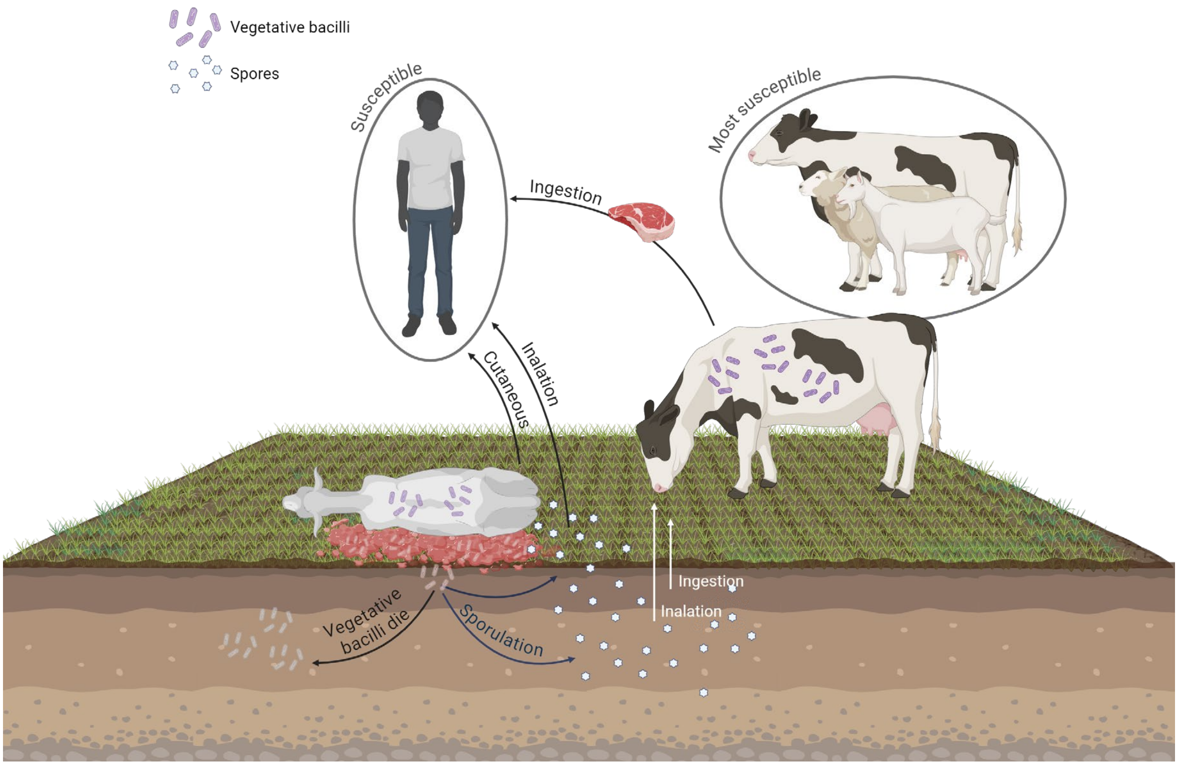


Figure 4: Transmission cycle of anthrax.

1.3.2 Brucellosis

1.3.2.1 The agent and epidemiology

Brucellosis is the generic term given to the highly contagious disease caused by *Brucella* spp., a facultative intracellular, non-spore-forming and non-capsulated, Gram-negative coccobacilli, which presents high tropism for the pregnant reproductive tract [60]. *Brucella abortus* and *Brucella melitensis* are zoonotic and the primary *Brucella* species respectively affecting cattle, and small ruminants [61]. Reproductive brucellosis plays a critical role in the spread and life cycle of the pathogen, through the shedding of large amounts of bacteria in vaginal discharges, foetuses, and foetal/calving membranes [62]. This process contaminates spaces shared with other animals in farms or pastures, allowing further spread of disease. Animal-to-animal transmission occurs through ingestion of infected materials, inhalation, cutaneous and conjunctival contamination, and udder inoculation from infected milking cups [63]. The bacteria can survive and remain infective outside the host for several weeks particularly in cool temperatures, high moisture, and dark environments, in the exudates of aborted foetuses and foetal membranes, faeces, water, wool, hay, and on equipment and clothes [64]. This disease has a high economic impact, especially in developing countries, where it is associated with animal losses due to culling, production losses due to reduced milk yields, abortion, and stillbirths, and public health concerns [65].

1.3.2.1.1 In ruminants

The disease caused by *B. abortus* and *B. melitensis* have similar in its pathology and epidemiology in large and small ruminants [61]. In pregnant females, it commonly leads to placentitis and metritis, which can result in late-term abortions, retained placenta, stillbirths, or the birth of weak offspring. The disease can also affect the mammary glands and supra-mammary lymph nodes, causing the pathogen to be secreted in colostrum and milk. This poses a risk of infection to the offspring through pooled colostrum and nursing, and represents a significant public health threat [61,65]. Additionally, it causes decreased milk yields and reduced fertility in both female and male ruminants. Brucella-infected young and non-pregnant female ruminants are usually asymptomatic [61].

Between herd transmission is facilitated by the commingling of animals from different herds, purchasing animals from unscreened sources, sharing a service male for breeding (sheep and goats) and mixing animals at livestock markets. In certain regions, transhumant practices are another significant risk factor [63].

1.3.2.1.2 In humans

B. melitensis is highly pathogenic, whereas *B. abortus* is moderately pathogenic for humans. Human brucellosis is one of the most widespread zoonoses globally, causing an estimated 500,000 new human cases yearly [66]. Transmission to humans can occur via direct contact with infected livestock, their abortive tissues, discharges, and by-products, or via consumption of unpasteurised milk, cheese made from unpasteurized milk, and undercooked meat [67]. The disease is often occupational, affecting farmers, shepherds, dairy or meat industry workers, veterinarians, and laboratory and health professionals [68]. Its average incubation period usually ranges from two to four weeks but can vary from five days to six months [69], before developing into an acute disease. If not promptly diagnosed and treated at this stage, it can progress into a chronic, sometimes lifelong, debilitating illness [62]. It is characterized by undulant or intermittent fever, joint pain, fatigue, and depression, but in fewer cases, and with disease progression, it may cause encephalitis, meningitis, endocarditis, and orchitis and prostatitis, in men. It rarely causes death. Human brucellosis rarely spreads between humans and treatment is available through an established protocol combining antibiotics [70].

1.3.2.2 Prevention and control

Brucellosis in livestock is a notifiable disease, yet it is often underreported. The nonspecific clinical signs in both animals and humans can complicate its diagnosis and early detection, requiring the use of specific diagnostics [71]. In eradication campaigns, reducing disease prevalence involves vaccinating all susceptible animals with available live attenuated vaccines (*B. abortus* S19 in cattle, *B. melitensis* strain REV-1 for sheep and goats), along with culling persistently infected animals. Once this is achieved, infected herds can be identified through individual serologic tests, skin tests in sheep and serosurveillance of milk or blood samples at sale or slaughter in cattle [71].

To prevent human brucellosis, the implementation of biosafety measures is crucial. This includes educational campaigns for farmers and other at-risk professionals promoting milk pasteurization, personal hygiene practices, and using personal protective equipment [63,70].

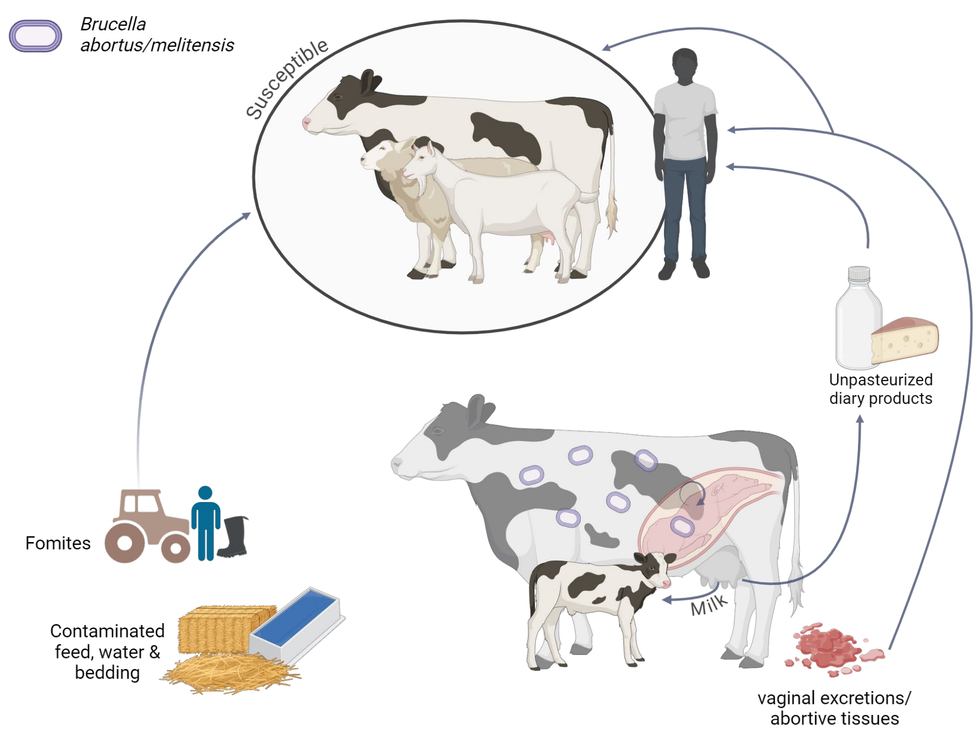


Figure 5: Transmission cycle of *Brucella abortus* and *Brucella melitensis*.

1.3.3 Crimean Congo haemorrhagic fever

1.3.3.1 The agent and epidemiology

Crimean Congo haemorrhagic fever (CCHF) is a tick-borne zoonosis caused by the CCHF virus (CCHFV), an enveloped single-stranded RNA *Orthonairovirus* [72]. CCHFV circulates unnoticed, relying on an enzootic tick-vertebrate-tick cycle. Additionally, viral transmission occurs tick-to-tick vertically, transstadially through the tick's various life stages, and via co-feeding on infected hosts [73,74]. Therefore, ticks are considered both vectors and reservoirs of CCHFV [75]. The virus induces viremia in most vertebrate species except birds, facilitating its spread through the trade of infected livestock. Migrating birds carrying infected ticks also contribute to its dissemination [76]. CCHF's endemicity and seasonal pattern are closely linked to the geographic range of its primary vector and reservoir, the *Hyalomma marginatum* tick [75], with peak activity occurring between spring and early autumn [77]. This disease poses a significant threat to public health worldwide due to its epidemic potential, high mortality rates, nosocomial infections, and challenges in treatment and control [74].

1.3.3.1.1 In ruminants

Domestic ruminants are considered the primary "maintenance hosts" of CCHFV. Following an infected tick bite, ruminants experience a brief viremia with high viral titres within two weeks of infection. Their role, along with other vertebrates, is crucial in the pathogen lifecycle, acting as a bridge between infected and uninfected ticks and thus contributing to CCHFV transmission and viral amplification [75]. Since ruminants are asymptomatic for CCHF, there is no direct economic impact on livestock production associated with the disease [76].

1.3.3.1.2 In humans

Humans contract CCHF through a tick-bite, handling an infected tick, or contact with infected blood, tissues, or contaminated materials. Individuals engaged in outdoor occupations or recreational activities, as well as those in direct contact with livestock, are at higher risk of disease. These include farmers, veterinarians, forest workers, hikers, shepherds, butchers, and slaughterhouse workers. Additionally, human-to-human and nosocomial transmission can occur, primarily affecting health care workers [74,76]. Humans are the only vertebrates that develop severe illness from CCHFV infection. The incubation period depends on the route of exposure to the virus, being one to three days through an infected tick bite, and five to six days through direct contact with infected tissues or blood [76]. Following the incubation period, the disease progresses through three stages:

prehaemorrhagic, haemorrhagic and convalescence. Symptoms in the prehaemorrhagic stage include high fever, dizziness, photophobia, myalgia, and intense headache. The haemorrhagic stage may present with petechiae, large haematomas, epistaxis, and internal and gastrointestinal haemorrhage, potentially leading to death [74]. The CCHF case fatality rate averages 30% but can range from 5% to 80% [78], depending on the viral dose, transmission route, and access to health care facilities, among other factors [79].

1.3.3.2 Prevention and control

Currently, there is no specific CCHFV antiviral drug or approved vaccine available for use in either livestock or humans and treatment in humans is symptomatic. Given that CCHF is asymptomatic in livestock, conducting serological tests on animal serum samples for CCHFV-specific antibodies is critical for detecting endemic areas, which indicate a high risk for human infections. Educational campaigns targeting at-risk occupations and hikers focus on raising awareness about the disease and contact with ticks. Additionally, the application of tick repellents can effectively decrease tick infestation in livestock and, consequently, reduce the seroprevalence of the disease in a region [80].

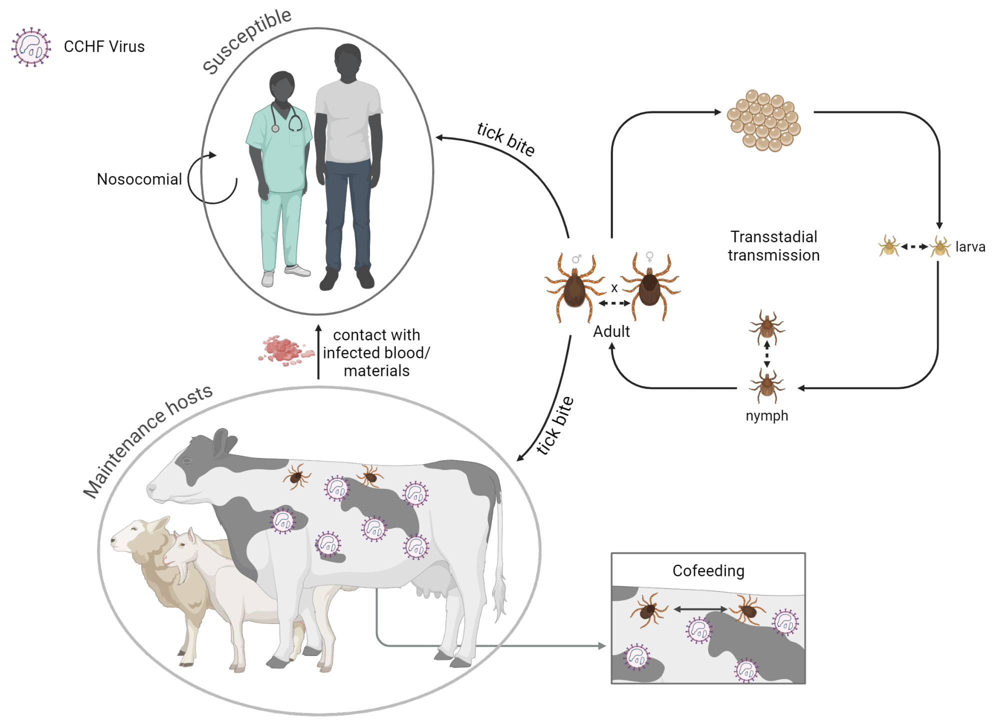


Figure 6: Transmission cycle of Crimean Congo heamorrhagic fever (CCHF).

1.3.4 Foot and mouth disease

1.3.4.1 The agent and epidemiology

Foot and mouth disease (FMD) is a highly contagious non-zoonotic viral disease of domestic and wild cloven-hoofed animals, including ruminants and swine. It is caused by the FMD virus (FMDV), a plus sense single-stranded RNA *Picornavirus* with seven serotypes that have delimited geographic distributions. Susceptible animals become infected with FMDV through direct contact with expired air of acutely infected animals or indirectly via aerosols resuspended from contaminated materials [81–83]. FMDV is excreted in the expired air, from ruptured vesicles, milk, semen, urine, and faeces of acutely infected animals. The virus can persist for months in the environment and animal products [82,84].

According to the WOAH, FMD is "*the most contagious disease of mammals*", posing the greatest burden on the international trade of animals and animal products, and potentially leading to significant economic impact. This impact is attributed to both direct losses, as well as indirect losses incurred from disease control costs, loss of market access, and loss of reputation of the country, region, or farmer [83].

1.3.4.1.1 In ruminants

In ruminants, FMD is characterized by fever, lameness, and blister-like sores (vesicles) on the tongue, snout, feet, teats, and hooves. The severity of clinical signs depends on the virus serotype, host species, genetic factors, the animal's prior viral exposure, and the vaccination history [85]. Compared to cattle, the disease tends to be milder in sheep and goats, which can result in delayed diagnosis and further disease spread. The incubation period ranges from 2 to 14 days, and clinical signs can last up to ten days. In young animals, FMD can also cause multifocal myocarditis, leading to high mortality rates. In contrast, there is generally low mortality in adult animals, but a significant impact on productivity, resulting in weight loss, and low milk yields that can persist even after recovery. After acute disease, cattle may become asymptomatic carriers with a subclinical persistent infection that can last from six months up to 3.5 years [81]. In sheep and goats, the carrier state is less common and usually does not last more than a few months. The role of the carrier state in the spread of FMDV remains a topic of debate in the field [83].

1.3.4.2 Prevention and control

"The Progressive Control Pathway for Foot-and-Mouth Disease (PCP-FMD)" developed by EuFMD and Food and Agriculture Organization (FAO) and endorsed by WOAH aims to assist FMD endemic countries in gradually reducing the impact of FMD and the FMDV viral load. This initiative, part of the Global FMD control strategy, guides the development of FMD control programmes worldwide. Successful progress within the PCP-FMD may lead to WOAH recognition of FMD-free status, with or without vaccination (of a country or region) [86].

In FMD-endemic or sporadic countries, control measures include strict vaccination programmes and sero-surveillance to identify new FMD cases and assess vaccination effectiveness [85]. Given the non-specific clinical signs of FMD, confirming suspected cases requires specific diagnostic tests [83]. In countries with FMD-free without vaccination status, disease prevention relies on strict trade restrictions for animals and their products from non-free countries [85].

FMD vaccines are serotype-specific and consist of inactivated whole virus vaccines, with multivalent options commonly used in endemic regions to protect against multiple serotypes. In these regions, livestock are typically vaccinated biannually until two years of age, and annually thereafter. While FMD vaccines effectively prevent clinical disease and help curb its spread, there remains a risk of vaccinated animals becoming persistently infected [85].

Depending on the scenario, FMD sero-surveillance uses tests to detect antibodies to viral structural proteins (SP), or viral non-structural proteins (NSPs). In FMD-free countries, NSP tests are crucial to confirm the absence of infection and monitor any potential introduction of the virus [87], while in FMD-endemic regions, both NSP and SP tests are used to confirm suspected cases or assess vaccination efficacy, respectively [83].

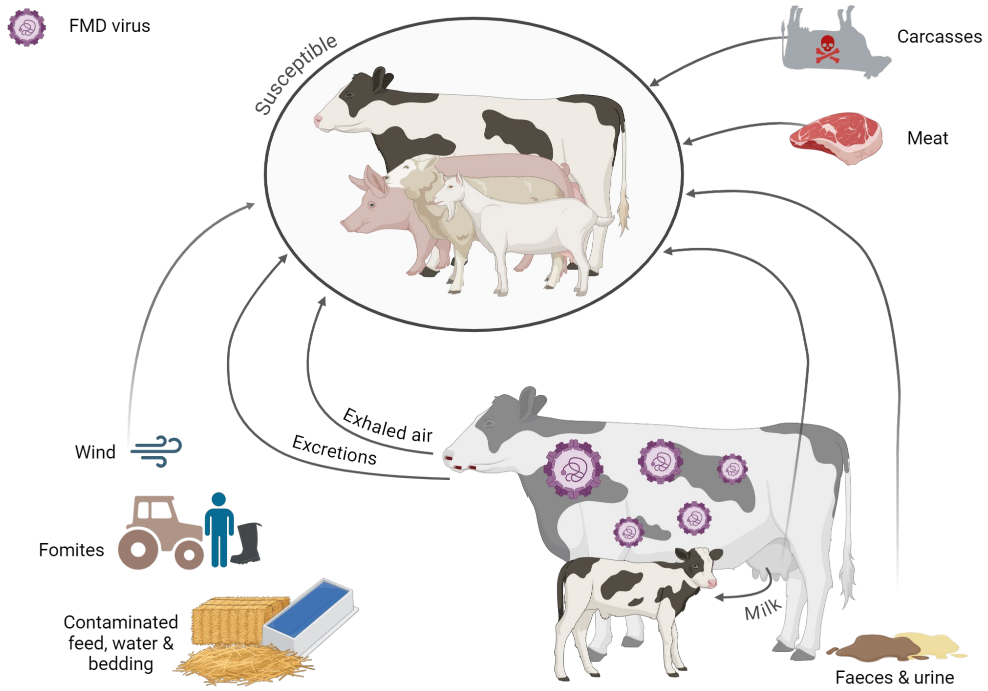


Figure 7: Transmission cycle of foot and mouth disease (FMD).

1.3.5 Lumpy skin disease

1.3.5.1 The agent and epidemiology

Lumpy skin disease (LSD) is a non-zoonotic, viral disease caused by the lumpy skin disease virus (LSDV), a double-stranded DNA *Capripoxvirus* affecting cattle (*Bos indicus* and *B. taurus*) and water buffalo (*Bubalus bubalis*). Infection of sheep and goats with LSDV has not been observed in natural conditions. LSDV spreads mechanically through blood-sucking arthropods carrying the virus in their mouthparts. Specific species of biting flies, mosquitoes, and male ticks are among the arthropods responsible for spreading LSDV. The disease presents a marked seasonal pattern, emerging in the summer months when arthropod abundance is high. Communal grazing and watering points, and the introduction of unscreened animals to a herd, are also associated with the occurrence of LSD [88–90].

LSD-associated morbidity and mortality rates are influenced by the virus strain, the vector carrying LSDV, and individual aspects of the host, such as breed, age, and immunological status [88–90]. Typically, morbidity and mortality rates range from 10% to 20% and 1% to

5%, respectively [91]. An LSD epidemic may cause high economic burden, mainly due to reduced milk yields, compromised hide quality, and restrictions in animal trade [90].

1.3.5.1.1 In cattle

LSDV causes mild to severe disease in cattle. It is characterized by its tropism to dermal tissues, forming multiple nodules in the skin and mucous membranes, and less frequently, in subcutaneous tissues, muscles, and internal organs. Other clinical signs include fever, lameness, weight loss, low milk yields, limbs and brisket oedema, lymphadenitis, pneumonia, abortion in pregnant animals, and infertility in bulls [90].

Skin lesions and scabs from LSD-infected cattle contain a significant viral load, which can remain viable for up to 39 days under moderate temperatures [91]. These lesions serve as a rich nutrient source where flies and other arthropods feed. Through this process, arthropods' mouthparts become contaminated with the virus, facilitating mechanical transmission to other cattle. Less frequently, transmission may occur through contact with contaminated feed and water, as well as contact with viraemic saliva, nasal discharges, semen, and vertically, through intrauterine infection or milk, infecting nursing calves. There is also a risk of within-herd transmission via contaminated needles used during vaccination campaigns [92].

1.3.5.2 Prevention and control

In LSD-free countries, control measures include the culling of affected animals and trade restrictions. In countries where LSD is sporadic or endemic, compulsory yearly vaccination is recommended in spring, prior to the period of high arthropod activity. Educational campaigns targeting veterinarians, farmers, and farm workers can help ensure timely diagnosis and rapid outbreak response [89].

Live attenuated vaccines against LSDV, available in analogous (LSDV-based) and heterologous (sheep pox and goat pox-based) forms, are used to control LSD in endemic regions. Vaccinations should be administered to young calves, or those older than six months if their mothers were previously vaccinated, as maternal immunity can interfere with vaccine-acquired immunity [91,93].

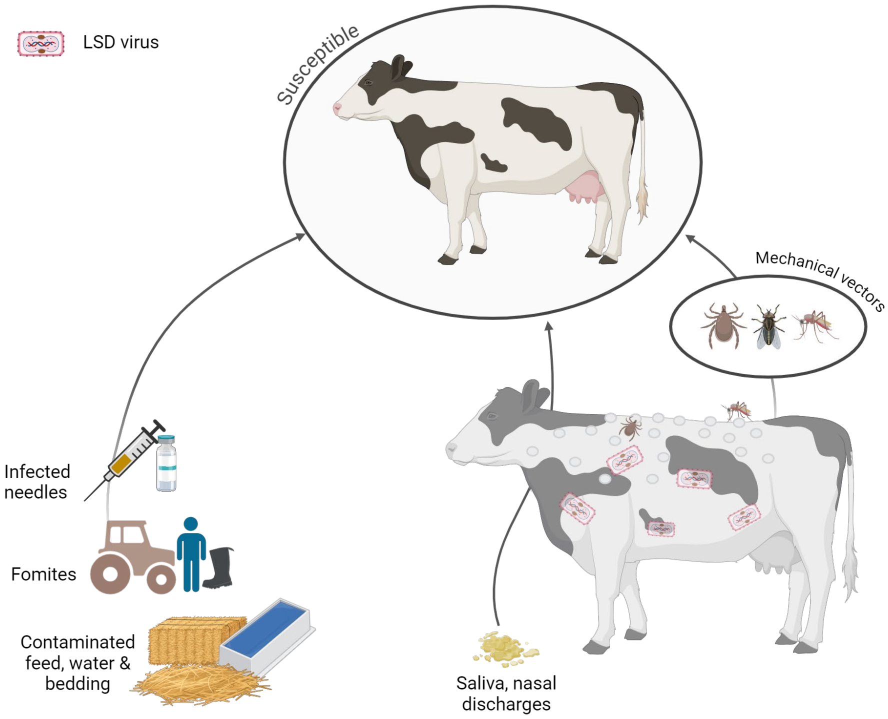


Figure 8: Transmission cycle of lumpy skin disease (LSD).

1.3.6 Peste des petits ruminants

1.3.6.1 The agent and epidemiology

Peste des petits ruminants (PPR) is an acute, non-zoonotic, highly contagious viral disease that affects domestic sheep and goats, as well as wild small ruminants. PPR is caused by the PPR virus (PPRV), also known as the small ruminant *Morbillivirus*. This enveloped negative-sense single-stranded RNA virus of the genus *Morbillivirus* is closely linked to the eradicated rinderpest virus [94]. Cattle, buffaloes, and camels can seroconvert PPRV and may exhibit mild clinical signs, however, their role in the epidemiology of PPR remains unclear, and they are typically considered to be dead-end hosts.

PPR main transmission route is through direct contact between infected and susceptible animals. In the early stage of the disease, infected animals exhale a significant viral load into the air. PPRV is quickly inactivated in the environment, making it less resistant outside the host. Indirect transmission is less common but can occur through contact with materials contaminated within a few hours [94,95]. PPR poses a high concern for rural communities that rely on small ruminants, causing significant economic losses and threatening food security in these populations [95].

1.3.6.1.1 In sheep and goats

PPR primarily affects domestic sheep and goats, with goats considered more susceptible than sheep. Sheep generally presents lower morbidity and mortality rates [96]. These rates are influenced by the virulence of the PPRV strain, the breed of the animals, and the population's immunological state. In naïve populations, the disease can cause up to 100% morbidity and result in high mortality rates [94,95].

The incubation period of PPR is between four and six days. Following this, affected animals enter an acute phase characterised by fever, depression, and anorexia, often followed by nasal and ocular discharges that may become mucopurulent, stomatitis, oral lesions, diarrhoea, and bronchopneumonia. In pregnant animals, the disease can cause abortion. The acute phase lasts for 10 to 12 days, after which animals may die or recover fully. Animals that recover from PPR typically develop lifelong immunity [94,95].

1.3.6.2 Prevention and control

In disease-free areas, the prevention of PPR is based on the implementation of strict restrictions on animal trade from non-free regions. In the event of an outbreak, control measures comprise the culling of infected and exposed animals and the disinfection of contaminated environments and materials [96].

In PPR-endemic countries, disease control relies on mass vaccination of small ruminants. For this purpose, a general framework for the control and eradication of PPR has been implemented by WOAH and FAO—PPR Global Control and Eradication Strategy (PPR-GCES)—, with the objective of global disease eradication by 2030 [97].

Currently available PPR live attenuated vaccines are recommended for all sheep and goats aged four to six months, very three years to maintain effective protection against PPR. However, these vaccines do not allow for differentiation between vaccinated and infected animals. To address this limitation, efforts are underway to develop recombinant PPR DIVA (Differentiating Infected from Vaccinated Animals) vaccines. These new vaccines will facilitate the combination of vaccination and sero-surveillance activities, ultimately improving PPR management by reducing its prevalence in endemic regions and aiding eradication campaigns [96].

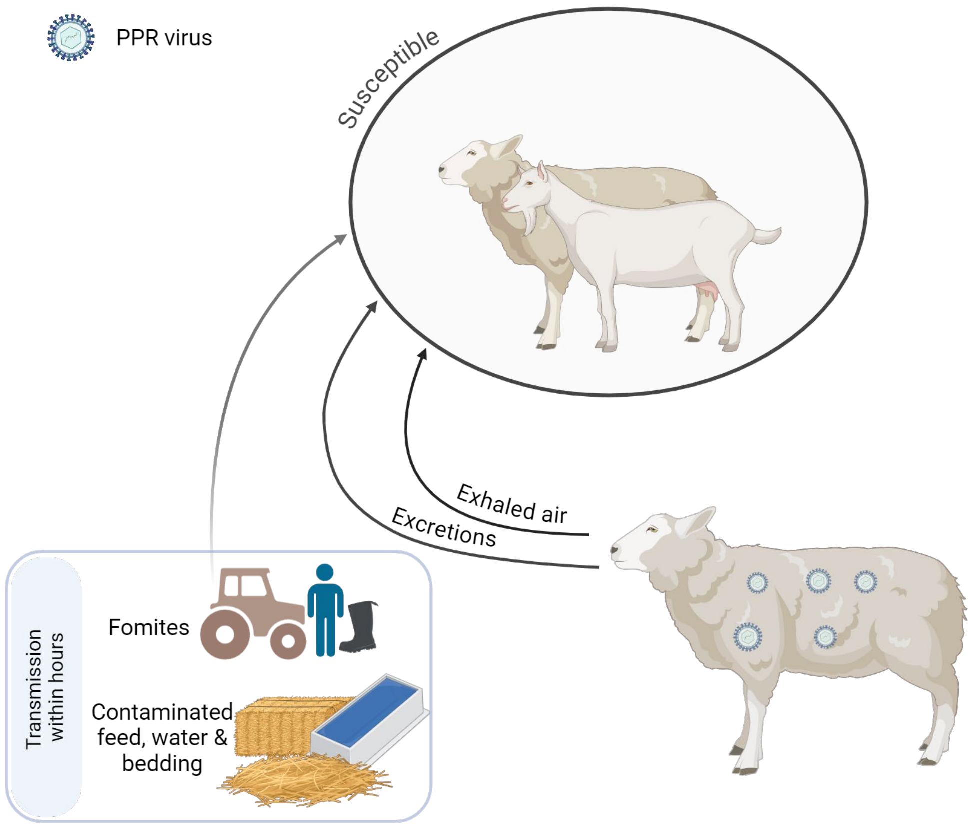


Figure 9: Transmission cycle of Peste des petits ruminants (PPR).

1.4 Animal health surveillance

In the 18th century, the compulsory notification of rinderpest outbreaks in the UK marked a surge in interest in animal health surveillance throughout Europe. This trend continued into the 19th century, as similar measures were implemented for FMD outbreaks in France. The establishment of the WOAH, previously known as the Office International des Epizooties (OIE), in 1924 played a critical role in raising the importance of animal health surveillance at the international level [98].

According to WOAH's Terrestrial Animal Health Code, **animal health surveillance** is defined as:

"a tool to monitor disease trends, to facilitate the control of infection or infestation, to provide data for use in risk analysis, for animal or public health purposes, to substantiate the rationale for sanitary measures and for providing assurances to trading partners" [99].

Surveillance entails systematic, ongoing, or repeated processes to measure, collect, compile, analyze, and interpret animal health and welfare data from specific populations. Unlike monitoring, surveillance is directly connected to taking actions to reduce the risks of identified hazards [100].

The primary aim of animal health surveillance is to maintain high standards of animal health and welfare and protect public health [98]. Specific surveillance purposes should be set early on the design, and before the implementation of animal health surveillance systems, as they define the type of information collected. This allows the system to be tailored to the needs and goals of a specific area, time, and population. Surveillance purposes can be categorized as:

- Early detection: Provide early detection or warning of disease events to enable prompt response and the implementation of control measures. This includes identifying endemic or sporadic disease events and addressing potential new emerging diseases.
- Confirmation of disease absence/freedom: Support trade, disease control, and prevention by confirming the absence of disease.

- Describe specific disease(s): Describe baseline levels, trends, and impacts of specific diseases.
- Animal health assessment: Assess changes in a population's health by studying disease incidence and health indicators, as well as variations in population structure or exposure to new risk factors that may impact health.

The surge in international trade of animals and animal products over recent decades has significantly increased the risk of the emergence of exotic diseases and the re-emergence of diseases previously eradicated in specific countries or regions. To counteract this trend and safeguard veterinary and public health, animal welfare, and prevent economic burdens, promoting collaboration and dialogue among various sectors is critical. This includes cooperation within a country and with neighbouring and trading partner countries. For this purpose, key stakeholders—such as national and international veterinary and public health official entities, the livestock industry, farmer organizations, and other personnel responsible for disease surveillance—must actively engage to understand the objectives and impact of surveillance and ensure effective disease prevention and control [100].

This need for collaboration is particularly evident in regions such as the Black Sea basin, where countries present varying animal disease statuses, socioeconomic levels, and resources for veterinary services. Furthermore, differing regional affiliations, surveillance objectives, and known limitations in data transparency further complicate disease management efforts.

In this line, the following subsection provides a summary of some surveillance-related terms that aim to facilitate comprehension of the subsequent chapters.

1.4.1 Active vs passive surveillance

The most commonly used terms to categorize the surveillance approach for data collection are "active" and "passive", which can also be referred to as "investigator-initiated" or "observer-initiated", respectively [100].

Active surveillance is the systematic or regular collection of animal health-related data, carried out using a detailed protocol with pre-scheduled actions. It can be disease-specific or target a group of diseases and has a specific objective for monitoring disease, leading to action [101,102]. This approach considers the known prevalence of a specific disease, as well as the sensitivity and specificity of available diagnostic tests, to sample a proportion of the population that enables disease detection. In summary, within a population, clinically affected animals (if the disease is present), carrier state and subclinical animals, and non-affected animals are surveyed. For rare or low-prevalence diseases, the costs associated with active surveillance are extremely high, which limits its application, especially in developing countries [98,102].

In contrast, **passive surveillance** relies on the reporting of animal health-related data by farmers or veterinarians to official entities. Case notification may be affected by several factors, including the awareness and knowledge level about a disease (of the farmer and/or veterinarian), fatality rate, production and public health consequences associated with the disease, availability of diagnostic tests for disease identification, and the level of trust with veterinarians and governmental entities [102]. Examples of passive surveillance include the notification of suspected cases or the use of existing surveillance data, such as laboratory reports, findings from slaughterhouse inspections, and abortion notifications. In this surveillance modality, only clinically affected or suspect animals are sampled for a specified disease [98,101].

1.4.2 Early-warning surveillance and syndromic surveillance

Early-warning surveillance involves (usually passive) monitoring of disease events and health indicators within a specified population and aims to increase the probability of early detection of new, exotic, or re-emerging diseases. Scanning surveillance, a term less commonly used nowadays, represents the same idea of early warning but instead is linked with the monitorization of endemic diseases. **Syndromic surveillance** is a more recent surveillance approach associated with both ideas of early warning and scanning surveillance, that uses data collected routinely (both actively and passively) to identify early changes in a population's health. It can be used to target both endemic and emerging diseases [98,100].

1.4.3 Enhanced passive surveillance

Enhanced passive surveillance is a passive collection of animal health-related data with the intervention of the investigator. This entails, for example, actively encouraging farmers to notify certain diseases or following up on reports of suspect cases [100].

1.4.4 Risk-based surveillance

Risk-based surveillance employs information about the likelihood of occurrence and the severity of consequences of a disease to plan, design, and interpret results from surveillance systems [100].

Key aspects of risk-based surveillance include:

- Prioritisation of diseases for surveillance considering their probability and potential magnitude of their consequences in case of occurrence.
- Requirement for surveillance intensity, involving revising the level of surveillance needed to meet a specific objective, based on existing or additional information about the likelihood and consequences for the occurrence of disease.
- Sampling design, targeting individuals that are more likely to be exposed, affected, detected, transmit infection, or cause significant economic burden or trade restrictions. Stratification of the target population can be based on age, production type, or geographical area, aiming to reduce costs and improve surveillance effectiveness.
- Analysis, using existing or additional data on the likelihood of disease and contextual information to update disease status information [100].

1.5 Spatial disease risk assessment

1.5.1 Disease risk analysis

Globalization, increased trade of livestock and animal products, and climate change have facilitated disease emergence, highlighting the critical need for thorough risk assessments in animal disease prevention and control [103]. Disease risk analysis involves estimating the likelihood and potential consequences of a disease within a defined population, taking into account the risk of exposure and the severity of its consequences [104]. This methodology has been extensively applied in the veterinary and public health fields, particularly following the development of structured guidelines for import risk analysis by the WOAH [105,106] and for food safety risk analysis by the *Codex Alimentarius Commission* [107]. Disease risk analysis is essential for guiding strategies to prevent and control the incursion and spread of diseases within populations [108].

Traditional risk assessment often neglects the spatial dimension of risk. However, incorporating this aspect can provide important insights into disease causality, which is particularly important when studying the transmission of infectious diseases and non-communicable diseases with an environmental link. These transmission processes are closely associated with the ideas of spatial and spatiotemporal proximity [109], adhering to Tobler's first law of geography: "Everything is related to everything else, but near [and more recent] things are more related than distant things" [110]. The spatial variation in disease risk is influenced by the interactions between pathogens, vectors, hosts, and their associated environment. This principle is particularly evident in infectious diseases, where transmission is more likely when at-risk individuals are close to each other in both space and time [109].

1.5.2 Disease risk mapping

Mapping disease events has been an important tool for several decades. One of the first and most well-documented examples is John Snow's map from 1854, which illustrated the addresses of victims of a cholera epidemic in London. The map showed the concentration of deaths in an area surrounding a public water pump, which was hypothesized to be the source of the contaminated drinking water [111].

Disease distribution maps can be created at various geographical scales, such as local, provincial, regional, national, and global levels. These maps reflect the spatial patterns of disease within the chosen scale. They are used to illustrate the location and extent of disease in space, to estimate disease risk, and to guide risk-based disease surveillance and control strategies. Analysing spatial disease risk requires solid background knowledge of the disease under study and its associated risk factors, as well as access to georeferenced data [112]. This includes data on disease occurrence, the population at risk, and potentially relevant risk factors. While disease occurrence data is often recorded through monitoring and surveillance activities, demographics and risk factor data can either be collected during those activities or obtained from census or environmental databases [109].

Nowadays, most veterinary and public health disease information systems include georeferenced data and Geographic Information System (GIS) integration, that can be used to easily produce descriptive maps depicting disease distribution at specific time points. Such disease maps, as shown by the simple map illustrated by John Snow, can offer valuable insights by summarizing complex spatial information and providing visual cues regarding baseline disease patterns, potential spatial clustering and hints on disease aetiology [113,114].

The increasing availability of free open-source data has revolutionized our ability to explore disease spatial patterns and quantify associated risks [115]. Technological advancements, including in GIS and global connectivity have streamlined the collection, collation, and accessibility of extensive, high-resolution datasets across various domains. GIS, a computer-based system, enables the integration of data from multiple databases and spatial scales, simplifying the description, analysis and mapping of risk factors, and hosts' susceptibility to potential disease impact [116]. Some examples of opensource datasets with applications for mapping/modelling disease distribution are host demographics (e.g. GLW3 [117]), vector species (e.g. Global Biodiversity Information Facility (GBIF) [118]), animal disease occurrence (e.g. WAHIS from WOAH [119]; EMPRESi from FAO [120]), bioclimatic variables (e.g. WorldClim [121], MERRAClim [122]), proximity to water bodies and main roads, soil (e.g. SoilGrids [123]), vegetation composition (e.g. MODIS/Terra [124]), socio-economic indicators (e.g. World Bank [125], FAOSTAT [126]), and veterinary surveillance and control measures (e.g. WAHIS [119]).

Disease distribution maps are crucial in modern risk-based disease management. By providing timely and accurate information, they support a proactive approach to disease control and enable early warning and response to emerging animal diseases, including zoonoses [112].

1.5.3 Methods for disease risk mapping

Disease distribution can be mapped using visualization methods or modelling techniques. **Visualization approaches**, such as relative risk surface, and standardized mortality or morbidity ratios (SMR), are used for early exploratory purposes or to describe existing data [109,127].

Spatial model-based methods are used to describe spatial disease patterns, infer biological mechanisms leading to disease occurrence, and predict disease patterns in unsampled locations or in the future [128]. Spatial modelling approaches can be grouped into data- and knowledge-driven methods. Data-driven methods can be further sub grouped into methods requiring "presence and absence data" and "presence-only data" [109,128] (Table 2).

Table 2: Methods used in disease risk mapping based on data requirements and methodological approach. *Indicates those methods used in this thesis.

Outcome data	Data-driven		Knowledge-driven
	Statistical	Machine learning	
Presence-absence	• Generalized linear model (GLM) • Generalized additive model (GAM) • Bayesian estimation methods • Multivariate adaptive regression splines (MARS) • Spatial autoregressive models	• Classification and regression trees (CART) • Ensemble trees (bagging, boosting, random forests) • Artificial neural network (ANN)	-
Presence-only	-	• Genetic Algorithm for Rule Set Production (GARP) • **Maximum entropy algorithm (Maxent)***	
No data	-	-	• Habitat Suitability Indices (HSIs) • Cartographic overlay models • **Spatial Multicriteria decision analysis (GIS-MCDA)***

Many of these methods of spatial risk mapping have been previously applied to the studied diseases, including: anthrax [129–142], FMD [143–150], Brucella [151–153], CCHF [154–160], LSD [161–165], and PPR [166–172].

1.5.3.1 Data-driven methods

Data-driven approaches employ statistical methods to establish relationships between risk factors and disease occurrence, producing quantitative risk estimates and determining the relative importance of each risk factor. Resulting risk maps represent the spatial variation of disease risk, that can be categorized into a sequential scale to facilitate the prioritization of disease management activities in high-risk areas [128].

These methods are often considered more valid than knowledge-driven approaches because they use objective and established methodologies. However, their quality is heavily dependent on the quality of their input data [109], which can be compromised by sampling biases, incompleteness, or recording errors, especially in resource-limited countries. Additionally, it is important to recognise the uncertainty associated with predictions, as they are risk estimates resulting from statistical methods extrapolating beyond georeferenced points of disease occurrence. These constraints can be addressed by presenting a map of statistical uncertainty, indicating the mean, lower, and upper confidence intervals, alongside the disease risk map [109,112,128].

Most statistical and machine learning methods require both presence and absence outcome data for effective model calibration. However, it is common for recorded data (e.g. diseases, pathogens, and species) to include only presence data [112].

Presence data of disease, often collected through official surveillance activities, originates from standardized processes and detailed metadata, including specific locations, making it more reliable. These data are traceable and derived from sensitive diagnostic tests (or with established sensitivity) and rigorous surveillance protocols. Additionally, presence data can be obtained from independent studies with transparent and accurate sample collection, documented within reasonable time frames [173]. International disease reporting systems compile comprehensive georeferenced disease data that allow the analysis of large-scale spatial epidemiology and generate disease maps [109,128,174].

In this context, absence data is usually unavailable, and when it is available, it may be biased and fail to accurately represent the full picture of disease absence, often reflecting a lack of observation or disease notification, other than true absence [112].

As a result, various sampling approaches have been developed to generate pseudoabsence data. While useful in some instances, pseudoabsence data have certain disadvantages. Although they aim to mimic absence data, they may include areas where the disease or species could actually occur, thereby risking inaccuracies [175].

Notwithstanding, spatial modelling techniques that require only presence data are also available and have been having growing utility in disease risk mapping. These methods, widely used in ecological niche modelling (ENM) and species distribution modelling (SDM) include Maximum Entropy (Maxent) [176] and Genetic Algorithm for Rule Set Production (GARP) [177].

1.5.3.2 Disease distribution and ecology

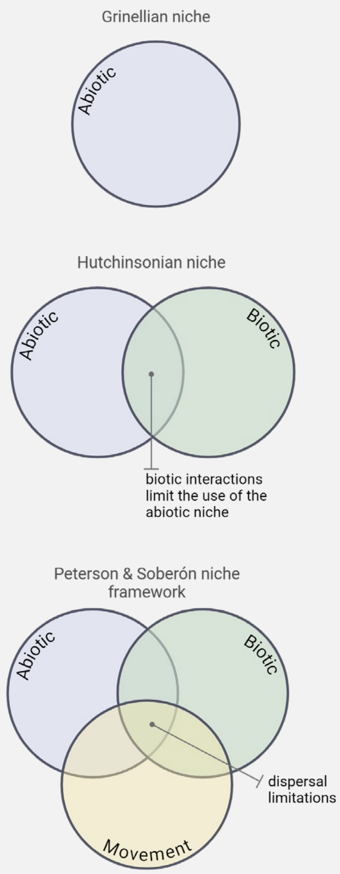
As previously referred, the environment associated with pathogens and hosts plays an important role in disease dynamics, resulting in a non-random distribution of disease across landscapes and regions [178]. This emphasizes the strong link between epidemiology and ecology, disciplines that share common terminology and the goals to respectively study the distribution of species (that can be pathogens), diseases and related factors [179]. Consequently, ecology has been suggested as a mean to understand why a disease occurs in one location, and not another [180]. The link between both disciplines is commonly named disease biogeography. Examining the ecological aspects of a disease, by quantifying the spatial variation of environmental factors associated with disease occurrence, can improve disease mapping, providing further insights into disease causality. In recent decades, ENM has been increasingly used to explore the biogeography of diseases in the fields of veterinary and public health [181]. These models estimate the likelihood of disease presence or habitat suitability relative to other spatial units within a defined study area, rather than the absolute risk outputs obtained through statistical methods [128]. *Suitability* has been defined as the combined effects of resource availability and environmental conditions on the reproductive success, demography, and survival rates of populations [182]. These methods are often used to study diseases or pathogens that have a strong environmental relationship (e.g. those influenced by temperature, moisture, soil conditions)[140], well-established vectors (e.g. mosquitoes, ticks)[183,184], or hosts that significantly affect transmission (e.g. wild birds for HPAI) [185].

The niche concept

In 1917, Grinnell introduced the term niche to define a set of environmental conditions that represent and restrict the geographical range of a species [138]. Later, in 1957, Hutchinson [139] proposed two new related terms: the fundamental niche and the realized niche. The former defined the combination of all abiotic factors that permitted the existence of a species without immigration; whereas the latter described the subsection of the fundamental niche that was actually occupied by the species due to its biological interactions (e.g. competition, facilitation) with other species.

In 2005, the BAM (i.e. Biotic, Abiotic, Movement) framework was described by Peterson and Soberon [140], introducing the component that was missed in previous definitions of a species niche—its ability to disperse and move to reach suitable areas.

Currently, an ecological niche is defined as the "environmental conditions that allow a species to maintain long-term populations without immigration". This niche is constrained by biotic interactions and dispersal limitations [136].



Adapted from Escobar & Craft, 2016 [181]

1.5.3.2.1 Maxent

In study 3 (Chapter V) of this thesis, we used the Maxent method to study the suitability of anthrax in the study region. The maximum entropy method, with origins in statistical mechanics, was introduced by Phillips et al. in 2006 for modelling species distributions [176]. This machine learning method requires only presence data and established predictor variables to estimate a target probability distribution, by identifying the distribution that is closest to uniform (i.e. maximum entropy) within the population. This is achieved by ensuring that the average environmental conditions in the predicted distribution match those in the observed locations [128,176]. Moreover, this algorithm allows the selection of a vast combination of parameters, including feature classes and regularization coefficients to generate multiple model outputs. Feature sets should accurately represent and constrain the selected environmental factors influencing the species distribution. This process ensures that the model's predictions are based on a realistic understanding of the species' habitat requirements and environmental influences [176]. Feature classes, which are further detailed in [176,186], are assigned based on whether the variable is continuous or categorical. The features of type linear (L), quadratic (Q), product (P), threshold (T), and hinge (H) are derived from continuous variables, whereas category indicator (C) features are derived from categorical variables.

Maxent outputs include the contribution percentage of each predictor variable for the studied outcome, and it is calculated through a jackknife approach [128,176]. This method assesses the importance of each variable's information for the species distribution and the unique contribution of each variable to the model's performance, by iteratively running the model and excluding one variable at a time. During this process, it determines the area under the receiver operating characteristic (ROC) curve (AUC) for each iteration, essential for model selection [187].

The Maxent algorithm presents several advantages, as further detailed in Phillips et al., 2006 [176]. Here we highlight, besides its flexibility for fine-tuning input parameters, it uses only presence data and accessible environmental data. It can accommodate various types of predictor variables (both categorical and continuous) and account for their interactions. Maxent can be successfully applied even with a small sample of presence records, and its outputs are easily interpreted [128,176]. In addition, Maxent presents an open-source modelling software to perform the analysis [188], that can be linked with RStudio [189] and relevant packages for further model calibration, evaluation, and selection.

1.5.4 Knowledge-driven methods

Knowledge-driven approaches to estimating the spatial risk of disease rely on prior knowledge of the causal relationships between risk factors and disease occurrence. These methods are not used to identify risk factors but rather to generate qualitative or quantitative estimates of spatial disease risk using weighted rules derived from published literature and/or expert knowledge [109]. Despite being assumed to have inferior predictive capacity compared to data-driven approaches, they have been identified as an alternative in situations when surveillance data is sparse, less reliable, or absent [128]. The most commonly used knowledge-driven method in veterinary and public health fields is Spatial-Multicriteria Decision Analysis (GIS-MCDA). Other methods, such as Habitat Suitability Indices (HSIs) and cartographic overlay models, which follow a similar concept, are applied in species distribution modelling. These methods identify suitable habitats by matching environmental conditions to known habitats [174].

1.5.4.1 Spatial multicriteria decision analysis (GIS-MCDA)

GIS-MCDA, also named Spatial-MCDA or spatially explicit MCDA, was the method applied in study 2 (chapter V). This methodology integrates geographic information systems (GIS) with multicriteria decision analysis (MCDA). GIS is an information system used for managing and presenting georeferenced data in maps across a wide range of fields, to obtain information for decision making. MCDA, originating from operations research, provides a structured approach to decision-making by identifying relevant criteria, assigning relative importance to each factor, and guiding decision-makers to make informed decisions based on priorities that are relevant to the situation.

In summary, integrating MCDA concepts and methods into GIS enables decision-makers to incorporate their preferences into GIS-based analyses, understand trade-offs among policy objectives, and develop systematic and defensible policy recommendations [190]. GIS-MCDA has been applied across various fields, including environmental management, agriculture, transportation, and urban planning. More recently it has seen growing application to veterinary and public health [191,192]. In these fields, when dealing with a disease or related hazard, assessing the spatial variation of risk and its associated management requires informed decision-making. This involves prioritizing actions for disease management and selecting appropriate prevention and control strategies for different areas. In disease risk mapping, GIS-MCDA offers the capability to create maps even in resource-limited settings where data is often sparse or less reliable, or in areas where disease is absent. The resulting risk maps are derived from incorporating existing knowledge about a disease from published literature or elicitation of expert opinion, following a well-established sequence of steps, depicted in Figure 10, to identify areas at higher risk or that are suitable for the occurrence or spread of disease [128,191].

GIS-MCDA, when using expert opinion has a large participatory component. Experts are responsible for identifying associated risk factors, defining relationships between the risk factors and outcome, and estimating the relative importance (or weight) of the risk factors. Additionally, the latter step most commonly applies Saaty's analytical hierarchy process (AHP) [193,194]. The AHP encompasses three principles: decomposition, comparative judgment, and synthesis of priorities. This method involves creating a pairwise comparison matrix, which decomposes the main question into a hierarchy of subproblems (factors). Experts then perform comparative judgments on these factors in pairs. The final step synthesizes these judgments into numerical weights, reflecting the relative importance of each factor [190].

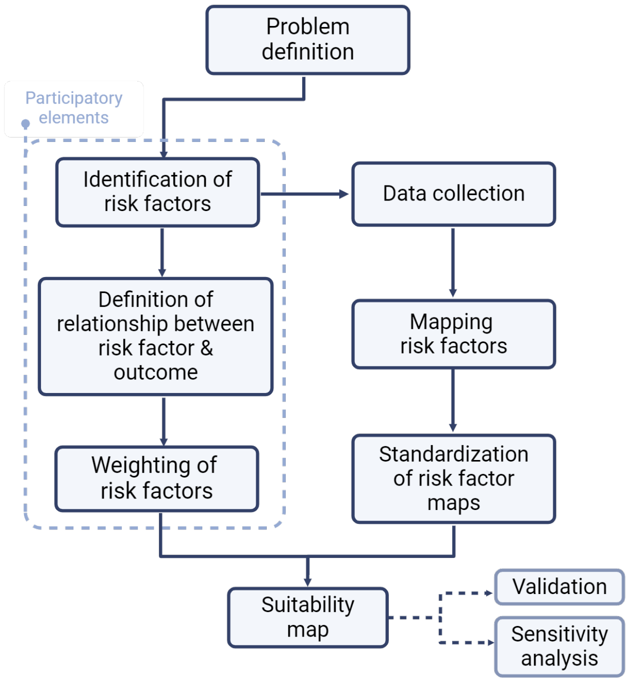


Figure 10: Sequence of steps for the Spatial multicriteria decision analysis.

One of the key advantages of using GIS-MCDA is its capacity to integrate diverse and often conflicting values of different stakeholders acting as experts, ensuring that the selected factors represent this wide range of values. Additionally, GIS-MCDA can account for spatial constraints, and it is highly flexible, allowing for the integration of new, higher-resolution, or more current data as resources improve. This makes GIS-MCDA a robust tool for addressing dynamic and complex decision-making challenges [109,128].

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Objectives

Chapter II

<u>The main objective of this thesis</u> was to assess the epidemiological status of six diseases affecting ruminants—anthrax, brucellosis, Crimean Congo haemorrhagic fever (CCHF), foot-and-mouth Disease (FMD), lumpy skin disease (LSD), and peste des petits ruminants (PPR)—in nine countries of the Black Sea basin: Armenia, Azerbaijan, Belarus, Bulgaria, Georgia, Moldova, Romania, Türkiye, and Ukraine—, and examining possible factors influencing these diseases spread in the region. Additionally, this study aimed to risk map the suitability of PPR and anthrax.

<u>The specific objectives of this thesis</u> were:

1. To characterise the epidemiology of six diseases affecting ruminants in the Black Sea basin, the following objectives were set:
    a. To collect existing information on ruminant production and target diseases, and associated disease management practices in each country of the region;
    b. To conduct an analysis of collected data, map ruminant production systems, identify knowledge gaps, and relate with available literature to hypothesize which factors influence the spread of these diseases in the region, and develop regional, disease-specific mitigation recommendations (presented in Chapter 3);
2. To risk map the suitability of two study diseases:
    a. To identify suitable methods to perform a spatial risk analysis of two diseases affecting ruminants in the study region and create risk maps;
        i. Create a risk map of the spread of PPR in the study region, using spatial multi-criteria decision analysis (presented in Chapter 4)
        ii. Create a suitability map of anthrax in the study region using ecological niche modelling approach (presented in Chapter 5).

Study 1

Chapter III

Examination of critical factors influencing ruminant disease dynamics in the Black Sea Basin

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Research Topic: Bridging Science and Policy for Animal Health Surveillance (ICAHS4 2022)

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3.1 Abstract

Introduction: Ruminant production in the Black Sea basin (BSB) is critical for national economies and the subsistence of rural populations. Yet, zoonoses and transboundary animal diseases (TADs) are limiting and threatening the sector. To gain a more comprehensive understanding, this study characterizes key aspects of the ruminant sector in nine countries of the BSB, including Armenia, Azerbaijan, Belarus, Bulgaria, Georgia, Moldova, Romania, Türkiye, and Ukraine.

Methods: We selected six priority ruminant diseases (anthrax, brucellosis, Crimean Congo haemorrhagic fever (CCHF), foot-and-mouth disease (FMD), lumpy skin disease (LSD), and peste des petits ruminants (PPR)) that are present or threaten to emerge in the region. Standardized questionnaires were completed by a network of focal points and supplemented with external sources. We examined country and ruminant-specific data such as demographics, economic importance, and value chains in each country. For disease-specific data, we analysed the sanitary status, management strategies, and temporal trends of the selected diseases.

Results and discussion: The shift from a centrally planned to a market economy, following the collapse of the Soviet Union, restructured the ruminant sector. This sector played a critical role in rural livelihoods within the BSB. Yet, it faced significant challenges such as the low sustainability of pastoralism, technological limitations, and unregistered farms. Additionally, ruminant health was hindered by informal animal trade as a result of economic factors, insufficient support for the development of formal trade, and socio-cultural drivers. In the Caucasus and Türkiye, where diseases were present, improvements to ruminant health were driven by access to trading opportunities. Conversely, European countries, mostly disease-free, prioritized preventing disease incursion to avoid a high economic burden. While international initiatives for disease management are underway in the BSB, there is still a need for more effective local resource allocation and international partnerships to strengthen veterinary health capacity, protect animal health, and improve ruminant production.

3.2 Introduction

Livestock production is critical for the subsistence of rural populations as a source of food, income, transportation, hides, and fertilizers, contributing to 40% of the agricultural economy worldwide (1). However, in recent decades, there has been a surge and spread of endemic and exotic diseases affecting livestock (2,3), which significantly impact the sector and threaten public health and welfare (4). This surge has been intensified by several factors, including the high increase in international trade of animals and animal products3, rise in intensive farming driven by higher market demands for animal protein and increasing middle-class purchasing power (5–7), changes in land use (8), shifts in migration and tourism patterns, and the effects of climate change (9).

TADs such as foot-and-mouth disease (FMD), lumpy skin disease (LSD), and peste des petits ruminants (PPR), along with zoonoses, particularly anthrax, brucellosis (Brucella abortus and Brucella melitensis), and Crimean Congo haemorrhagic fever (CCHF) (Table 1) are diseases that are either threatening ruminants or emerging in the Black Sea Basin (BSB). Ruminant production is the most important livestock subsector in most countries in the region, ensuring food security for rural populations and contributing significantly to national economies (10–19).

Nevertheless, key aspects linked with the dynamics of these diseases in the region remain poorly understood. Knowledge gaps include disease geographic coverage and prevalence, morbidity and mortality rates, economic impact, and risk factors influencing their spread and persistence. These gaps arise from weaknesses in a country's veterinary management programmes, which can be associated with lack of human resources (authorities, veterinarians and technicians) to sustain them, inadequate government funding for agriculture or livestock sectors, limited surveillance coverage (20), insufficient legislative action, and lack of support for implementing biosecurity measures (21). As a result, disease reporting is delayed, incomplete or biased, leading to ineffective responses to disease outbreaks (22,23). These challenges are more pronounced in rural areas of lower to middle-income countries, as the BSB, where social inequality persists. In these regions, livestock, particularly ruminants, are ubiquitous and critical for livelihoods, and animal diseases hinder food security and the sector's development.

Table 3: Overview of the studied diseases; CCHF: Crimean Congo haemorrhagic fever, FMD: foot-and-mouth disease, LSD: lumpy skin disease, PPR: peste des petits ruminants; g.: genus, f.: family.

		Disease	Agent	Main domestic host(s)	Transmission	Vaccine availability
Zoonoses	Bacterial	Anthrax (24)	Bacillus anthracis	All mammals	Contact with *B. anthracis* spores	Yes
		Brucella (25)	*Brucella abortus*	Cattle	Direct/indirect contact	Yes
			Brucella melitensis	Sheep and goats		
	Viral	CCHF (26)	CCHF virus • g. Orthonairovirus • f. Nairoviridae	Cattle, sheep, and goats	Tick-borne	No
TADs		FMD (27)	FMD virus • g. Aphthovirus • f. Picornaviridae	Cattle, sheep, goats, and swine	Direct/indirect contact	Yes
		LSD (28)	LSD virus • g. Capripoxvirus • f. Poxviridae	Cattle	Arthropod vector	Yes
		PPR (29)	Small ruminant morbilivirus • g. Morbillivirus • f. Paramixoviridae	Sheep and goats	Direct contact	Yes

This study characterizes ruminant production and its importance around the BSB and describes the disease status and management efforts (i.e. surveillance and control activities) for the selected ruminant diseases (Table 1) in nine countries of the region (i.e. Armenia, Azerbaijan, Belarus, Bulgaria, Georgia, Moldova, Romania, Türkiye, and Ukraine). It also explores the most relevant factors that may influence the incursion and spread of these diseases in the region.

3.3 Materials and methods

The current paper is a component of the GCP/GLO/074/USA project, which contributes to the broader "Global Framework for the Progressive Control of Transboundary Animal Diseases (GF-TADs)" initiative. This project targets nine countries located around the BSB, namely Armenia, Azerbaijan, Belarus, Bulgaria, Georgia, Moldova, Romania, Türkiye, and Ukraine. Herein, Armenia, Azerbaijan, and Georgia are referred to as "Caucasus", when the statement is true for the three countries, and Türkiye is referred to as either "Thrace" or "Anatolia" when specific differences apply to each of the regions.

The primary focus of the project is on six diseases that are relevant for the region: anthrax, brucellosis, CCHF, FMD, LSD, and PPR. Consequently, this study focused on domestic ruminants (cattle, sheep and goats), which are the animal species most impacted by these diseases. These species are also interchangeably referred to as large ruminants (LR) and small ruminants (SR).

A report template was designed to collect information from each of the participating countries (S1). This document was developed by four authors of this paper (AA, DB-A, JC, and MA) as a semi-structured questionnaire. The selection of topics was based on the project's objectives and aimed at addressing knowledge gaps in the BSB about the ruminant sector and the impact of the selected diseases. The initial version of the document was presented and shared with respondents from the nine participating countries during a virtual meeting. The final version of the report template accounted for edits and suggestions provided by the participants.

The report template was divided into two sections. The first section focused on the ruminant demographics, types of ruminant production, national and international trade, livestock markets, slaughterhouses, seasonal movements, and value chains. The second section focused on the six targeted diseases, requesting information on disease status, recent outbreaks, surveillance and control activities, awareness campaigns, and research activities in place.

Moreover, each report template requested information in two formats: narrative answers (e.g. description of a system or production type) and quantitative data in a database format (e.g. Excel datasheet). In some cases, quantitative data could complement descriptive information. To have high-quality figures, we requested the highest level of detail (e.g. the number of smallholder farms at the smallest administrative level) and, when applicable, exact locations (e.g. georeferenced locations of a livestock market). Further instructions prompted respondents to refer to additional documents like local veterinary authority national reports and national publications (i.e. grey literature).

One focal point (FP) of each participating country was appointed by FAO to answer the report template and collect country-specific information. FPs were carefully selected based on previous collaborations, the quality of their work, their expertise in the ruminant sector and selected diseases, and access to the data necessary for further analyses. FPs were based in each respective country and were working (or had recently worked) within relevant national institutions (e.g. veterinary services, food safety authorities, or national laboratories), during data collection. All nine FPs are co-authors of this paper.

FPs received the report template via email, filled it in with preliminary information, and iteratively and upon request, added further detail, following a back-and-forth exchange of emails and virtual meetings. Data collection was carried out by the FPs in collaboration with local peers, and all activities were coordinated with national authorities to request and obtain approval for data sharing. Data collection took place between October 2020 and December 2021.

Descriptive information and quantitative data were obtained and analysed from completed report templates. Then, data were assessed, and specific topics were selected to examine in this paper. To complement data on these topics, information was sourced from national reports and websites of the Food and Agriculture Organization of the United Nations (FAO), the World Organisation for Animal Health (WOAH), and the World Bank. To assess the economic importance of ruminant production for each country, we sourced data for the gross production value (GPV) of the main domestic production species from FAOSTAT (30). To find the proportional contribution of ruminant GPV to each country, we divided GPV for cattle, sheep, and goats, by the total GPV for all domestic species in 2020. Finally, ruminant distribution maps for ruminant populations (31) were sourced from FAO-NSAL (FAO's Livestock Information, Sector Analysis and Policy) branch.

Quantitative data was managed, cleaned, harmonized, and collated in Microsoft Office Excel (2019), RStudio® (32), and analysed and visualised in Quantum GIS (33) and RStudio® (32).

3.4 Results

Selected topics from the nine participating countries were organized into two sections following the structure of the report template: 1) study region and ruminant-specific information, and 2) disease-specific information.

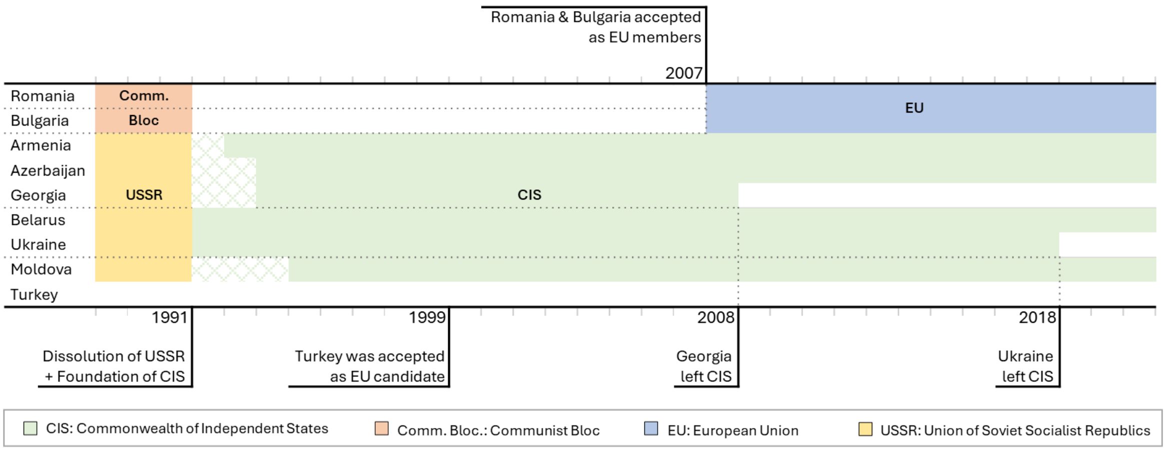

Figure 1: Political affiliations from 1988 to 2021 for the studied countries.

3.4.1 Study region and ruminant-specific information

Study region

The main political changes and affiliations from countries of the study region between 1988 and 2021 are illustrated in Figure 1. S2 summarizes data for human and ruminant demographics, relevant economic indicators, and other characteristics of ruminant production. In 2020, most countries were classified as upper-middle-income economies, with the exceptions of Ukraine and Romania, which had a lower-middle-income economy and a high-income economy, respectively (34). The median GDP per capita of each region in 2020 was $4,547 USD, ranging from $3,725 USD in Ukraine to $12,896 USD in Romania. For livestock production indicators, Moldova and Bulgaria had the lowest contribution to agricultural GDP at 23%, while Belarus had the highest at 57% (30). The proportion of ruminant GPV (per total domestic production species) ranged between 23% in Moldova to 92% in Belarus (30). Further details about this indicator are supplied in S3.

Ruminant demographics

The ruminant distribution varied significantly throughout the study region, both for LR and SR. LR heads ranged from 159,000 in Moldova to 18 million in Türkiye, whereas SR heads were lowest in Belarus (148,000) and highest in Türkiye (54 million). Figure 2 illustrates the spatial distribution for LR and SR in the region and shows higher abundance of LR in Belarus, certain regions of Türkiye, western Georgia, and Azerbaijan, and higher number of SR in parts of Türkiye (Thrace and southeast Anatolia), Romania, and Azerbaijan. Additionally, the figures highlight lower LR populations in Ukraine, Moldova, southern Romania, and northern Bulgaria, and lower SR populations in Belarus, Ukraine, Moldova, and northern Bulgaria.

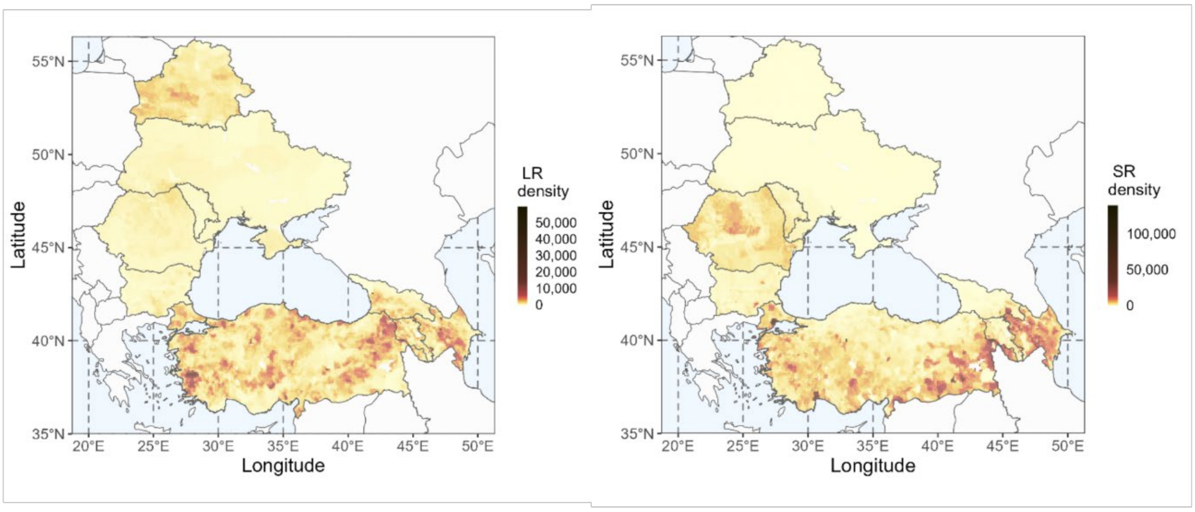

Figure 2: Distribution of large ruminants (LR) - cattle - and small ruminants (SR)—sheep and goats— in the study region. Source: GLW4 (Gridded Livestock of the World) data modified with countries' data and adjusted for FAOSTAT 2020 (31,35–37).

Production types

Countries classified ruminant production types using distinct terminology. To allow for comparisons, production types were grouped based on herd size and commercial purpose into smallholder and commercial farms, as defined in S6. In the Caucasus and Romania, over 90% of cattle farms were smallholdings, while Belarus had the highest proportion of cattle production in commercial herds. Across the entire region, more than 75% of herds keeping sheep and goats were smallholdings.

Animal identification and registration systems

Most countries in the BSB had established National Animal Identification and Traceability Systems (NAITS). In contrast, the Caucasus had NAITSs under development, but not yet fully implemented at the time of data collection. In Azerbaijan, this system was being developed through a European Commission (EC) framework. It entered a regional pilot stage in late 2021 and began a country-wide phased implementation over 2022 (38). In Armenia, the Centre of Agribusiness and Rural Development (CARD), with support from the Austrian Development Agency (ADA) (39,40), developed and conducted a pilot of its NAITS in the cattle sector in January 2022. Similarly, in Georgia, after a 5-year project supported by FAO and financed by the ADA and the Swiss Agency for Development and Cooperation (SDC), the system was launched nationwide in February 2022 (41).

National trade of live ruminants

Recordings of live animal movements were linked to the existence of a NAITS in each country. Therefore, most countries in the region recorded these movements within a national centralized database. Each registration included information regarding the individual identification of the animal and the farm of origin, the destination farm, and a veterinary health report issued by an official veterinarian.

Conversely, Georgia did not have a recording system for animal movements. In Armenia and Azerbaijan, movements between provinces were registered, but the record consisted solely of a paper-based veterinary health certificate. These records were issued by official veterinarians and archived in regional divisions. There were no centralised databases for recording live animal movements in these three countries.

Live animal movements were characterized by a seasonal pattern that is not detailed in this paper. Nevertheless, it is worth noting that these movements significantly surged during cultural-religious celebrations such as Novruz, Kurban Bayram, and Ramadan Bayram in

Azerbaijan and Türkiye, in which animals are transported to cities to be ritually slaughtered. Similarly, Easter and St George's Day in Bulgaria and Romania were also preceded by an increase in live animal movement due to the traditional consumption of mutton.

Furthermore, it is important to highlight that livestock trade was closely linked to animal density in each region, the demand for animal protein in densely populated areas, the location of slaughterhouses, and specific commercial partnerships with regions or countries. For example, in Georgia, ruminant trade primarily occurred from west to east due to the high exports to Azerbaijan. As for Bulgaria, the southern regions, where LR and SR production was more intense, also had an increased movement of ruminants. Moreover, in Türkiye, ruminants were moved from small to large provinces, and more specifically from east to west and north to south of the country.

Livestock markets

The role of livestock markets in live ruminant trade varied across the region. Azerbaijan and Türkiye run ten and 150 licensed live animal markets, respectively, which played a significant role in ruminant trade. During Kurban Bayram in these two countries, markets worked exceptionally to sustain the surge in animal movements. In Armenia, Georgia, and Bulgaria, these facilities existed but were not as relevant for animal trade. In Belarus, official markets for live ruminant trade were absent, instead occasional fairs and exhibitions were held at the district level and on a small scale. In the same country, ruminant trade for breeding purposes occurred through state breeding companies. In Ukraine, smallholders used live animal markets for local ruminant trade.

Seasonal movements

Pastoralism includes seasonal movements to pastures and can be sub-classified as nomadism, transhumance, or agropastoralism (definitions provided in S6). These practices are key to the seasonal sourcing of graze and water for livestock and were common across the study region. In Bulgaria, the Caucasus, Romania, and Türkiye, transhumant animals were moved to summer pastures, often found in mountainous areas, in spring and summer, and to lowland pastures or stables in autumn and winter. Migrating months had slight variations yearly depending on weather and pasture conditions. Georgia, Azerbaijan, and Türkiye set up Veterinary Surveillance Points (VSP) along migration routes. These premises primarily focused on mass vaccination campaigns in Azerbaijan, but also served as rest points for supplying feed and water, as sanitary checkpoints for health status control, and anti-parasitic application in Georgia and Türkiye. The mingling of animals from various herds, regions or even neighbouring countries was common in seasonal pastures. Consequently, these animals were vaccinated either before going to pasture or during migration in VSPs. Furthermore, movements to seasonal pastures were recorded in centralized systems for movement control in Bulgaria, Romania 42 and Türkiye; however, these recordings, similarly to national movements, were not done in the Caucasus.

In Belarus, Moldova, and Ukraine, ruminants kept in smallholdings or smaller private farms in rural settings grazed seasonally in fields surrounding their holdings, in an agropastoral manner.

International trade of live ruminants

Partner trading countries with the BSB region are presented in the last two columns of S2. International trade of live animals was done based on country partnerships, contingent on the trust in the exporting country's animal health capacity and/or the sanitary status for the main contagious zoonoses and TADs (at a specific time) 43. To guarantee disease freedom on entry into a country, imported live ruminants were accompanied by a health certificate validated by a veterinarian of the exporting country’s competent authority. Particularly for the importation of live animals (and animal products) into the EU, the intra-EU trade, and EU exports of live animals, TRACES (Trade Control and Expert System) 44, an EC online platform, facilitates sanitary certification required for trade and centralizes trade information. Thus, Bulgaria and Romania along with other BSB countries exporting live animals or animal products into the EU, used this platform.

Similar to national live animal movements, international trade was influenced by cultural-religious events. Therefore, a surge in live animal imports preceded Kurban Bayram and Ramadan Bayram in Azerbaijan and Türkiye, and Easter and St George's Day in Bulgaria and Romania.

3.4.2 Disease-specific information

Disease status, surveillance, and control activities

Figure 3 illustrates the country-level disease statuses for each selected disease. Countries self-classified their disease status as endemic, sporadic, or absent (definitions in S6). An Absent status was subclassified for brucellosis as "officially free" and for FMD as "officially free with or without vaccination" when WOAH officially recognised these disease statuses.

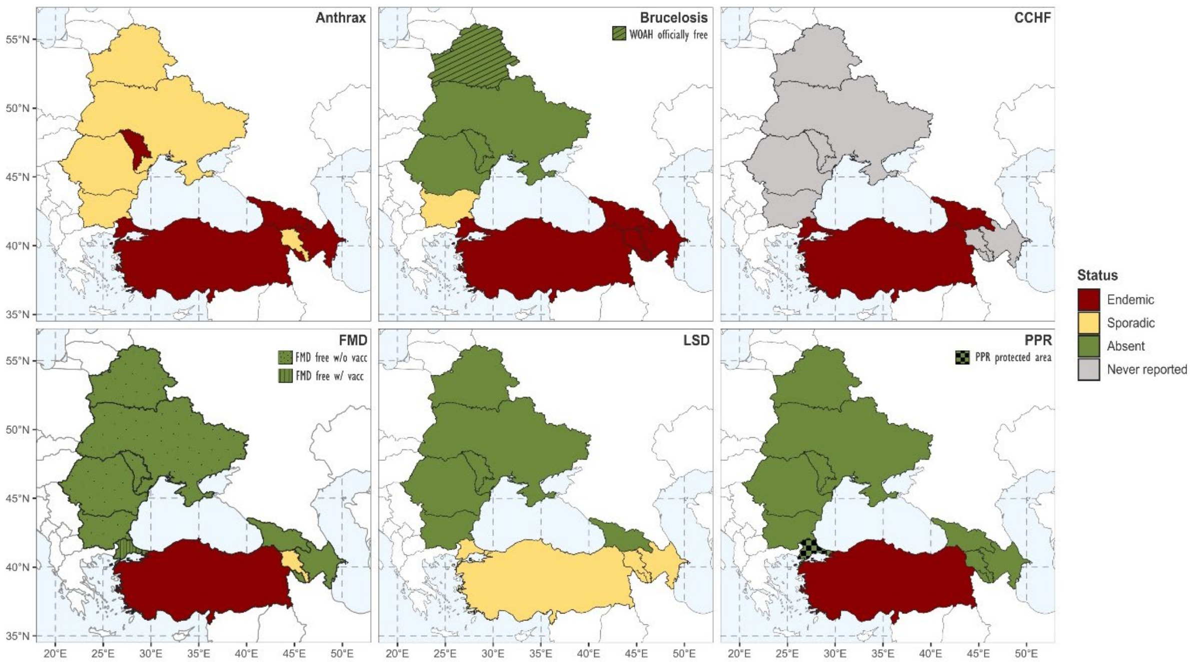

Figure 11: Status of target diseases in the study region. Brucellosis status refer to Brucella abortus and Brucella melitensis.

In S4, a table summarizes key details for the six studied diseases in each of the countries of the BSB. Moreover, temporal trends of disease outbreaks per country from 2010 to 2020 are shown in S5. In this subsection of the results, we review the disease status and management practices applied in the region.

Anthrax

Anthrax was endemic or sporadic in all countries. All countries implemented passive surveillance and, upon suspicion, applied further clinical examinations, sampling, and testing. Due to the environmental nature of this disease, most national management programmes, in addition to guidelines for disease containment and carcass disposal, also included regulations for historically infected fields (e.g. signalling, fencing, digging restrictions, and awareness campaigns). Vaccination was compulsory for all ruminants in Azerbaijan, and Moldova, and all LR in Armenia. A risk-based vaccination approach was applied for all ruminants in Bulgaria, Georgia, Romania, Türkiye, and Ukraine, and exclusively for SR kept or moved to high-risk areas in Armenia. In Belarus, anthrax vaccination was not conducted.

Brucellosis

Brucellosis was endemic in the Caucasus and Türkiye, sporadic in Bulgaria, and absent in all other countries of the BSB. In 2012, Belarus was officially recognised by WOAH as brucellosis-free, and to maintain this status, serosurveillance was conducted every three years. Moreover, surveillance was exclusively passive for Georgia, and active and risk-based in all other countries. In most of the BSB, passive surveillance for brucellosis was associated with the report and investigation of abortions in ruminants, which is a syndrome of this disease, but not exclusive to *Brucella spp.* infection. In Azerbaijan, Georgia, and Türkiye, vaccination for brucellosis was mandatory for all ruminants and performed at the same time as serosurveillance. Brucellosis vaccination was not part of the national veterinary control plan in Belarus, Bulgaria, Moldova, Ukraine, or Romania.

Crimean Congo haemorrhagic fever

CCHF was endemic in Georgia and Türkiye. These countries applied control measures upon outbreak identification, focusing on tick control and community awareness campaigns. These activities comprised the application of acaricide sprays to ruminants, including during seasonal migrations from early spring to late autumn, and environmental tick elimination.

Educational campaigns in Türkiye promoted contact restriction between livestock and wildlife, and tick management. These campaigns were included in the state budget at no cost to farmers. For the remaining countries, CCHF had never been reported in ruminants and no national surveillance programmes were in place" with " there was no national surveillance programme in place. At the time of data collection, no licensed vaccine was available for CCHF in ruminants.

Foot-and-mouth disease

The WOAH official FMD status varied between the two regions of Türkiye: Anatolia was classified as endemic, and Thrace held FMD-free status with vaccination. FMD was sporadic in Armenia, absent in Georgia and Azerbaijan, while in all other countries, WOAH recognised the official status FMD-free without vaccination.

FMD surveillance was active in the Caucasus and Türkiye, as well as in regions of Bulgaria and Romania. The countries of the Caucasus were collaborating with EuFMD through the Progressive Control Pathway for Foot and Mouth Disease (PCP-FMD) to design and establish risk-based surveillance programmes. As part of these efforts, they implemented NSP (Non-Structural Protein) and SP (Structural Protein) serosurveys to evaluate the FMD virus circulation, seroconversion, and vaccination coverage. In regions bordering Thrace, Bulgaria conducted risk-based serosurveys on a sample of ruminants every three months. While in Romania, surveillance focused on clinical examination of LR and SR on high-density premises (e.g.: live animal markets, exhibitions, ports, and airports), serosurveillance of all ruminants close to international borders, and SR upon their arrival from seasonal pastures.

In Türkiye, the FMD management programme in 2021 aimed to achieve FMD-free status without vaccination in Thrace and FMD-free status with vaccination in Anatolia by 2025 (45). In Thrace, control measures comprised suspect FMD case culling, restrictions on live animal imports from Anatolia, and strict adherence to sanitary legislation. In Anatolia's southeast provinces bordering FMD-endemic countries, surveillance activities were enhanced and risk-based. Moreover, in case of an FMD outbreak, Türkiye conducted a field investigation, and vaccination, established a *cordon sanitaire*, animal quarantine, and thorough cleaning and disinfection, organized training, and awareness campaigns, and closely monitored all premises within a 10 km radius of the event.

FMD vaccination varied throughout the BSB. Türkiye vaccinated LR twice a year, and SR once a year only in Thrace. In case of an outbreak in Anatolia, SR were also vaccinated in established protection and surveillance zones. In Azerbaijan, LR were vaccinated twice a year (spring and autumn) and SR once a year, while Armenia, applied the same strategy only in high-risk areas. Since 2017, Georgia has conducted vaccination exclusively in high-risk areas, based on risk assessments, which considered seasonal migration, international borders with FMD-endemic countries, live animal markets, and informal trade.

Lumpy skin disease

LSD was sporadic in Armenia, Azerbaijan, and Türkiye, and absent in all other countries. Surveillance activities varied: clinical examination was conducted in Belarus to a sample of LR in spring and summer, and in the six regions of Bulgaria bordering Thrace monthly. Georgia had active participatory surveillance, Türkiye implemented both active and passive surveillance activities, and all other countries only applied passive surveillance. Compulsory vaccination was practised nationwide in Azerbaijan, Bulgaria, and Türkiye, and in high-risk areas of Armenia and Georgia. Vaccination was not applied in Belarus, Moldova, Romania, or Ukraine.

Peste des petits ruminants

PPR was endemic in Türkiye and absent in all other countries. In March 2021, Thrace was granted the classification of "PPR-protected area". PPR surveillance varied across the BSB: Belarus did not conduct it, Moldova, Ukraine, and Anatolia exclusively applied passive surveillance, while Thrace and all other countries applied active surveillance. In Bulgaria, areas previously affected by PPR (2018 outbreak) implemented enhanced surveillance, and regions bordering Thrace applied risk-based serosurveillance on a sample of SR every two months. In Romania, active surveillance included clinical inspection of a sample of SR herds before and after pasture season.

Vaccination was implemented in Georgia, following the first PPR occurrence in 2016. In Türkiye vaccination was conducted, yet it ceased in Thrace after the region was granted a “PPR-protected area” classification in March 2021. This measure, coupled with strict live SR movement restrictions from Anatolia to Thrace, aimed at Thrace’s application for WOAH PPR zonal freedom status in 2023. In Anatolia, PPR vaccines were applied to all newborn SR and unvaccinated adults.

3.5 Discussion

In this paper, we summarized the ruminant production sector and reviewed the sanitary status and management of six diseases affecting ruminants (anthrax, brucellosis, CCHF, FMD, LSD, and PPR) in the BSB. Furthermore, we explored key factors contributing to the introduction and spread of these diseases in the region.

Post-Soviet Union reform: The fall of the Soviet Union caused a deterioration of public infrastructures and services across the former Soviet Union (FSU) and Communist Bloc countries, significantly affecting agricultural and livestock sectors (11,46–49). In BSB countries, except Belarus, changes included the shift from collective and state-owned farms to private ownership, removal of government subsidies to the livestock sector (50), closure of large slaughterhouses (51), and depletion in resource allocation to veterinary services (52). Such factors left livestock production in the hands of unspecialized farmers, and unsupervised by veterinary services (53), resulting in increased disease incidence (53,54). Thereafter, the region suffered a steep decline in the number of ruminants (50,55) and, in some countries, as Ukraine and Belarus, a significant abandonment of agricultural lands (56). These abrupt structural changes were followed by a transition phase with gradual agricultural recovery and increasing productivity (57). Yet, rural poverty, particularly in the Caucasus and Moldova, persists and requires new and efficient policy measures that enable technological development and access to market channels and services (52). EU’s farmer association model could aid smallholders of the FSU to actively engage to improve their marketing, input supplies, and support services (58).

Rural livelihoods and pastoralism: Pastoralism played a critical role in rural areas in most countries of the BSB (10–15,17–19,47,59–61), creating a unique interdependence between ruminants, farmers, and the environment 62,63. Preserving this practice is crucial, given its resilience to severe climates in arid and inhospitable areas, socio-cultural importance, and the potential opportunities brought to younger generations (63). However, its sustainability in the BSB is a matter of concern. Ageing rural farmers show reluctance to adopt new technologies and measures to improve animal production and health, and the mass migration of younger populations to urban centres leaves families without essential support for farming activities (58). Moreover, they have limited access to veterinary services also caused by ageing rural veterinarians, and difficulties in attracting young graduates due to low-income prospects and prevailing urban migration trends (58). These factors result in underperforming veterinary services 64 and high costs for disease management impeding improvements, even when advancements are made at higher levels (22). Solutions for these challenges need to be explored, as building private veterinary capacity and developing training programmes for veterinary paraprofessionals.

In addition, initiatives addressing pastoralism's limited sustainability and its associated risks to ruminant health and welfare are underway (65,66). In Georgia (63), Türkiye, and Azerbaijan, VSPs were established along migration routes. In Armenia, the "Project Coordination Platform for Sustainable Management of Natural Grazing Lands - Pastures and Grasslands" was launched to address pasture management-related problems in the country (67). Internationally, the Pastoralist Knowledge Hub (PKH) by FAO aids the development of synergies for dialogue and pastoralist development, while an extension of the Performance of Veterinary Services (PVS) (68) evaluation tool prioritizes finding solutions to control animal diseases in pastoralist areas (64). Collectively, these initiatives aim to foster and protect pastoralism while ensuring its sustainability.

Disease management and related factors: Disease management in the Caucasus and Türkiye was often inefficient. Nonetheless, improvements were being made in the field. Particularly in the Caucasus, the full operability of the NAITSs is expected to make disease management programmes (69) and disease traceability (70) more efficient. As a result, these improvements will positively influence animal health and ruminant production, ultimately, leading to better trade opportunities and economic growth in these countries.

Sociocultural-religious events in Türkiye and Azerbaijan prompted the implementation of contingency plans and extraordinary measures, which, at times, proved inefficient in preventing disease introduction and spread. In fact, the epidemiological investigation conducted upon the PPR incursion to Bulgaria in July 2018 concluded that the high demand and resulting price difference of mutton between Bulgaria and Thrace during these festivals contributed to increased informal movements of people and animals (71).

In the BSB, only Türkiye reported the presence of all studied diseases. This can be attributed to its unique conditions, including a large ruminant population, vast geographical area with socio-economic disparities, and extensive rural regions. Moreover, its shared borders with six countries including Syria and Iraq, where social unrest leads to informal movement of people with their livestock, create a significant pathway for disease spread (72,73). Recognising the high risk to animal and public health through this route, Türkiye introduced legislative acts for border control and supervision of the main roads (74,75). These acts are open to amendment, and they aim to manage and identify informal/illegal trade for livestock and products of animal origin, along with enforcing animal culling. Following the implementation of these controls, a national report highlighted a significant reduction of nearly 95% and 50% of confiscated smuggled animals and animal products, respectively, caught during border controls conducted in 2011 and 2018. This demonstrates the successful impact of these actions.

EU countries, such as Bulgaria and Romania, had high resource allocation for disease management and prioritised the prevention of disease incursion to reduce economic losses. These countries followed harmonized live animal trade regulations set by the EC, enforcing additional control measures and trade restrictions (76) in the event of an exotic disease incursion. Therefore, responses to Bulgaria's FMD (2011), LSD (2016), and PPR (2018) outbreaks were quick and intensive (77). And LSD and FMD outbreaks resulted in an economic burden estimated at €8 million (78), and $1.5 billion USD annually (79), respectively. To prevent disease re-emergence and further economic losses, disease management activities established upon these events, were still in place as of 2021.

Moreover, Thrace's proximity to Europe and shared borders with the EU through Bulgaria and Greece, prompted the establishment of partnership programmes between the EU and Türkiye. These initiatives involved significant investments to curb disease introduction and spread into Europe, while also promoting trade opportunities (80,81). Therefore, FMD and PPR statuses varied between Thrace and Anatolia, leading to distinct classifications by WOAH, along with distinct approaches for disease management and movement control in these two regions.

The exception of CCHF: Türkiye and Georgia were the only countries in the BSB reporting the presence of CCHF in ruminants. In spite of this, past studies identified CCHF virological or serological evidence and the presence of competent vectors in most countries of the study region, except for Belarus (26,82–84), while CCHF human cases were also notified in Bulgaria and Türkiye (83). Non-reporting of CCHF in ruminants was linked to two factors. Firstly, its exclusion from national veterinary programmes resulted in the absence of routine official surveys, and secondly, the subclinical nature of the disease in these species allows it to circulate unnoticed (85–87). Nevertheless, domestic ruminants play an important role in the epidemiology of the disease as they are involved in its vector life cycle 84 and amplification and spread of the virus (88,89). Moreover, ruminant CCHFV antibody titres correlate with virus presence in a region (83), as well as human disease incidence (82). Given CCHF's public health threat, including potential human incurred deaths, the prudent course of action is to include the disease in national veterinary programmes. This would ensure regular disease monitoring and prompt response to any reported cases.

Current Initiatives: Achieving effective disease management requires not only efficient resource allocation for national disease preparedness and response but also promoting collaborations with other countries and unions. An initiative that strengthens regional alliances for TADs management is the GF-TADs, a joint FAO and WOAH effort, created to support capacity building and the establishment of disease management programmes based on regional priorities (77). GF-TADs' priority diseases in the BSB include brucellosis, FMD, LSD, and PPR. Under this initiative, the Global Strategy for the Control and Eradication of PPR aims to control and eradicate PPR and strengthen veterinary services (90,91). Additionally, FAO's PCP-FMD guides endemic countries in progressively managing FMD risks and reducing its impacts and viral circulation (92–94).

Limitations: Study limitations were linked to country-specific factors and data quality issues. Absent or not fully operable NAITs are likely to have affected data validity, and completeness is limited due to unregistered herds along with underreporting across the BSB. Underreporting is often linked to farmers' poor disease awareness, distrust in governmental authorities, risk of penalty or stigmatization, or at a higher level, lack of capacity to enforce regulations (95) and low transparency. Additionally, variability in data availability and spatial resolutions between countries led to reduced accuracy of certain indicators or made it impossible to compare and examine others. Finally, data quality might have been affected by resource reallocation during the COVID-19 pandemic, which partly coincided with the two-year data collection period.

The Armed Conflict in Ukraine; The armed conflict in Ukraine, starting in February 2022 had a significant impact on its livestock sector. Since its beginning, the conflict led to decreased agricultural production due to land abandonment, animal losses from death or forced slaughtering, and reduced demand for meat and milk due to mass emigration (96). It has disrupted the accessibility to veterinary services, vaccines, medication (97), and critical inputs, such as feed and fodder (96), compromising disease prevention and control, and increasing the risk of stress, malnourishment, and susceptibility to disease in livestock. Moreover, amongst security issues, unavailability of consumables and equipment, and competing urgent priorities, appropriate carcase disposal became challenging. These effects are expected to reshape ruminant demographics, its associated production sector, and value chains, particularly in front-line regions. International cooperation is vital to address the consequences on livestock health and revive the sector post-conflict. Guidelines aiming to support the livelihoods of livestock-keeping communities in humanitarian emergencies that affect livestock are in place (98,99), and being used to alleviate the consequences of the presented conflict.

3.6 Conclusions

This study provides a comprehensive overview of the ruminant production sector and the management of six major diseases of concern in the BSB. By examining the effects of the post-soviet reform, the importance of pastoralism, differences in disease management and countries' response to disease incursion, as well as the influence of cultural events and political affiliations on live animal trade, we have gained a valuable understanding of how these different factors work together to determine disease dynamics in the region.

Unlike the other studied diseases, CCHF was not included in veterinary management plans, and not surveyed in ruminants across the region, presenting a public health threat. Furthermore, the armed conflict in Ukraine starting after data collection will likely have a significant impact on ruminant production and animal disease emergence in this country, with potential spread to neighbouring countries.

Finally, despite recent developments in veterinary infrastructures, including the implementation of NAITSs in the Caucasus, substantial support from international agencies and targeted initiatives for ruminant disease management, the need to improve animal health persists, particularly in rural and remote regions. A thorough understanding of the primary challenges, needs, and constraints faced by smallholders in each specific country context is essential. Establishing priorities and closely assessing them in collaboration with farmers, national stakeholders, and international agencies, will aid in identifying opportunities for more effective disease management strategies contributing to alleviating and preventing future outbreak scenarios. These considerations go hand in hand with providing incentives for rural development, by seeking financial aid, efficiently allocating financial and human resources, and most importantly ensuring the sustainability of the implemented strategies.

Data Availability

The data that supports the findings of this study are available on request from the corresponding author. The data are not publicly available due to confidentiality or ethical restrictions.

Conflict of Interest

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

Author Contributions

AA, DB-A, JC, and MA developed the report template and contributed to the conception and design of the study. JA, TC, IK, TM, DM, AP, MP, NS, and AZ were hired as country FPs to fill in the report template and provide quantitative data and descriptive information for the project. SO wrote a document summarizing preliminary information. MA performed the data management, descriptive analysis and visualization materials, and wrote the first draft of the manuscript. All authors contributed to the article and approved the submitted version.

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Supplementary Materials

S1: Report template.
S2: Proportion of gross production value (GPV) per production species (cattle, goats, poultry, sheep, swine) in each country.
S3: Demographics, economic indicators, livestock, and ruminant production indicators in the study region.
S4: Overview of disease status, surveillance activities, and vaccination for anthrax, brucellosis (*B. bovis* and *B. melitensis*), Crimean Congo heamorrhagic fever (CCHF), foot and mouth disease (FMD), lumpy skin disease (LSD) and peste des petits ruminants (PPR) in the study region.
S5: Temporal distribution of outbreaks for the selected diseases by country from 2010 to 2020.
S6: Definitions.

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3.8 Supplementary Materials

S1: Report template

Name			
Date		Country	
Name of contributors (add more rows if necessary)		Email of contributors	

This report template has the objective of gathering information about the national ruminant production sector, and six ruminant diseases - anthrax, brucellosis, Crimean Congo haemorrhagic fever (CCHF), foot-and-mouth disease (FMD), lumpy skin disease (LSD) and peste des petits ruminants (PPR) - including the related risk factors, surveillance, and control strategies.

Please follow the structure provided below to write the report, replying to each question in detail, and referencing complementary documents, which do not need to be translated at this stage.

These complementary documents should be attached as appendices. They may include:

- Internal industry reports.
- Veterinary Service or Laboratory reports.
- National databases, e.g.: outbreaks, surveillance results, livestock numbers, etc.
- National agricultural magazine's articles.
- National scientific publications.
- Maps/ Graphs.
- Master or PhD thesis (documents not published in international journals).

Note:

a. If the source document is written in a language other than English, indicate it with reference to the question and add a brief summary of the information it contains and the language, so we can decide if it needs translation.

b. Scientific publications in international journals (in English) do not need to be included, since they will be covered by FAO research partner.

RUMINANT SPECIFIC INFORMATION

1. Include data at the maximum resolution level (i.e. individual farm or the lowest administrative level available). Please note that the classification provided is generic, but may be different in your country. Please provide additional categories (e.g. mixed purpose, dairy goats or sheep, extensive systems, nomadic herds, etc. to reflect the existing categories within your country).
    - Refer to an Excel file

2. Provide an outline or narrative of the main commercial and/or backyard ruminant production systems in the country and their characteristics, e.g. definition of each farm type (how is a backyard, commercial or semi-commercial defined), how do they operate in rough terms, proportion of farms with mixed species, etc.

3. Did the proportion of ruminant farms/ animals change in the last 5 years? Describe how.

4. Provide an outline of the value chains for ruminant production in the country (i.e. who is involved and what is the contribution and the profit of the participants). If available, provide also major documents/studies about this topic.

5. Animal trade markets: describe where live animals are traded, how often, and under what conditions.

6. **Animal movements**

    6.1. Are movements between farms recorded and available in a database? If so, please describe the data fields captured and the level of detail. Please describe the rough amount and type of movements that are not recorded.

    6.2. Are there seasonal animal movements, e.g. animals that go to summer pastures or large nomadic/transhumance movements? If yes, are these movements recorded in a database and available? If so, please describe the data fields captured and the level of detail. If not, describe the movement season and pattern (i.e. frequency and location), as well as the approximate number of animals involved.

7. **Trade**

    7.1. For each ruminant species, describe imports and exports of the following products, including countries involved and quantities:

        7.1.1. Live animals

        7.1.2. Animal products

            7.1.2.1. Meat

            7.1.2.2. Milk and dairy products

            7.1.2.3. Semen and embryos

            7.1.2.4. Hides

7.2. Main trade routes within the country. Describe the geographical aspect of trade routes and transport media for the domestic market, as well as the actors involved, e.g. existence of middlemen, live animal markets or agricultural fairs, animals are sent straight to slaughterhouses, etc.

7.3. Has illegal animal trade been identified within the country and with other countries? Describe in what instances this happens and what are the most difficult borders to control.

DISEASE-SPECIFIC INFORMATION

Disease	**Endemic / Sporadic / Absent**	**If absent or sporadic, state the date of the last introduction**	**Is the disease reportable?**
Anthrax			
Brucellosis			
CCHF			
FMD			
LSD			
PPR			

8. **For each specified disease**

8.1. Provide the database for the outbreaks and/or surveillance results existent in the country in the last 10 years (if available one row per affected farm), if possible, with the following information:

8.1.1. Date

8.1.2. Location (or region)

8.1.3. Geocoordinates (if available)

8.1.4. Species (i.e. cattle, goat or sheep) plus production system if available, e.g. dairy, beef, extensive, etc.

8.1.5. Number of animals present on the farm.

8.1.6. Number of animals affected.

8.1.7. Number of dead animals.

8.1.8. List other fields captured in the national database.

8.2. Provide the database of the cases in humans in the last 10 years for anthrax, brucellosis, and CCHF, if possible, with the following information:

8.2.1. Disease (anthrax, brucellosis, or CCHF)

8.2.2. Date

8.2.3. Location

8.2.4. List other fields captured in the national database.

8.3. For each disease, if there is no outbreak database, please describe the outbreaks that occurred in the last 10 years:

8.3.1. Where did it occur in the country?

8.3.2. What was the source of the introduction of disease into the country?

8.3.3. How did it spread?

8.3.4. How many animals were affected/ killed?

8.3.5. Economic impact?

8.3.6. How was it controlled?

9. **Surveillance Plans**

9.1. Are National Surveillance Programmes implemented? If yes, describe the surveillance program for each of the diseases.

10. **Control measures**

10.1. Is there a national vaccination plan for the different diseases or any other sort of control plan? If yes, please describe.

10.2. Is it common practice the application of insecticides/repellents/acaricides on ruminants to control ticks? (Possible vectors of LSD and CCHF)

10.3. Are there any distribution maps and info about relevant vectors for CCHF, i.e. Hyalomma ticks? If yes, please describe.

10.4. Are there any wild animals known or suspected to be responsible for the spreading or being reservoirs of any of these diseases in the country? If yes, please describe.

11. **Disease Awareness**

11.1. Do authorities (or others) organize training sessions, seminars, brochures, and leaflets to inform/prevent (about) the referred diseases? Indicate for which diseases this has been done and describe briefly the awareness actions implemented.

11.2. Are there any biosecurity improvement programs?

12. **University/ NGOs/ Government research of disease**

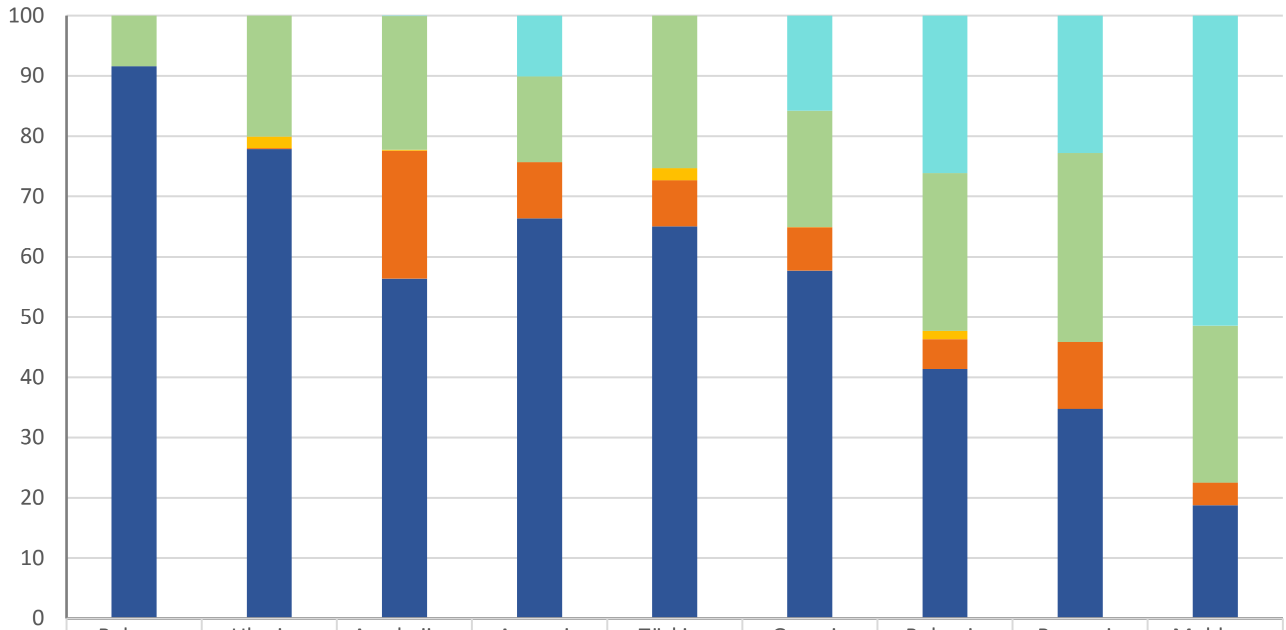
12.1. Indicate if there is any national research for any of the six diseases in agricultural/ veterinary schools/ NGOs. If yes, could you provide a contact person and/ or any publication/ report referring to it? Please include their contact details (i.e. email) and area of expertise.

S2: Demographics, economic indicators, and ruminant production indicators in the study region.

Country	Human population (2020)[2]	GDP/capita (2020-S$)[3]	% Livestock production/ agricultural GDP (2020)[1]	% GPV ruminants/ GPV domestic species (2020)[1]	LR population*		LR production types (%)*		SR population*		SR production types (%)*		Animal identification and traceability system	International trade (live animals)	
					Head (Thous.)	% LR in region	Smallholder farms	Commercial farms	Head (Thous.)	% SR in region	Smallholder farms	Commercial farms		Exports to	Imports from
Armenia	2 963 234	4 266	46	76	600	1.8	95	5	690	3	95	5	No (under development)	GEO, Middle East	EU, KAZ, RF, UKR
Azerbaijan	10 093 121	4 221	43	78	2 484	7.5	91	9	8 189	10.2	82	18	No (under development)	GEO, TK, UAE	BLR, EU, GEO, KAZ, RF, TK, UKR
Belarus	9 379 952	6 424	57	92	4.300	13.1	2	98	148	0.2	91	9	Yes	KAZ, UZB	EU SR: low imports
Bulgaria	6 934 015	10 079	23	48	722	2.2	60	40	2 015	2.5	76	24	Yes	Balkans, TK, Caucasus	EU
Georgia	3 722 716	4 267	38	65	721	2.2	95.5	4.5	685	0.9	95	5	No (under development)	ARM, AZE, Iran, Middle East	ARM, AZE, BLR, EU, RF, UKR
Moldova	2 620 495	4 547	23	23	159	0.5	74	16	845	1.1	87	13	Yes	AZE, Middle East	BLR, CH, EU, KAZ, RF, TK, Serbia, UKR, UK
Romania	19 257 520	12 896	31	46	1 867	8.8	95	5	12 541	15.6	96	4	Yes	EU, Middle East[4]	EU[4]
Türkiye	84 339 067	8 536	29	76	18 158	55.1	80[5]	20[5]	54 113	67.3	93	7	Yes	AZE, Iraq, Cyprus, PK, Middle East,	AZE, EU, South America
Ukraine	44 132 049	3 725	24	80	2 900	8.8	66	44	1 144	1.4	87	13	Yes	ARM, AZE, EU, KAZ, TK, MDV, UZB, Middle East	EU

* Ruminant census values refer to 2021. GPV: Gross production value, LR: large ruminants, SR: small ruminants, Thous.: Thousand. ARM: Armenia, AZE: Azerbaijan, BLR: Belarus, CH: Switzerland, EU: European Union, GEO: Georgia, KAZ: Kazakhstan, MDV: Moldova, PK: Pakistan, RF: Russian Federation, TK: Türkiye, UAE: United Arab Emirates, UKR: Ukraine, UZB: Uzbekistan.

S3: Proportion of gross production value (GPV) per production species (cattle, goats, poultry, sheep, swine) in each studied country, in 2020.



	Belarus	Ukraine	Azerbaijan	Armenia	Türkiye	Georgia	Bulgaria	Romania	Moldova
Swine	0.0	0.0	0.1	10.1	0.0	15.7	26.1	22.8	51.4
Poultry	8.4	20.1	22.2	14.2	25.3	19.3	26.2	31.4	26.1
Goats	0.0	1.9	0.1	0.0	2.0	0.0	1.4	0.0	0.0
Sheep	0.0	0.1	21.3	9.3	7.6	7.2	4.9	11.1	3.7
Cattle	91.6	77.9	56.4	66.4	65.0	57.7	41.3	34.8	18.8

Cattle Sheep Goats Poultry Swine

*Source FAOSTAT[1]

S4: Overview of disease status, surveillance activities, and vaccination in the study region in 2021, for domestic large ruminants (LR) and small ruminants (SR).

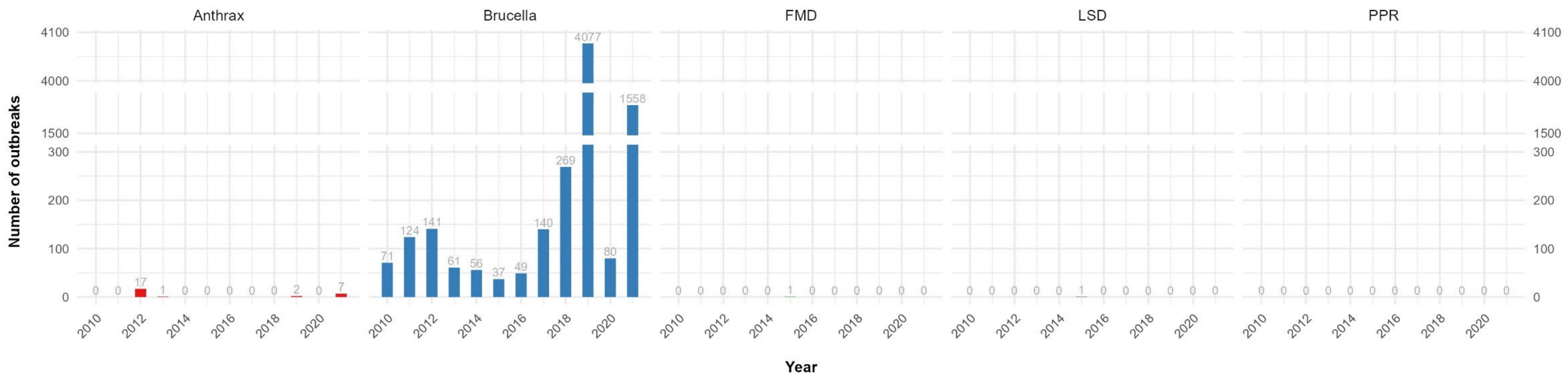
Country / Disease	Armenia	Azerbaijan	Belarus	Bulgaria	Georgia	Moldova	Romania	Türkiye	Ukraine
Anthrax	Armenia	Azerbaijan	Belarus	Bulgaria	Georgia	Moldova	Romania	Türkiye	Ukraine
Status	Sporadic	Endemic	Sporadic	Sporadic	Endemic	Endemic	Sporadic	Endemic	Sporadic
Last outbreak	2019	-	[1*]	2018	-	2016	2020	-	2017
Surveillance	Passive	Passive	Passive	Passive	Passive	Passive	Passive	Passive	Passive
Vaccination	Yes LR: young 2x/ yr., adult: 1x/ yr. SR: risk-based 1x/ yr.	Yes LR & SR 1st year: 2x/yr. Adults: 1x/yr.	No	Yes (risk-based) All SR & LR kept or moved to areas w/ 1 (or +) past outbreaks in last 50 yrs.: 1x or 2x/yr.	Yes (risk-based) Susceptible LR & SR in high-risk areas	Yes (All)	Yes (risk-based)	Yes (risk-based) Susceptible animals before seasonal movements	Yes (risk-based) areas w/outbreaks in <5yrs: all LR & SR (2x/yr.), stalling/ grazing >5yrs: adult LR & SR - 1x/yr., young LR & SR - 2x/yr.
Brucellosis	Armenia	Azerbaijan	Belarus	Bulgaria	Georgia	Moldova	Romania	Türkiye	Ukraine
Status	Endemic	Endemic	Absent WOAH official free status	Sporadic	Endemic	Absent	Absent	Endemic	Absent
Last outbreak	-	-	XX century	2019	-	1995	1965	-	[2*]
Surveillance	Active Roz-Bengal (risk-based): ELISA/CFT confirmation All LR & SR: 2x/yr. (spring and autumn)	Active ELISA and Roz-Bengal Sample of 50% of LR and 20% of SR.	Active Every 3 yrs. to maintain the official free status	Active, passive LR: non-dairy: 1x/yr. >24m 2x/yr. BTM; SR: 1x/yr. for SR >6m based on herd size	Passive (2018–present)	Active, passive ELISA and Roz-Bengal	Active, passive All LR: BTM >3x/yr. ea.3m. or blood sample 1x/yr. [3;12]m; SR: 1x/yr.	Active, passive	Active LR & SR 1x/yr for all adult animals
Vaccination	No	Yes (REV1 and S19) LR: S19 to all females 3-8m and all non-pregnant females. SR: REV1 all female 3-8m and all non-pregnant female[6]	No	No	Yes Started in 2019	No	No	Yes (all female LR and SR) LR: first dose 3–6m; second dose: 4 to 12m after the 1st; SR: 3–6m-old female lambs and kids and breeding male animals	No
CCHF	Armenia	Azerbaijan	Belarus	Bulgaria	Georgia	Moldova	Romania	Türkiye	Ukraine
Status	Absent	Absent	Absent	Absent	Endemic	Absent	Absent	Endemic	Absent
Last outbreak	Never reported	Never reported	Never reported	Never reported	-	Never reported	Never reported	-	Never reported
Surveillance	No surveillance	No surveillance	No surveillance	No surveillance	Passive Non-notifiable disease	No surveillance	No surveillance	Passive Non-notifiable disease	No surveillance
Vaccination	Not available	Not available	Not available	Not available	Not available	Not available	Not available	Not available	Not available
FMD	Armenia	Azerbaijan	Belarus	Bulgaria	Georgia	Moldova	Romania	Türkiye	Ukraine
Status	Sporadic	Absent (of clinical cases)	Absent	Absent Free without vaccination	Absent (of clinical cases)	Absent	Absent	Anatolia region Endemic	Absent Free without vaccination

		No WOAH official status	Free without vaccination (WOAH official status)	(WOAH official status)	No WOAH official status	Free without vaccination (WOAH official status)	Free without vaccination (WOAH official status)	Thrace (Free zone w/ vaccination since 2010) Thrace has the WOAH official status	(WOAH official status)
Last outbreak	2016	2001	1982	2011	2002[7]	1979	Never reported	-	1988
Surveillance	Active Risk-based, (NSP, SP) 1x/yr. post-vaccination spring/autumn	Active Risk-based (NSP, SP) 1x/yr. post-vaccination spring/autumn	Passive	Active in 6 southern regions bordering Thrace, tests every 3m. Passive in whole country	Active Risk-based (NSP, SP)	Active	Active, passive Clinical exam. & serosurveillance in high-risk areas	Active Clinical exam. since 2013 Thrace(only): serosurveillance	Active
Vaccination	Yes High-risk areas LR: 2x/yr. SR: 1x/yr.	Yes LR: 2x/yr. spring-autumn SR: 1x/yr. spring/autumn	No	No	Yes (Risk-based since 2017) All susceptible LR& SR in high-risk areas)	No	No	Yes; LR: 2x/yr. spring-autumn. SR: only Thrace, 1x/yr. 21d pre-seasonal pastures	No
LSD	Armenia	Azerbaijan	Belarus	Bulgaria	Georgia	Moldova	Romania	Türkiye	Ukraine
Status	Sporadic	Sporadic	Absent	Absent	Absent	Absent	Absent	Sporadic	Absent
Last outbreak	2016	2014	Never reported	2016	2018	Never reported	Never reported	2021	Never reported
Surveillance	Passive	Passive	Active (clinical examination) Passive	Active: regions bordering Thrace, clinical exam. Passive: whole country	Active, passive	Passive	Passive	Active, passive	Passive
Vaccination (Only LR)	Yes Adult cattle: high-risk zones (borders with neighbouring countries)	Yes	No	Yes 2016: blanket vaccination Last 5 yrs.: vaccination coverage 84% to 98%	Yes Risk-based	No	No	Yes >3m whole country	No
PPR	Armenia	Azerbaijan	Belarus	Bulgaria	Georgia	Moldova	Romania	Türkiye	Ukraine
Status	Absent	Absent	Absent	Absent	Absent	Absent	Absent	Anatolia: Endemic Thrace: PPR-protected area	Absent
Last outbreak	Never reported	Never reported	Never reported	2018	2016	Never reported	Never reported		Never reported
Surveillance (Only SR)	Active Risk-based (ELISA and PCR in 2019/2020 w/ no positive results)	Active ELISA	No programme	Active & risk-based (regions bordering Thrace): samples every 2m; Enhanced in regions w/ PPR in 2018 Passive: whole country	Active	Passive	Active, passive Clinical exam. before & after pasture season	Passive	Passive
Vaccination	No	No	No	No	Yes	No	No	Thrace: No (since March 2021); Anatolia: >3m; unvaccinated adults + all SR in outbreak areas	No

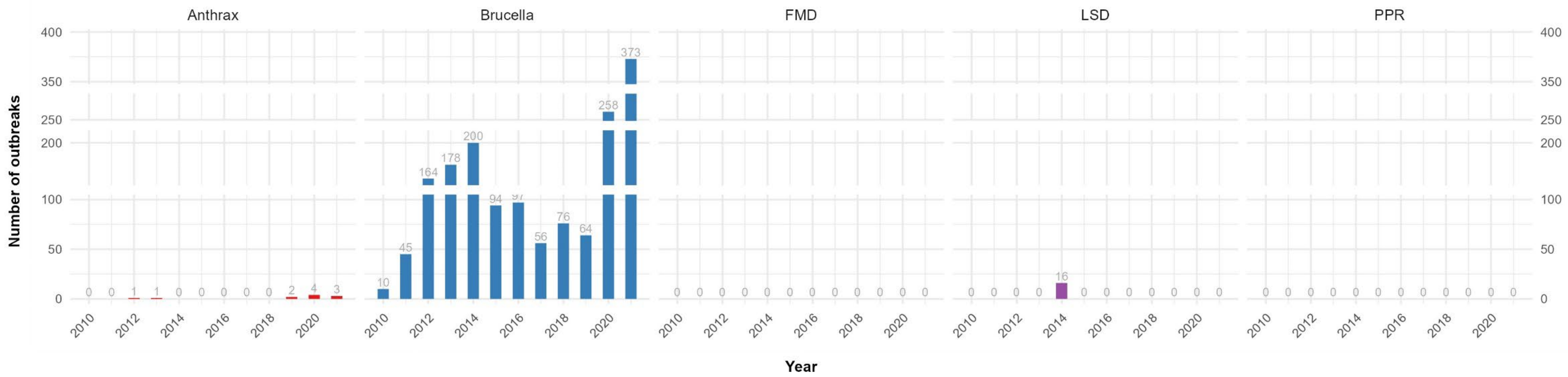
LR: large ruminants, SR: small ruminants, yr.: year; m: month; d: day, BTM: Bulk tank milk. [1]*last reported case affected equine (2019); [2]*last reported case affected swine (2008).

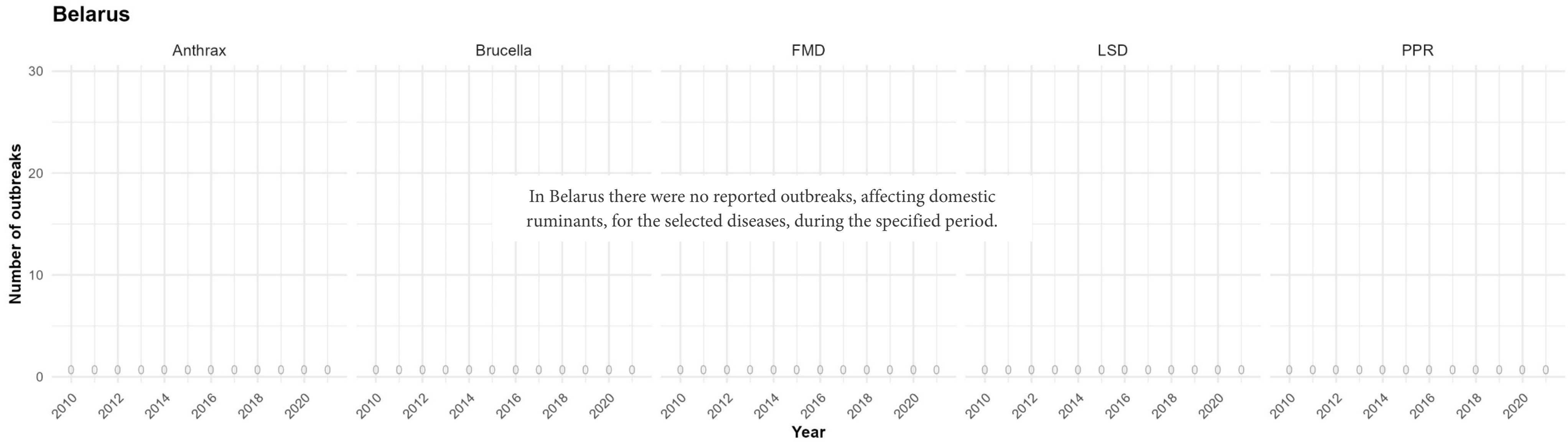
S5: Temporal distribution from 2010 to 2021 of outbreaks in large ruminants (LR) and small ruminants (SR) for the selected diseases by country.

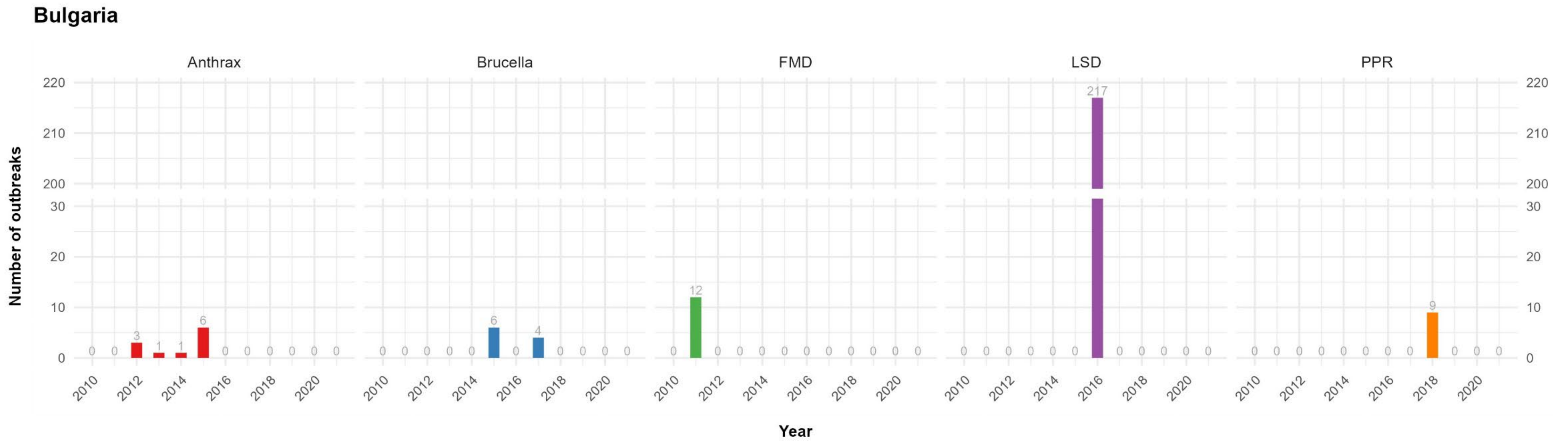
Armenia



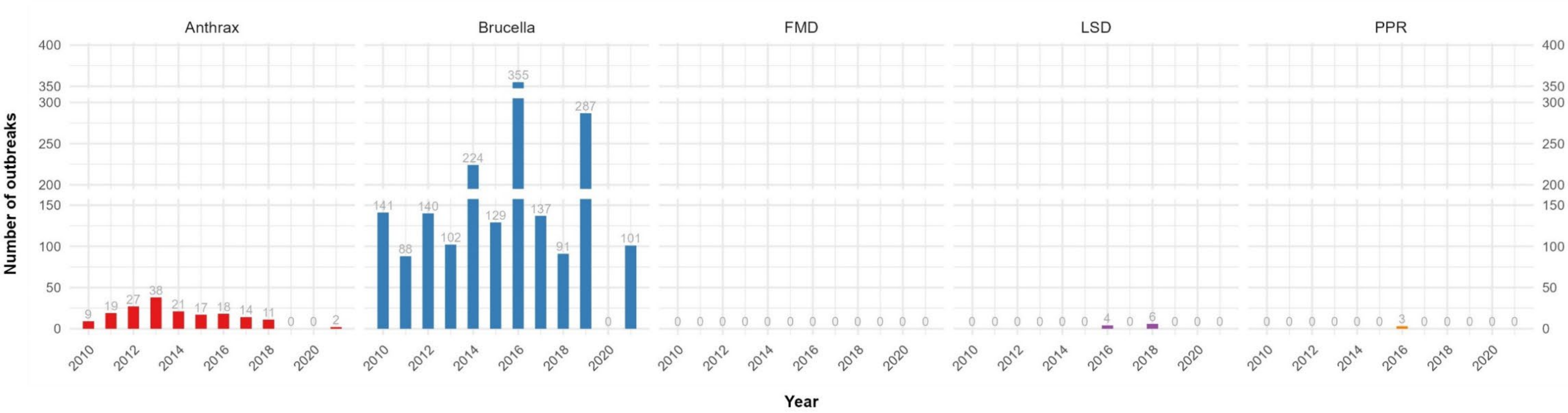
Azerbaijan



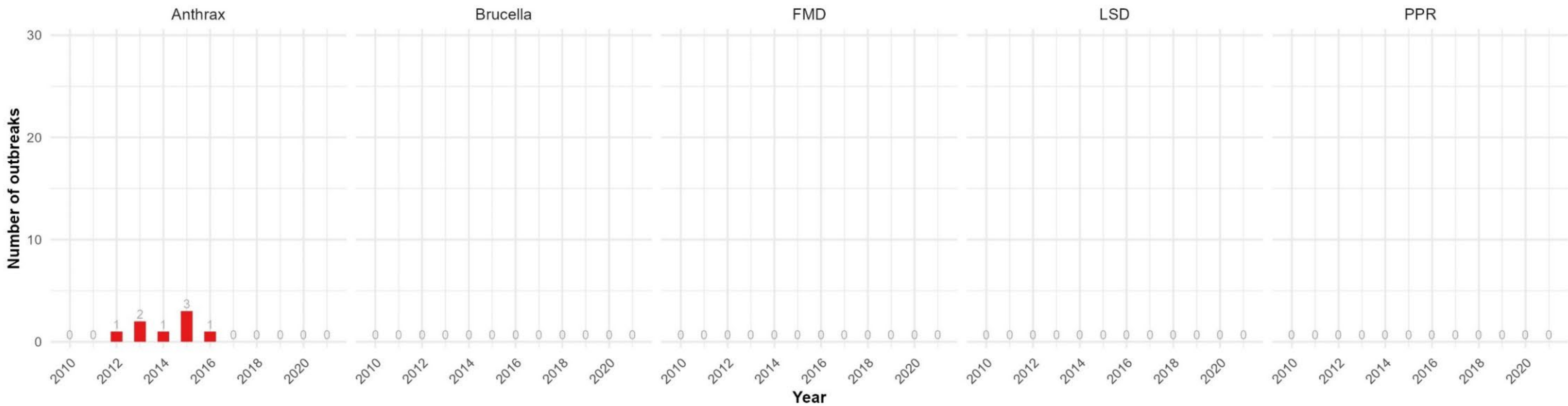

Belarus
Anthrax
Brucella
FMD
LSD
PPR
Number of outbreaks
0
10
20
30
In Belarus there were no reported outbreaks, affecting domestic ruminants, for the selected diseases, during the specified period.
2010
2012
2014
2016
2018
2020
Year

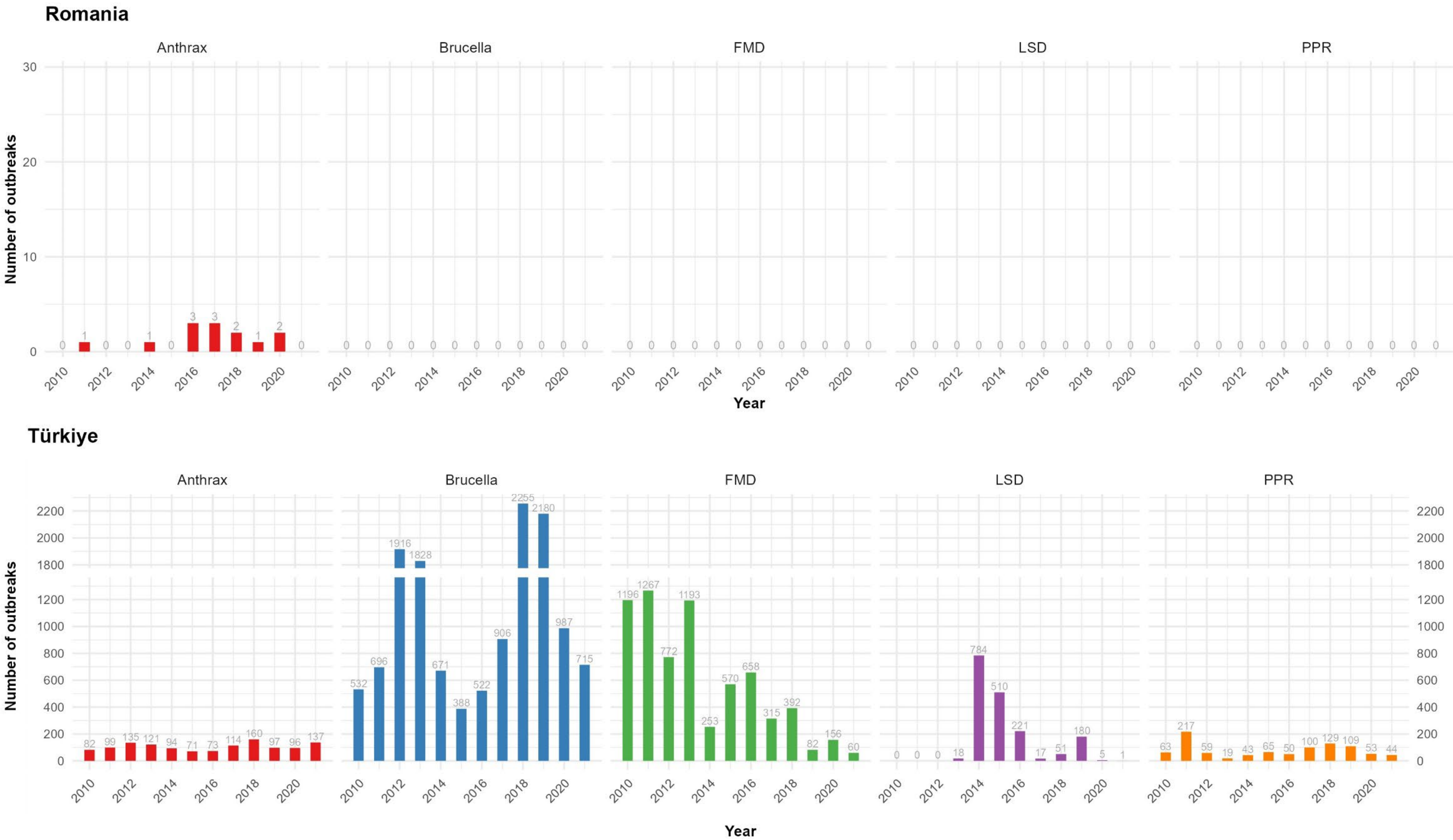

Bulgaria
Anthrax
Brucella
FMD
LSD
PPR
Number of outbreaks
0
10
20
30
200
210
220
3
1
1
6
4
12
217
9
2010
2012
2014
2016
2018
2020
Year

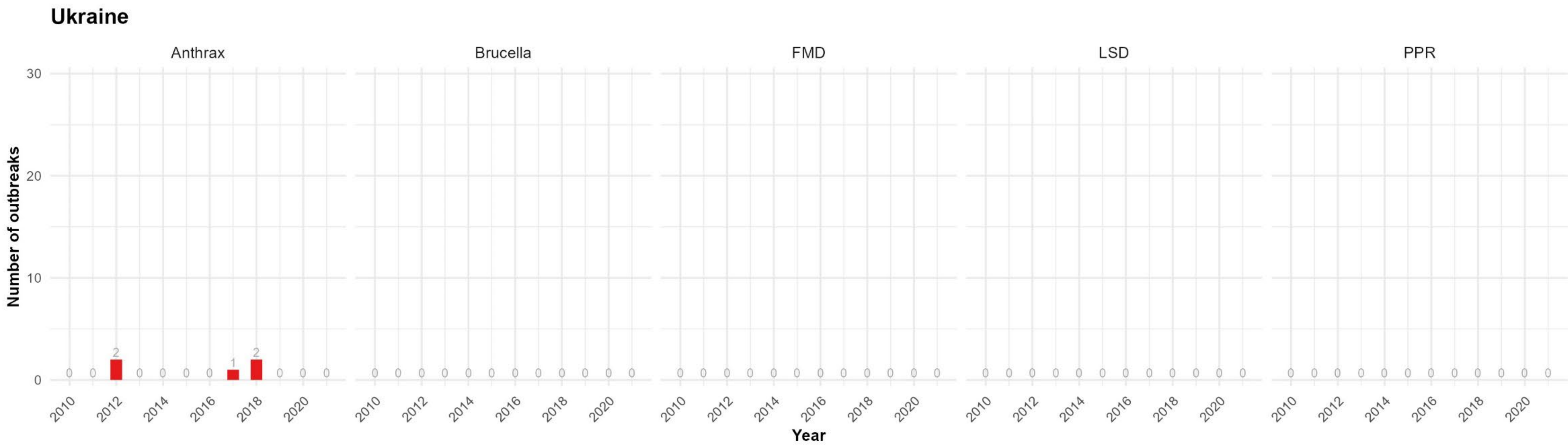
Georgia



Moldova




Romania
Anthrax
Brucella
FMD
LSD
PPR
Number of outbreaks
Year
Türkiye
Anthrax
Brucella
FMD
LSD
PPR
Number of outbreaks
Year


Ukraine
Anthrax
Brucella
FMD
LSD
PPR
Number of outbreaks
Year

S6: Definitions

Farm type classification:

- **Smallholder farms**, interchangeably called family or backyard farms, include a range of producers, from the most impoverished to those that gradually become involved with markets at a local or national level [8]. This term is related to a holding with a smaller size (lower number of animal heads), often characterized by having fewer resources and low productivity, and its main purpose is subsistence or semi-subsistence.
- **Commercial farms** are defined as having a larger scale and a higher number of animals. They are associated with a high investment, for their use of modern technology and wider access to resources, present higher efficiency, and have the main purpose of commercializing final products.

Pastoralism is an extensive livestock production practised in drylands and characterised by seasonal movements and common use of natural resources [9].

- **Nomadism** is based on the flexible seasonal migration of livestock that rarely has a home base.
- **Transhumance** is the regular movement of herd animals between fixed points to utilize pasture and water seasonal availability. It can be vertical when movements are based on ancient routes to mountainous regions; or horizontal, based on opportunistic movements developed over a few years, in disrupted areas due to climatic, political, and/or economic changes.
- **Agropastoralism** is the mixed production of crops and livestock that are grazed close to their village [10].

Disease Status

- **Sporadic disease:** is a disease that occurs infrequently and irregularly in space and time[11,12].
- **Endemic disease:** is the presence of a disease or infectious agent over a long time in a population within a geographical area [11,12].
- **Transboundary animal diseases (TADs),** as the key feature that defines them, are diseases that can spread rapidly between countries and reach epidemic proportions, leading to significant socioeconomic impacts in a region [13,14]. Moreover, effectively managing and controlling these diseases requires constant cooperation between countries [14]. Which justifies constant cooperation between countries for effective disease management and control [14].
- **Zoonoses:** are naturally transmissible diseases between animals and humans [15], that raise additional concerns for public health, in addition to their impact on livestock

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Study 2

Chapter IV

Risk Mapping the peste des petits ruminants spread in the Black Sea basin: A spatial multicriteria decision analysis approach

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4.1 Abstract

Peste des petits ruminants (PPR), a highly contagious viral disease affecting small ruminants (SR), is distributed across Africa, Southeast Asia, and the Middle East. After the successful eradication of rinderpest in 2011, PPR was targeted as the next animal disease for worldwide eradication. Nonetheless, in the past two decades, PPR has spread into countries where it had never been reported. In the Black Sea Basin (BSB), where the SR sector plays a critical role in the subsistence of rural populations and supports national economies, PPR has become endemic in Türkiye and emerged for the first time in Georgia and Bulgaria, raising concerns about its potential spread into the European Union (EU). This study aimed to identify areas in the BSB with high suitability for PPR spread, assuming its incursion, using a Spatial Multicriteria Decision Analysis (GIS-MCDA) approach. We focused on nine countries: Armenia, Azerbaijan, Belarus, Bulgaria, Georgia, Moldova, Romania, Türkiye, and Ukraine. Key risk factors (RFs) for PPR spread, including SR abundance, smallholder farming, seasonal movements of SR, proximity to livestock markets, and proximity to previous outbreaks were identified and weighted through elicitation of opinions from BSB focal points and international PPR experts. Expert elicitation used a pairwise comparison matrix exercise. After consistency assessment, 18 out of 39 responses were used to calculate the RF weights. Georeferenced RF data were then geoprocessed and combined with RF weights through a weighted linear combination (WLC) to generate the final suitability map for PPR spread in the BSB region. High suitability for PPR spread was observed throughout Türkiye (eastern to central Anatolia, interior Anatolia, and near the Armenian border), the Bulgaria-Türkiye (Thrace) border, and southern-central Georgia. The lowest suitability was found in Belarus and Ukraine, western, central, and northern Bulgaria, and across Armenia. The resulting risk map can guide the prioritization of PPR management activities and raise disease awareness in high-suitability areas, supporting the goal of PPR eradication by 2030 and its parallel objective of reducing the impact of other high-priority SR infectious diseases.

Keywords: Peste des petits ruminants, Black Sea basin, Spatial multicriteria decision analysis, GIS-MCDA, disease spread

4.2 Introduction

Peste des petits ruminants (PPR) is a highly contagious disease caused by the PPR virus (PPRV), a *Morbillivirus* of the family *Paramyxoviridae*, which is closely related to rinderpest virus (1–3). PPRV is an enveloped virus with a non-segmented, negative-sense RNA genome (2). It primarily affects domestic small ruminants (SR), namely sheep and goats, but can also infect and cause disease in wildlife species (4). The acute form of the disease is characterized by fever, anorexia, diarrhoea, ocular and nasal discharge, erosions, and ulcers in the digestive mucosae (3). Mortality and morbidity rates vary depending on host-pathogen factors and level of disease endemism but may reach 90% in naïve populations (5,6). Ultimately, PPR threatens the productivity and sustainability of SR production (7), animal health and welfare, and the livelihoods of SR-dependent communities. PPR is distributed across Africa, Southeast Asia, and the Middle East (6,8), where nearly 2.5 billion SRs, accounting for over 80 percent of the global SR population, are kept. Within this vast region, countries classified as “PPR-free” are at a high risk of transboundary PPR spread. As a result, PPR causes an annual global economic impact ranging from USD 1.4 billion and USD 2.1 billion (9).

In 2011, following the global eradication of rinderpest, PPR was identified as the next livestock disease to be eradicated by 2030 through the PPR Global Control and Eradication Strategy (GCES). This initiative is coordinated by the PPR Secretariat, a collaborative effort between the Food and Agriculture Organization (FAO) and the World Organization for Animal Health (WOAH) (9). Nevertheless, over the past two decades, PPR has continued spreading, including into countries where it had never been previously reported. In the Black Sea basin (BSB), the first official report of PPR dates back to 1999 in Türkiye, where it subsequently became endemic (10). In recent years, the disease emerged for the first time in Georgia in 2016 (11) and in Bulgaria in 2018 (12). This region, which spans the border between Asia and Europe, has been recognized as a potential pathway for the introduction of PPR into the European Union (EU) (7,8,13). However, few studies have investigated the PPR distribution pattern, including its potential introduction and spread, in the region (13,14).

The study of spatial patterns of disease risk falls within the purposes of spatial modelling (15), which in turn, has one of the primary objectives to aid decision-makers in developing effective strategies for disease management (16). Spatial disease risk modelling is often data driven. However, these methods are difficult to apply when surveillance coverage is limited or when dealing with disease-free regions. In such cases, knowledge-driven methods, as GIS-based multicriteria decision analysis (GIS-MCDA), are applied. These methods rely on existing knowledge about risk factors (RFs) associated with the disease risk of interest to generate risk maps (15,16). They have previously been used to assess the introduction and spread of PPR in South Africa (17), and East Africa (18), as well as to evaluate other similar transboundary animal diseases (TADs) affecting ruminants, such as foot and mouth disease (19–22) and Rift Valley fever (23,24), in Africa and Asia.

In low- and middle-income countries (LMICs), including some within the BSB, animal disease data are often incomplete or unreliable. These issues can be attributed to underreporting and the limitations of a country's animal health surveillance systems and the underlying structural constraints of the livestock sector. The latter encompasses issues such as a high proportion of unregistered farms and undeveloped national animal identification and traceability systems (NAITSs). The absence or limited operability of such systems hinders the effectiveness of disease surveillance and control programmes, as well as the quality of disease data.

To address the existing gaps in spatial risk of PPR within the BSB, this study aims to identify areas in this region with higher suitability for PPR spread (assuming an initial PPR incursion) using a GIS-MCDA approach. We believe the resulting risk maps can effectively support decision-makers with the implementation of targeted and cost-efficient prevention, control, and surveillance activities while also contributing to raising disease awareness in areas at high risk for PPR spread within the region.

4.3 Material and Methods

GIS-MCDA, thoroughly described elsewhere (16,25), transforms and combines georeferenced data and value judgments (i.e., stakeholders' preferences) to generate information for decision-making (25). In epidemiology, its application aims to map the risk or suitability of disease, assisting decision-makers in the implementation of risk-based disease management strategies (16,26).

This framework consists of the following sequence of steps: 1) definition of the study's objective; 2) identification of factors and constraints associated with the objective; 3) collection of georeferenced data and geoprocessing of each factor; 4) risk factor (RF) weight elicitation and generation of the relative weight for each RF; 5) definition of the relationship between the RF and the outcome and standardization of factor data; 6) combination of the standardized RF layers and relative weights to produce a final weighted estimate of suitability for each cell in the study area; 7) suitability map validation; and 8) uncertainty and sensitivity analysis (15,16).

4.3.1 Definition of the study area and objective

The current paper is a component of the GCP/GLO/074/USA project, which contributes to the broader "Global Framework for the Progressive Control of Transboundary Animal Diseases (GF-TADs)" initiative. This project targets nine countries located around the BSB, namely Armenia, Azerbaijan, Belarus, Bulgaria, Georgia, Moldova, Romania, Türkiye, and Ukraine.

Herein, we aim to identify suitable areas for the spread of PPR in these countries and to evaluate the predictive ability of the resulting suitability map using PPR outbreak data from Türkiye.

4.3.2 Identification of risk factors

The RFs associated with the risk of PPR spread were identified through an extensive literature review and narrowed down by the authors. They were selected according to their relevance for SR production in the study region and the availability of data or proxy data in all participating countries. The final RFs that were considered for the model and their associated hypotheses are detailed in Table 1. Supplementary materials 1 (S1) presents an overview of the SR sector key characteristics for each studied country.

Table 1: Selected risk factors (RFs) and associated hypothesis with the PPR spread.

Risk factor:	**Associated hypothesis**
Small ruminant (SR) abundance	Sheep and goat abundance is associated with a higher risk of PPR spread (18,27–31), as PPR virus transmission is more likely to occur when there is a higher contact rate between susceptible and infected animals and/or their fresh secretions or faeces (7).
Proximity to areas previously affected by PPR outbreaks	Areas previously affected by PPR outbreaks (or outbreaks of similar TADs) have been associated with a higher risk of spread of PPR (or of similar TADs) (22,32). It can be inferred that the proximity to these areas have a combination of conditions that may influence PPR spread, such as low farm biosecurity, certain husbandry or management practices, poorer access to veterinary services, and informal live animal trade, which hinder disease management activities and facilitate the unrestrained introduction of infected animals and further spread of disease.
Proportion of smallholder farming	Smallholding production has been associated with a higher risk of PPR spread (17,33–35). This production type is associated with traditional practices and usually, poorer management which can hamper activities for disease control and prevention. In certain countries, this production type involves communal animal keeping, which results in the intermingling of SR from different herds, and a consequent higher contact rate between animals.
Proximity to live animal markets	These sites have been associated with PPR spread (18,27,36–40), as they gather SR from different herds, regions, or even countries, and facilitate direct contact between them. We hypothesize that farms located closer to a livestock market are more likely to trade animals in these markets, and the surroundings are therefore associated with a higher risk of PPR spread.
Seasonal pastures	Seasonal movements to pastures (33,35,36,39,41–45) have been associated with a heightened risk of PPR spread. This practice facilitates direct contact between animals from different herds, regions, or even neighbouring countries, on shared grazing areas and water points. Or indirect contact with fresh secretions or faeces on pastures, water points, and animal shelters.

4.3.3 Collection of georeferenced data and geoprocessing of RF layers

SR abundance data was sourced in a raster format from the Gridded Livestock of the World (GLW4) (46,47) modified with sheep and goat census data from participating countries and adjusted to FAOSTAT 2020. This raster-based layer was used to create a raster template to rasterize the other RF layers.

All the other georeferenced factor data were provided by one consultant of each participating country and further processed. These RF layers were pre-processed in QGIS in a ETRS89-extended / LCC Europe (EPSG: 3034) projection. They were then imported into Rstudio (48) and rasterized based on the raster template to a common coordinate reference system (World Geodetic System 1984 (WGS_84), at a resolution of 0.0833 by 0.0833 decimal degrees (approximately 10 by 10km).

The RF "proximity to previous outbreaks" was derived from a total of 395 PPR outbreak georeferenced locations (10 from Bulgaria, 1 from Georgia, 384 from Türkiye) reported from 2016 to 2019 to the World Animal Health Information System (WAHIS) of WOAH. The RF "proximity to livestock markets" was based on 324 georeferenced livestock markets located across the BSB. Both RFs were pre-processed in QGIS using the tool "distance to nearest Hub (points)". This function was used to calculate the Euclidean distance from centroids of a 10 by 10km grid with the same extent of the study region to the nearest reference point. This resulted in two vector layers depicting the distance from PPR outbreaks and livestock markets, respectively.

The RF "proportion of smallholder farming" referred to the ratio of SR smallholder farms to the total SR farms for each administrative area. Regarding the RF "seasonal movements", systematic records were not maintained across most countries of the BSB, and as a result, provided data varied in format. These formats comprised text descriptions of animal movements to pastoral sites, images of maps with arrows that indicated the SR origin and the pasture of destination, or quantitative data for movements to pastures at province or herd level. To standardize the seasonal movement data, it was harmonized and assigned to the smallest available administrative area in each country. The resulting RF layer reflects the count of administrative areas of origin that relocated animals to pastures for each respective administrative area.

4.3.4 Risk factor weight elicitation

Opinions were elicited through a pairwise comparison matrix exercise (S2), based on the analytical hierarchy process (AHP) conceived by Saaty (49). To complete the elicitation exercise (EE), we actively recruited individuals with knowledge of the SR sector in the BSB and/or PPR disease dynamics. Participation in the exercise was voluntary. Participants were divided into two expert groups: 1) country experts, comprising academics and veterinary authorities from participating countries; and 2) international PPR experts from academic or research institutes, as well as representatives from the PPR Secretariat, the PPR Global Research and Expertise Network (PPR-GREN), FAO, and WOAH.

The EE was developed using Microsoft Office Excel (2019) and paired with a supplementary document detailing the project's background and instructions for the exercise. Both documents were prepared in English and then translated into Russian, for participants from countries where Russian is widely spoken. The participants were familiarized with the exercise during a regional training workshop focused on risk-based approaches for PPR prevention, control, and eradication. The workshop was organized by the FAO Regional Office for Europe and Central Asia (FAO-REU), the PPR Secretariat, and the Autonomous University of Barcelona (UAB). It was conducted online, over three days (on 31 January, 2, and 4 February 2022), in English with simultaneous interpretation into Russian. Attendees comprised all country experts and some international experts who were sent the EE and supplementary documents during the workshop. Afterward, the same documentation set was emailed to the remaining previously selected experts, mostly constituted by the PPR secretariat's network.

This exercise aimed to determine the relative importance of the five selected RFs for PPR spread in the BSB based on the opinion of each expert. The participants were requested to compare the RFs in pairs by filling in each cell with one value from the sequential key of nine expressions that ranged from "extremely less important" to "extremely more important" (S2).

4.3.5 Generation of risk factor weights

The RF weights attributed by each expert were derived from individual matrices based on a few calculation steps (S3). First, we converted key expressions into the corresponding numerical values (S3). After, the normalized eigenvector was calculated by dividing the nth root product of each row by the sum of these values. The normalized eigenvector of each row gives an approximation of the weight attributed to each factor (25).

Additionally, considering that any human judgment has a degree of inconsistency, and to avoid including matrices filled in at random, we determined the consistency ratio (CR) of each response (50). CR calculations are presented in S3. If the CR value was ≥0.14 (51), the response was found inconsistent, and the matrix was excluded from the study. Otherwise, matrices were kept and used to calculate the average RF weights for all participating experts and the two predefined expert groups.

4.3.6 Standardization of risk factor layers

RF layers were standardized to a common continuous scale between 0 and 1 using fuzzy membership functions (16). The shape (e.g., sigmoidal or linear) and direction (e.g., increasing or decreasing) of the membership function assigned to each RF layer reflects its association to the risk of PPR spread in the region (52). Function thresholds were assigned to minimum and maximum RF raw values or a predefined limiting value. For this study, the membership function for the standardization of each RF was selected based on literature using similar RFs to estimate the spatial risk of PPR spread (18) or other TADs (18,21–23). Standardized RF layers were generated applying the membership function to the range of RF raw values falling within the specified thresholds (16,53). Standardization of rasterized factor layers was computed in Rstudio (48) with a final resolution of 0.0833 by 0.0833 decimal degrees (approximately 10 by 10km).

Table 2: Selected risk factors (RFs), minimum and maximum thresholds, and the membership function applied for the standardization of each RF layer.

Risk Factors	**Minimum value**	**Maximum value**	**Membership function**
Small ruminant abundance	0	Max SR heads/pixel	Increasing linear monotonical
Proximity to PPR outbreaks	0	50 km radius	Sigmoidal Decreasing - between 0 and 50 km, >50km negligible risk
Proportion of smallholder farming	0	1	Increasing linear monotonical
Proximity to live animal market	0	50 km radius	Decreasing linear monotonical - between 0 and 50 km, >50km negligible risk
Seasonal pastures	0	Max number of origins/pixel	Increasing linear monotonical

4.3.7 Combination of the spatial layers and creation of a suitability map

To create the final suitability maps, a weighted linear combination (WLC) (54) (Equation 1) was applied to integrate the standardized RF layers and final average RF weights. The suitability index for PPR spread was conveyed on a continuous scale ranging from 0 (unsuitable) to 1 (totally suitable).

Equation 1

$$Suitability\ index = \sum_{i=1}^{n} w_i \times RF_i, 1 \leq i \leq n$$

n is the number of RFs, w_i the weight and RF_i the pixel value of RF i.

Three suitability maps were generated: one using the average of RF weights from all consistent matrices (CR<0.14), and the other two applying the average of the RF weights attributed within the predefined expert groups, national and international experts.

4.3.8 Validation

The predictive ability of the final suitability map was evaluated for Türkiye, where there using 90 georeferenced points for PPR outbreaks in Türkiye reported in 2020 and 2021. For this purpose, we applied the receiver operating characteristic (ROC) analysis (55) that calculates the area Under the Curve (AUC), with the package *pROC* in RStudio (48). Since no absence data was available from active or field surveillance, pseudoabsence points were randomly generated at the same ratio as outbreak data, under the condition of being located at a minimum of 25 km distance from either an outbreak point or another pseudoabsence.

4.3.9 Sensitivity and uncertainty analysis

Sensitivity analysis was done by applying the one-at-a-time (OAT) method56. In this process, the values of the factor layer (input), are changed one at a time, to evaluate the effect on the change of the suitability index (output). For the proposed framework (57), we set a stepwise change of 1%, with a ±25% range, to the mean weight of each RF. The weights of all the other RFs were adjusted proportionally to ensure the sum of RF weights was 1. This process generated 250 alternative suitability maps for the spread of PPR in the region and these results were presented in a graph depicting the mean of the absolute change rate (MACR) for all 250 simulations. Thus, the original suitability map (with the original RF weights) was compared quantitatively for all pixels to the alternative simulated maps. Thereafter, uncertainty values were derived from the standard deviation of the alternative maps generated through the sensitivity analysis (SA). These values, presented in a map of the region, depict the uncertainty surface associated with the method applied (58).

4.4 Results

A total of 39 EEs were completed and returned by the participants. Of these, 18 EEs were found consistent (CR<0.14), retained, evaluated and assigned to the two predefined expert groups: national and international experts. Frequency for EE responses and those considered consistent are shown in S5. Table 3 presents the RF average, minimum, and maximum weights calculated for the total number of consistent responses within each expert group. Among international experts, the highest weight was attributed to the *proximity to PPR outbreaks*, followed by *small ruminant abundance*, and the least weight to *proximity to live animal markets*. National experts assigned the highest weight to *small ruminant abundance*, followed by *proximity to PPR outbreaks*, with the lowest weight given to the *proportion of smallholder farming*.

Table 3: Factor weights: average, minimum, and maximum weights (indicated in square brackets) attributed by all experts, and per expert group.

Risk Factor	Weight		
	Total (n=18)	International experts (n=8)	National experts (n=10)
Small ruminant abundance	0.307 [0.084, 0.526]	0.232 [0.084, 0.483]	0.367 [0.093, 0.526]
Proximity to PPR outbreaks	0.287 [0.027, 0.616]	0.300 [0.033, 0.616]	0.277 [0.027, 0.454]
Proximity to live animal market(s)	0.127 [0.034, 0.279]	0.120 [0.034, 0.277]	0.133 [0.042, 0.279]
Proportion of smallholder farming	0.140 [0.037, 0. 496]	0.183 [0.037, 0.497]	0.105 [0.037, 0.176]
Seasonal pastures	0.138 [0.024, 0.564]	0.163 [0.024, 0.564]	0.118 [0.028, 0.400]

The resulting standardized RF layers are presented in S4. The final suitability map for PPR spread in the BSB generated through the GIS-MCDA (Figure 1) used the mean RF weights of the total 18 EE consistent responses. The suitability index (SI) is displayed by a graduated scale, for which low and high values indicate, respectively, low and high suitability for PPR spread. We classify blue and green areas (below 0.3 SI) as having low suitability, yellow and light orange areas (between 0.3 and 0.5 SI) as having medium suitability, and darker orange and red areas (above 0.5 SI) as having high suitability for PPR spread. Suitability of PPR spread created with RF weights within each expert group is presented in S6.

We observe high suitability for PPR spread throughout Türkiye (eastern to centre Anatolia, interior western Anatolia, and close to the Armenian border), on the border of Bulgaria with Türkiye (Thrace), and in southern-central Georgia. The lowest suitability was observed in Belarus and Ukraine, across west, centre, and northern Bulgaria, and across Armenia.

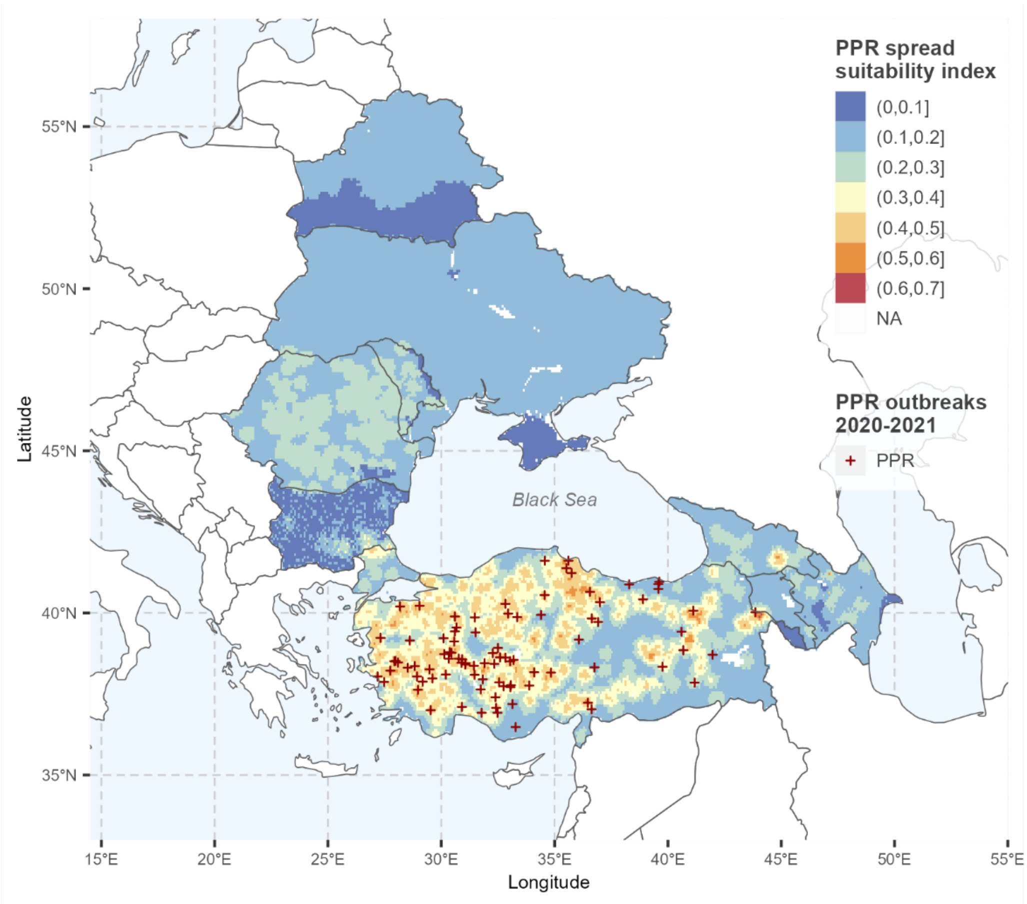

Figure 1: Suitability map for the spread of peste des petits ruminants (PPR) in small ruminants (SR) and location of PPR outbreaks reported between 2020 and 2021 in the Black Sea Basin (BSB). Maps were generated using Rstudio (48).

4.4.1 Validation

Validation was performed using PPR outbreak data from Türkiye reported in 2020 and 2021, noting that the georeferenced outbreaks for the suitability map RF 'Proximity to PPR outbreaks' were from 2016-2019. The ROC AUC associated with the suitability map for the PPR spread demonstrated the capacity of the model to distinguish "presence" from “pseudoabsence” with good predictive accuracy (AUC=74.2%; 95% CI [66.9% - 81.5%]). ROC curves for the three suitability maps are presented in S7.

4.4.2 Sensitivity and uncertainty analysis

The global sensitivity analysis depicted the MACRs for each factor, for which higher absolute values have a positive correlation with its sensitivity. The graph shows that *proportion of smallholder farms* had the highest RF sensitivity, followed by *small ruminant abundance*, *distance to previous PPR outbreaks*, *seasonal movements*, and finally, *distance to markets* (S8).

The uncertainty map, illustrated in Figure 2, based on 250 maps with adjusted weights, shows a maximum standard deviation value of less than 0.025. This value indicates that the predictive ability of the risk map was stable when RF weights changed. This map also features spatial heterogeneity, with higher uncertainty corresponding to high suitability areas of PPR spread.

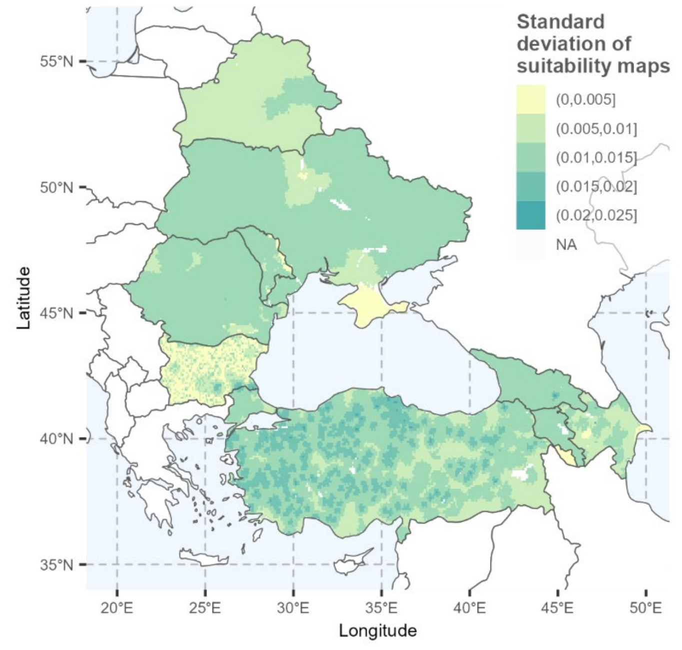

Figure 2: Uncertainty map. The map shows the standard deviation of the suitability maps for peste des petits ruminants (PPR) spread in small ruminants (SR) in the Black Sea Basin (BSB). Maps were generated using RStudio (48).

4.5 Discussion

In this paper, we evaluate the spatial suitability for the spread of PPR in the BSB using a knowledge-driven approach. While in the BSB, PPR was endemic only in Türkiye, there is a risk of its incursion and spread into other countries of the region. Recent outbreaks in Georgia and Bulgaria have highlighted this threat and underscored concerns about its reintroduction into the EU.

Our findings show that suitability for PPR spread is consistent with known PPR distribution in the BSB. High suitability is observed in Türkiye, where PPR is endemic, and in central Georgia (11) and southeast Bulgaria (12), where PPR outbreaks occurred in 2016 and 2018. These regions implemented effective control measures, including epidemiological investigations, stamping out, delimitation of protection zones, and in Georgia, vaccination of all susceptible animals. As a result, swift and effective PPR control was achieved. Additionally, risk-based surveillance activities, awareness campaigns, and yearly vaccination of young unvaccinated SRs in Georgia continued into 2022 (13), demonstrating close PPR monitoring in these areas. Conversely, the PPR spread suitability index was lowest in Belarus and Ukraine, where SR abundance was low and the SR sector had less socioeconomic importance. In these countries, livestock markets were not used for SR trade, and grazing pastures were located near the farms. As a result, the respective RFs had a negligible contribution to the final suitability map in these areas.

Among the selected RFs, "SR abundance" and "proximity to previous outbreaks" were top-ranked by both national and international experts. However, the importance of these RFs differed between the groups. National experts attributed greater importance to "SR abundance", while international experts considered "proximity to past outbreaks" as the most influential factor for PPR spread. This finding aligns with a similar study on the introduction and spread of foot and mouth disease, another TAD affecting ruminants, where expert opinions also differed based on professional backgrounds. In that study, academic professionals prioritized the distance from previous outbreaks, whereas professionals in national veterinary services prioritised animal density (21).

While the top two highest-weighted RFs were created using uniform, high-resolution data from across the study region, providing robustness to the final suitability map, it is important to acknowledge that other RFs had to be derived from a combination of data from various sources, each with varying levels of quality. Malczewski (60) advises against this practice, stating that criteria should be measurable and complete, covering all relevant aspects of the decision problem. However, regions typically studied using GIS-MCDA for animal health, as discussed by Clements *et al.* (23), often include LMICs where thorough data on the most influential RFs for disease transmission is unavailable. Consequently, we relied on the limited data sources available and used proxies to illustrate some of these recognized RFs.

The RFs “seasonal movements” and “proportion of smallholders” were generated using data with varying resolutions between countries, due to data privacy concerns and inadequate data recording. The absence or recent implementation of NAITSs in Armenia, Azerbaijan, and Georgia (61–63) during data collection, raises concerns about the quality of previously available SR demographic data, which was likely affected by informal and unstandardized recording methods. In Türkiye, despite SR data being registered in TURKVET (the Turkish NAITS) since 2010 (64), detailed data on each farm’s production purpose and head counts per farm were unavailable. Consequently, the proportion of smallholders was assumed to be consistent nationwide based on input from Turkish peers, likely affecting its accuracy. The RF "seasonal movements" was derived from data with a wide range of formats and resolution levels, including quantitative information, reference maps, and narrative text, which also likely impacted its accuracy.

Furthermore, in cases where direct measurements for specific RFs were unavailable, we used data proxies. SR movement data, previously linked to long-distance spread of infectious diseases like PPR (65), was unavailable or not systematically recorded in most BSB countries. To address this gap, we used “proximity to livestock markets” and “seasonal movements” as proxies, like in other studies (17,18). These proxies only partially illustrate the SR movements network but support the idea that the risk of PPR spread increases in areas where SRs from different origins move to and mingle. However, a complete representation of national SR movements ideally requires systematically recorded data or a comprehensive study of the live SR movement network (18). As data quality for indirect RFs, or the recording of direct RFs becomes available, especially with the implementation of NAITSs in three countries of the region, suitability maps can be updated accordingly.

Knowledge-driven risk maps must be interpreted with an understanding of the underlying subjective nature of the methodology (15,60), including in its elicitation step. The pairwise comparison matrix is widely used as an opinion elicitation tool due to its straightforward implementation and ease of interpretation by both modelers and decision-makers (66). This approach derives priorities based on pairwise comparisons of criteria. As with any human judgment, it allows for a degree of inconsistency or randomness by the respondents, caused by lack of information or concentration, clerical issues, or issues intrinsic to the topic (67,68). In this study, we addressed this issue by calculating the matrices CR and excluding those that were inconsistent. In this instance, we considered that "allowing for some inconsistency is reasonable" (67) and the CR was set to below 0.14 (instead of 0.1). Nevertheless, we believe we largely reduced the degree of randomness of our responses.

We obtained 18 consistent responses to the EE. While there is no core guideline stipulating a minimum number of experts, our number of consistent responses aligns with (69) or surpasses most studies using GIS-MCDA within this field (17,23,68). This provides robustness to our derived weights. Our EE was conducted during a BSB regional training for PPR management (detailed in the methods section), engaging numerous country experts. Moreover, the involvement of the PPR Global Secretariat in disseminating the EE through their PPR international expert network, linked with the PPR GCES, provided access to a wider network of PPR international experts.

Our expert opinion elicitation, based on individual responses to the EE, enabled us to evaluate each response for its consistency and compare the RF weights derived from consistent responses across different expert groups. Alternatives to this approach include nominal group techniques, brainstorming groups, focus groups, and Delphi techniques (70,71), in which respondents reach a consensus (72). Future research could explore these alternative methods by comparing our approach with a consensus-based method, applying it to individual countries or groups of countries with similar characteristics to obtain region-specific RF weights.

Moreover, we compared RF prioritization between the two main expert groups (e.g.: national and international experts). Expert opinions on the selected RFs are influenced, as previously referred, by their professional backgrounds, and may also be influenced by their country of origin. Our study area comprises countries with significant socio-economic differences, SR demographics and production focus, and disease management capacity. As a result, expert opinions are likely influenced by regional prevailing ideas or the epidemiological disease status in each country or neighbouring countries. As suggested by Paul *et al.* (68), future research should explore the impact of experts' backgrounds on their opinions, given there is a sufficient number of experts to support meaningful statistical analysis.

Finally, in this study, we successfully validated the suitability map using outbreak data from Türkiye, a critical step often omitted due to the unavailability of georeferenced outbreak data. Its predictive power was 74.2%, 95% CI [66.9% - 81.5%], which is considered acceptable (73). However, we acknowledge that the validation results are mostly applicable to Türkiye and that the extrapolation of this result to other countries should be interpreted with caution. Additionally, the predictive ability might have been influenced by one of the highest weighted RFs, "proximity to previous outbreaks", derived from data spanning 2016 to 2019 when PPR outbreak notifications peaked in Türkiye. These outbreaks prompted the implementation of various control measures (74), which coupled with the PPR lifelong immunity developed in PPR-surviving and vaccinated animals, along with herd renewal rates of SR (18), is likely to have contributed to a decrease in PPR incidence in the following years. In fact, PPR notifications decreased by approximately half in 2020 and 2021. This period also coincided with the implementation of extraordinary measures linked with the cessation of PPR vaccination in Thrace. These measures included intensified national surveillance and control activities and tighter restrictions on SR movements from Anatolia to Thrace. These activities were carried out in Thrace due to the acknowledged threat of PPR reintroduction into the EU (8) to reach PPR zonal freedom in 2023 (13,74) by the WOAH.

4.6 Conclusion

The resulting risk map for PPR spread provides valuable insights for national authorities to strategically target their interventions to areas with high suitability for PPR spread. These risk-based interventions may involve strengthening passive or active surveillance for early detection. Additionally, training and awareness activities could be directed toward various stakeholders within the SR value chain, such as field veterinarians, SR farmers, middlemen, and individuals working at livestock markets and abattoirs. These programmes aim to improve both internal and external biosecurity and stress the importance of timely disease reporting.

In future work, this approach could be easily adapted to map the risk of PPR spread in BSB neighbouring countries and could further inform the risk for other SR infectious TADs, due to shared RFs. This aligns with the objective of the PPR GCES to reduce the impact of other high-priority SR infectious diseases.

Towards the deadline of PPR eradication by 2030, it will be critical that countries that have never reported PPR or are officially recognised as PPR-free by WOAH maintain vigilance and have robust contingency plans in place so that gains are not lost and PPR does not re-emerge. Risk mapping, including the approach used in this study, conducted both at national and regional levels, is a key tool to support this aim.

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Conflict of interest

The authors declare no conflict of interest. The views expressed in this information product are those of the authors and do not necessarily reflect the views or policies of the Food and Agriculture Organization of the United Nations.

Figure descriptions:

Figure 1: Suitability map for the spread of peste des petits ruminants (PPR) in small ruminants (SR) and location of PPR outbreaks reported between 2020 and 2021 in the Black Sea Basin (BSB). Maps were generated using RStudio (48).

Figure 2: Uncertainty map. The map shows the standard deviation of the suitability maps for peste des petits ruminants (PPR) spread in small ruminants (SR) in the Black Sea Basin (BSB). Maps were generated using RStudio (48).

Supplementary Materials

S1: Key characteristics of the small ruminant (SR) sector in the study countries.

S2: Pairwise comparison matrix exercise.

S3: Risk factor weight calculation steps.

S4: Maps of standardized risk factor layers.

S5: Number of Responses to the elicitation exercise (EE) and associated consistency ratio (CR).

S6: Suitability maps for PPR spread in the BSB by expert group.

S7: ROC curves for the validation of the PPR spread suitability maps.

S8: Global sensitivity analysis of the PPR spread suitability map.

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4.8 Supplementary Materials

S1: Key characteristics of the small ruminant (SR) sector in the study countries.

Country	Human Population (M)	GDP/ capita 2020 (US$)	Agriculture to GDP (%) (2015-2020)	Livestock production for agricultural GDP (%)	Employment in agriculture (%)	SR population (2021)		Production types		National Animal identification and traceability system (NAITSs) (Ruminant ID/ Farm ID)	Seasonal movements	Markets	Notes
						Heads (M)	% SR in region	Smallholder farms	Commercial farms				
Armenia	2.963	4.623	17,2-**11,7**	32%	42%	**690** (0.23 hds/ capita)	0,9%	95%	5%	Under development/ implementation	SR are sent to pastures during spring-summer and are kept in stables during autumn-winter.	Farmers sell their products almost exclusively through two channels: directly to consumers or to traders and trading companies. Therefore, livestock markets do not play a significant role in the SR trade.	The livestock sector contributes to food security countrywide and provides animal draught power and animal manure as fuel and fertilizer.
Azerbaijan	10.110	4.806	6,1-**6,9**	> 50%	37%	**8.189** (0.81 hds/ capita)	10,2%	82%	18%	Under development/ implementation	SR are grazed all summer on mountain pastures and pastures closer to the holdings in winter.	Markets are located on the outskirts of towns and cities where SR are present in large numbers. Typically, these markets have large open spaces without fences, sheds, drinking water, or feed containers. They are often organized by private entities without mandatory legal control procedures.	Nationwide, sheep and, to a lesser extent, goats play an important role in the rural families' economy.
Georgia	3.714	4.698	7,8-**7,3**	50%	38%	**685** (0.18 hds/ capita)	0,9%	95%	5%	Under development/ implementation	SR flocks are kept in lowlands in Autumn-Winter and mountains in spring-summer.	Live animal markets are officially registered and animals from different species are traded on each market open day. There is no official registration of animal movements in markets.	41% of the population lives in rural areas where agriculture activities are the major source of their subsistence or semi-subsistence.
Belarus	9.399	6.839	6,2-**6,8**	-	11%	**148** (0.015 hds/ capita)	0,2%	91%	9%	Yes	No	Live SR are not traded in livestock markets. However, legal acts regulate potential animal trade, requiring compliance with biosecurity measures such as quarantine and diagnostic tests.	SR production is not socio-economically important in the country.
Bulgaria	6.927	9.828	4,0-**3,4**	26%	11%	**2.015** (0.29 hds/ capita)	2,5%	76%	24%	Yes	SR graze in pastures from March to November and are kept indoors or in nearby fields	Eight registered live animal markets in the country are authorized to trade SR, complying with national regulations. These markets have veterinary supervision and movement certification. However,	SR production is concentrated in the Southern regions bordering Türkiye (Thrace). Sheep farming is a traditional practice with

											during winter. Movements are recorded in a national system.	they do not play a substantial role in the country's animal trade.	critical importance for the subsistence of rural communities and the development of rural areas.
Moldova	2.618	4.494	11,5-**9,5**	12%	27%	**845** (0.32 hds/capita)	1,1%	87%	13%	Yes	Yes	Animal markets are regulated by legal acts that regulate conditions relating to animal trade, transport, and their use for advertising purposes, in shows, exhibitions, competitions, and similar events.	Sheep and goat rearing focuses on milk production. Goats provide milk and cheese for families, while sheep milk is used for cheese that is consumed by the family or sold in markets.
Romania	19.286	12.890	4,1-**3,8**	26%	21%	**12.541** (0.65 hds/capita)	15,6%	96%	4%	Yes	Yes	Since Romania joined the EU in 2007, EU legislation on live animal movements and traceability applies to the animal trade in livestock markets in the country.	The top 5 EU countries exporting live sheep and goats are Greece, Italy, Bulgaria, France, and Spain. Their main destinations are the Middle East, Greece, Italy, and Bulgaria. In 2019, exported more than 20% of its livestock.
Türkiye	84.339	9.127	6,8-**6,6**	25%	18%	**54.113** (0.64 hds/capita)	67,3%	93%	7%	Yes	Yes	Livestock markets and the trade of SR are regulated by official legal acts, to control the sanitary status of the animals traded. The information is registered and centralized under the national monitoring and reporting system (TURKVET).	Cattle, goats, and sheep fulfil multiple roles in generating income and ensuring food security as well as generating employment and limiting rural depopulation.
Ukraine	44.135	3.663	12,0-**9,2**	-	14%	**1.144** (0.026 hds/capita)	1,4%	87%	13%	Yes	No	Live animal markets and fairs are used for the trade of other species (poultry, rabbits, and swine). However, ruminants are not involved in this trading chain.	In 2019, rural households were responsible for the production of 86% of sheep and goat meat, 72.3% of beef and veal, and 71.8% of milk in the country.

GDP: Gross domestic product; hds: number of heads; M: thousand.

S2: Pairwise comparison matrix exercise

The pairwise comparison matrix of the analytical hierarchy process (AHP) for risk factors (RFs) associated with the spread of peste des petits ruminants (PPR) is shown below. This table illustrates the elicitation exercise (EE) created in Excel and sent to experts. The EE aimed to compare the relative importance of each pair of RFs, from the row RF to the column RF, as illustrated by the arrows. To do this, selected experts completed each cell indicating "Select a key value" with one value from the key table shown below.

KEY

Less important				Equivalent				**More important**
Extremely	Very strongly	Strongly	Moderately		Moderately	Strongly	Very strongly	Extremely
$^1/_9$	$^1/_7$	$^1/_5$	$^1/_3$	1	3	5	7	9

Elicitation Exercise

Column RF / Row RF	**Sheep and goat density**	**Proximity to areas previously affected by PPR**	**Smallholder farming**	**Proximity to markets**	**Seasonal pastures**
Sheep and goat density		Select a key value	Select a key value	Select a key value	Select a key value
Proximity to areas previously affected by PPR			Select a key value	Select a key value	Select a key value
Smallholder farming				Select a key value	Select a key value
Proximity to markets					Select a key value
Seasonal pastures					

S3: Risk factor (RF) weight calculation steps

RF weights for each completed matrix were calculated based on analytical hierarchy process (AHP) calculation steps, adapted by Coyle, G.[1].

Having a pairwise comparison matrix with n number of criteria (4) and hypothetical attributed values. We calculated 1) the n^{th} root for the product of each row; and 2) the normalized eigenvector: the quotient of the value calculated in 1) by their total.

For a specific matrix, the normalized eigenvector is the weight attributed to each criterion.

	A	B	C	D	n^{th} root of the product of row values	Eigenvector
A	1	1/3	1/9	1/5	0.293	0.058
B	3	1	1	1	1.316	0.262
C	9	1	1	3	2.279	0.454
D	5	1	1/3	1	1.136	0.226
Total					5.024	1

Then, we calculated the Consistency Index (CI) and Consistency Ratio (CR) to assess the consistency of each matrix.

- To achieve this, the lambda max (λmax) is calculated for each row, in two steps. First, we calculate the sum of products of the eigenvector and attributed value for each column and row, respectively (e.g.: Lambda max of 1st row, 1*0.058+1/3*0.262+1/9*0.454+1/5*0.226 = 0.240), which should be larger than ***n***. Second, we calculate the lambda max value by dividing the vector calculated previously by the eigenvector.
- The CI is calculated by:

$$CI = \frac{\lambda max - n}{n - 1}$$

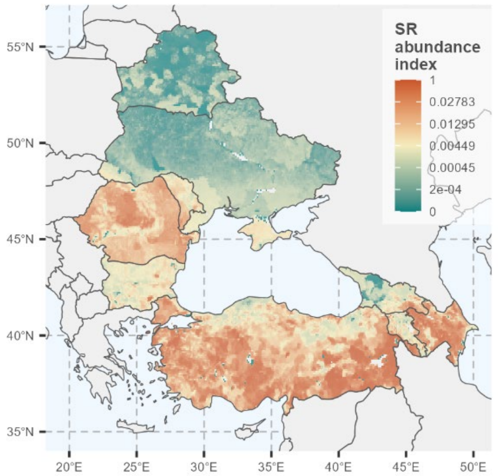
- The CR is calculated by the CI, using a random index based on the ***n*** and the values of CI of matrices filled in at random, from the following table.

	Matrix size (number of criteria)							
n	1	2	3	4	5	6	7	8
RI	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

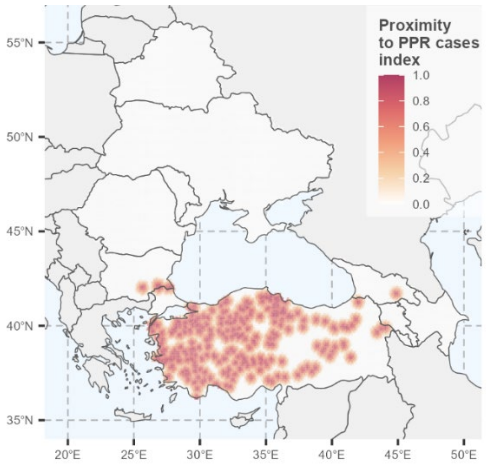
$$CR = \frac{CI}{RI}$$

S4: Standardized spatial peste des petits ruminants (PPR) suitability indices for each risk factor (RF) in the Black Sea basin

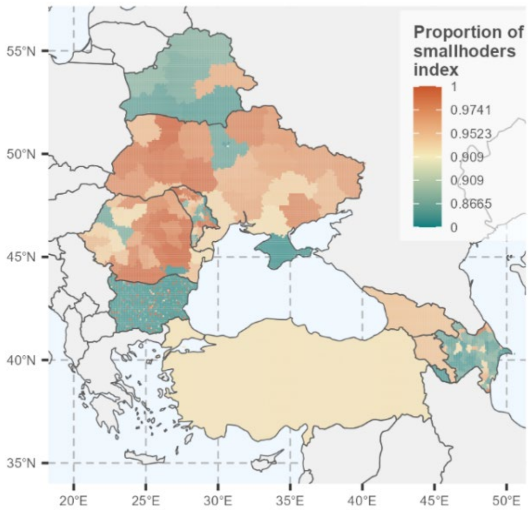
Small ruminant abundance



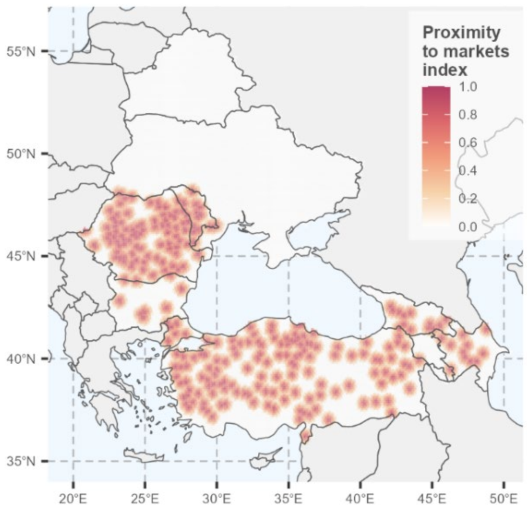
Proximity to previous PPR cases



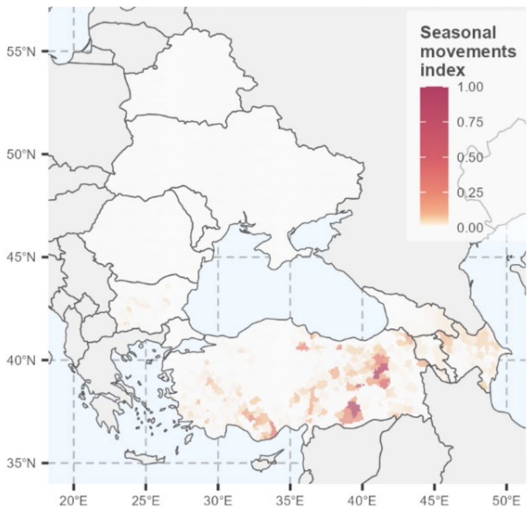
Proportion of smallholders



Proximity to livestock markets

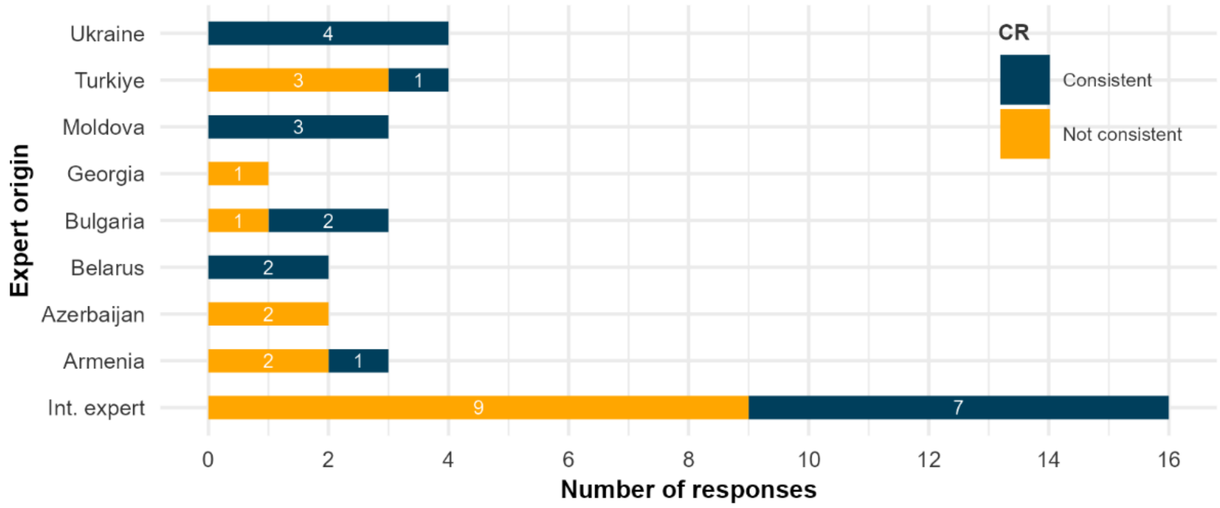


Seasonal Movements



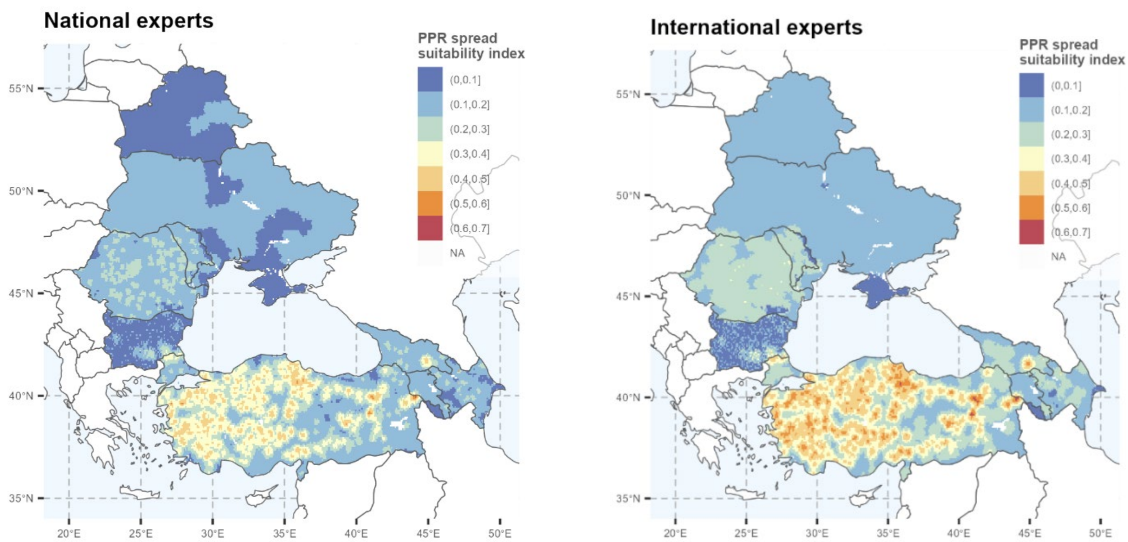
S5: Responses to the elicitation exercise (EE)

This bar chart presents the number of responses obtained to the EE for each country of origin (within the BSB) and for the group of international experts. Moreover, it illustrates for each of these, the number of consistent (CR<0.14) and inconsistent (CR≥0.14) responses.



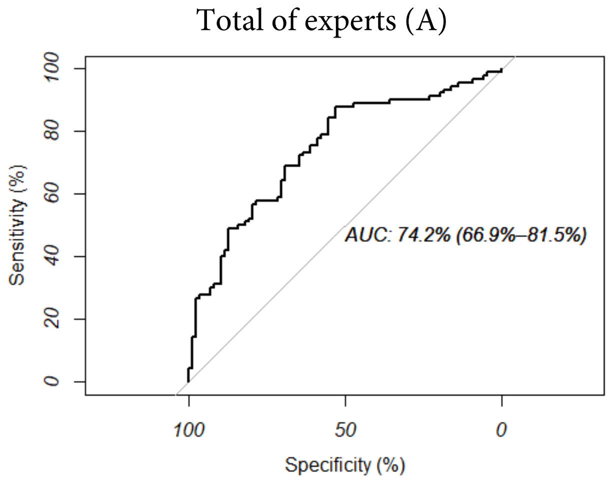
S6: Suitability maps for peste des petits ruminants (PPR) spread in the Black Sea basin (BSB) by expert group

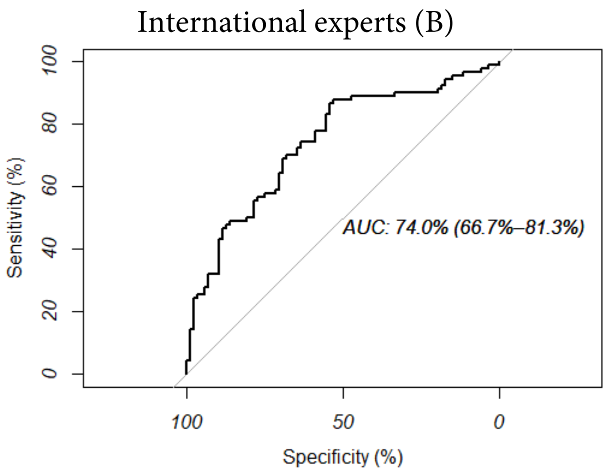
The maps below illustrate the suitability maps for the spread of PPR in the BSB generated with the mean RF weights attributed by each expert group (national and international experts).

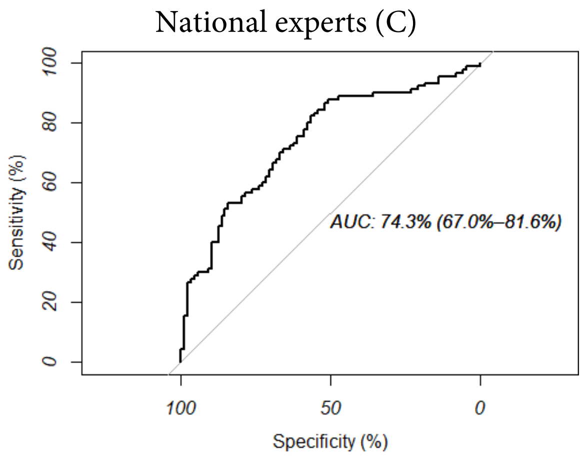


S7: The receiver operating characteristic (ROC) curve for the validation of suitability maps.

The graphs below present the ROC curves for the validation of suitability maps for peste des petits ruminants (PPR) spread based on the mean risk factor (RF) weights from all experts (A), international experts (B) and national experts (C). The validation was conducted using PPR outbreak locations from Türkiye notified between 2020 and 2021, along with generated pseudoabsences.

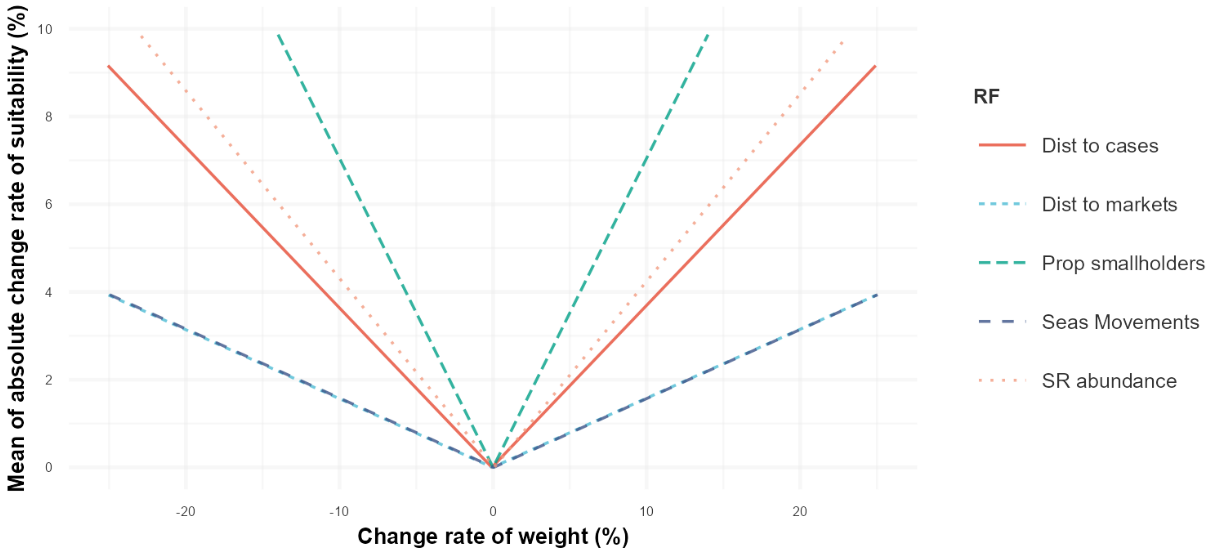






S8: Global sensitivity analysis of the PPR spread suitability map

The graph below shows the mean of absolute change rate (MACRs) for the suitability map of peste des petits ruminants (PPR) spread generated with mean risk factor (RF) weights from all experts. It depicts the MACR of the suitability for each RF (proportion of smallholder farms, small ruminant abundance, proximity to previous PPR outbreaks, seasonal movements, and proximity to livestock markets) change rate in a range of -25% to +25 %. Each coloured line reflects how the suitability for PPR spread changes in response to weight changes in the respective RF.



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Study 3

Chapter V

Suitability of Anthrax (Bacillus anthracis) in the Black Sea Basin through the scope of distribution modelling

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5.1 Abstract

The Black Sea basin has a strategic geographical location bridging Asia and Europe and depends on traditional livestock practices. Anthrax, a zoonotic bacterial disease caused by *Bacillus anthracis*, poses a significant global threat impacting public health, food security, pastoralist communities, and national economies. The disease is endemic or sporadic in the Black Sea basin, however, the study of its distribution has seldom been addressed, despite its burden and the presence of historical *B. anthracis* burial sites in the region. The viability of *B. anthracis* in a particular region is going to be influenced by multiple environmental factors, such as soil composition, climate, vegetation, and host abundance. To characterize the potential distribution of *B. anthracis* in the Black Sea basin, and therefore, the potential for anthrax outbreaks, we applied an ecological niche modelling framework using the Maxent algorithm, analyzing multiple variable combinations, and proposing a novel approach for interpreting in-risk anthrax areas. Our findings underscored the importance of host abundance to the anthrax dynamics in the region. We identified anthrax-suitable areas spanning central and eastern Türkiye, Armenia, southern Georgia, southern Russia, Bulgaria, southern and eastern Romania, Hungary, Moldova, and southern Ukraine, which align with findings from previous global and regional studies on the potential suitability of anthrax. The insights gained from our research might facilitate the development of targeted interventions and policies to mitigate the spread of this disease in pastoralist communities in the Black Sea basin.

5.2 Introduction

Anthrax, a zoonotic bacterial disease, is caused by *Bacillus anthracis*, a spore-forming, Gram-positive, and rod-shaped bacterium [1]. While wild and domestic ungulates are the primary hosts of *B. anthracis*, it can also affect other mammals, including humans [2,3]. Ruminants are typically infected through environmental exposure by ingesting the pathogen's spores when grazing or browsing. In humans, the most common route of transmission occurs through occupational exposure to infected animal carcasses or animal products [1].

Anthrax is present in all continents, causing high yearly mortality in domestic livestock and wild animals, along with high morbidity in humans. As a result, this disease threatens worldwide public health, food security, the livelihoods of pastoralist communities, and national economies [1]. *B. anthracis* is endemic in areas of Sub-Saharan Africa, central and southwestern Asia, Central and South America, and limited regions within the United States (US). In Europe, the disease is sporadic in animals, with a higher prevalence in southern Europe, and linked to historical foci in northern areas [2]. Across the Black Sea basin, as of 2023, anthrax remained endemic in Türkiye, Azerbaijan, Georgia, and Moldova, and it was reported sporadically in Bulgaria, Romania, Ukraine, Belarus [4], and the Russian Federation [5]. Even in endemic countries, surveillance systems for anthrax are limited, contributing to underreporting and gaps in understanding its geographic extent [6]. More importantly, organic matter, calcium richness, and a neutral to alkaline pH, characteristic of black steppe soils found in central Europe, are favourable for the viability of *B. anthracis* spores in the environment [7,8]. As the environmental availability of spores is a hallmark of *B. anthracis* exposure to hosts, characterizing its ecological niche has been proposed as a way to understand its distribution [9]. The concept of the ecological niche was first introduced by Grinnell [10] as a "limited range of ecological variables that could maintain a population without immigration" exclusive to a single species. This concept was later developed by Hutchinson [11] as a quantifiable ecological area that determines species fitness and survivorship [12]. By studying the *B. anthracis* ecological niche, we aim to describe the environmental patterns that support anthrax spores' survival which eventually leads to hosts' exposure in the Black Sea basin [7,13].

Traditional ecological niche modelling (ENM) relies on abiotic predictors (e.g., climate) to characterize a species distribution and considers biotic interactions (e.g., host dynamics) to have negligent effects in modelling, a hypothesis called the Eltonian noise effect [14]. However, there is growing evidence that its inclusion can be crucial to describe broad-scale species distributions, especially when modelling a disease system [15]. In this study, we explored ecological niche modelling approaches based on various combinations of predictor variables, incorporating only abiotic (climate, soil, and vegetation) or introducing a biotic predictor (ruminant abundance) to assess whether the inclusion of ruminant abundance improved model performance. Additionally, we proposed a novel approach to visualize and interpret Maxent algorithm outputs by leveraging uncertainty levels to further refine the output. This allows us to suggest high-risk areas of potential *B. anthracis* outbreaks in the Black Sea basin with higher accuracy, which can guide decision-makers to prioritize awareness campaigns, surveillance, and control activities.

5.3 Methods

This study explores the potential suitability of anthrax in the Black Sea basin through distribution modelling, using anthrax occurrences in domestic animals, from nine countries of the region, namely: Armenia, Azerbaijan, Belarus, Bulgaria, Georgia, Moldova, Romania, Türkiye, and Ukraine.

Occurrence data and geoprocessing

We curated a database of *B. anthracis* confirmed georeferenced occurrences causing disease in domestic animal species (i.e., cattle, sheep, goats, swine, and equine) that have been reported in the participating countries between 2006 and 2021 (hereafter anthrax occurrences). The data were procured internally by FAO, sourced directly by national experts, or available online. The consolidated database included international repositories, such as EMPRES-i and the World Animal Health Information System (WAHIS), regional sources, as the Animal Disease Information System (ADIS), and national databases from Moldova and Türkiye. Finally, it includes anthrax occurrences from Deka *et al.* [16] (S1 File and S1 File Table 1).

Anthrax occurrence locations were processed in R Statistical Software (v4.2.1) [17]. We started by removing duplicates based on location and excluding records with a level of precision of less than three decimal degrees of latitude or longitude. Finally, to avoid overfitting due to spatial autocorrelation and sampling bias [16,18], we applied a spatial thinning method of 30 km [19], using the R package *SpThin* [20]. The resulting thinned occurrences were used to develop ENMs, the final dataset comprised 226 occurrences (Fig. 1).

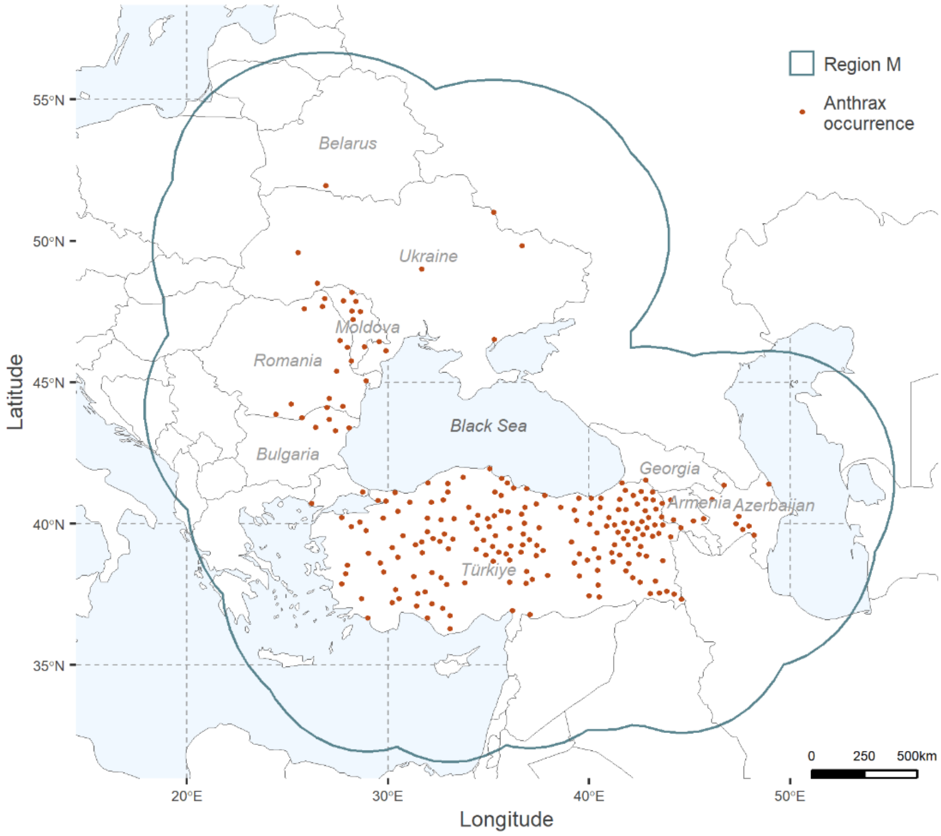

Fig 12: Anthrax georeferenced occurrences and calibration area (region M). Bacillus anthracis confirmed georeferenced occurrences (in dark orange) considered for the calculation of parameter M (outlined in teal). Maps were developed using R Statistical Software (v4.2.1) [17].

Calibration area

The calibration region, or parameter M, is the area used to calibrate the model. The correct delimitation of M is critical as it may impact any step of an ENM, from its parameterization, validation, and model comparison [21], to the modelling outputs [22,23]. M should combine a spatial extent and environmental diversity that has been accessible to the studied species [24] during a time period that is relevant to the study [16,21]. Here, we defined M by a buffer surrounding the occurrences which distance was calculated as the mean of the distances from each occurrence to the geographic centroid [25] (Fig 1).

Variable selection

B. anthracis environmental and demographic predictors were identified based on previous literature studying anthrax spatial distribution [6,19,26]. We selected four environmental categories relating to climate (i.e., temperature and moisture), soil, and vegetation, plus one demographic variable. We included 15 bioclimatic variables for temperature and moisture extracted from the MERRAclim dataset [27] at a 5 arc-minute resolution for the period 2000 to 2010, which partially matched the timeframe of our occurrences. In this study, we excluded the variables describing interactions between temperature and moisture—BIO8, BIO9, BIO18 and BIO19—due to known modelling artefacts [28]. MERRAclim is a high-resolution global repository of satellite-based bioclimatic variables, offering advantages over other commonly used climate data sources for ENM, specifically, MERRAclim shows less uncertainty in interpolated values when compared with WorldClim [27].

We selected four soil-related layers—pH, cation exchange capacity, carbon content, and nitrogen—extracted from the Global Soil Information Facilities, SoilGrids, database [29], available at https://soilgrids.org/, at a 0-5cm depth and 250m resolution. SoilGrids is a repository for chemical and physical soil properties, based on a global compilation of soil profile data sets and environmental layers. It is the result of contributions from various national and international agencies and is developed by the International Soil Reference and Information Centre (ISRIC)—World Soil Information [29,30].

As a measure of vegetation greenness, we used the Enhanced Vegetation Index (EVI) [31]. EVI's version 6.1 was obtained through the 16-day composite images from the MOD13Q1 product at 250 m resolution [31] captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor, located in NASA's TERRA satellite [32]. We processed satellite images to obtain the median from a composite of satellite images from 2005 to 2021 via Google Earth Engine [33]. EVI offers advantages over the Normalized Difference Vegetation Index (NDVI) in correcting atmospheric conditions and background noise [31].

Finally, we included a demographic variable representing ruminant abundance, resulting from the sum of three raster layers for cattle, sheep, and goats abundance sourced from the Gridded Livestock World Distribution (GLW4) and adjusted to FAOSTAT 2015 country totals at 1km resolution [34–37]. All variables were resampled to 1km resolution using the *resample* function and bilinear method in R. Further details on anthrax environmental predictors and data sources are detailed in S1 File Table 2.

To reduce high dimensionality and variable autocorrelation, we used a principal component analysis (PCA) [9,38]. We used different sets of PCAs to determine three ENM approaches. For the first approach, we calculated principal components (PCs) for the entire set of 20 environmental variables. The two other approaches comprised PCs for each environmental domain (i.e., temperature, moisture, soil, and vegetation). The third approach treated environmental domains as in the second approach, also including the ruminant abundance variable. For each of these approaches, we used the PCs retaining at least 90% of the variation in the original data [39]. PCAs were developed using the *'kuenm_rpca'* [40] function from *kuenm* package in R [40].

Ecological Niche Modelling

Maximum Entropy algorithm (MaxEnt version 3.4.4) [41] was implemented to define the ENMs. For this purpose, we applied the package *kuenm* [40] (https://github.com/marlonecobos/kuenm) in R Statistical Software (v4.2.1) [17] to calibrate MaxEnt ENMs and select optimal parameters for each of the three combinations of PCs as described earlier. We investigated different parameters, including combinations of MaxEnt feature classes (i.e., response types: linear, linear+quadratic, linear+quadratic+product), and five regularization multipliers (i.e., 0.1, 0.5, 1, 1.5, and 2).

Model evaluation

We partitioned anthrax occurrences randomly: 70% of occurrences for model training (calibration), and 30% of occurrences for model testing (evaluation) [42,43]. Models were primarily evaluated and selected via the *kuenm* package [40] following a three-step approach. First, models were assessed for statistical significance (*p*-value<0.05) based on the partial area under the curve of the Receiver Operating Characteristic (*pROC*). Then, those models with a lower omission rate (OR, threshold=5%), [44], were selected. Lastly, the resulting models were further narrowed down using the Akaike information criterion corrected for sample size (*AICc*) [45] to ensure low model complexity and good fit to the underlying data.

Final Model

Final models were generated with the function *'kuenm_mod'* from *kuenm* [40]. For the three modelling approaches, we specified the output format as logistic, with a continuous scale from 0 (non-suitable) to 1 (suitable). Additionally, we used 50 bootstrap replicates to calculate the median and assess model uncertainty, i.e., the difference between the rasters with maximum and minimum values. Final model outputs were categorized (i.e., suitable vs. non-suitable) considering the suitability value from the 95% of the calibration points (E=5%) as threshold for binarizing the model [46].

From the three modelling approaches, we selected the best model based on the following criteria: lowest OR, lowest number of parameters, larger predicted area, and lowest uncertainty. Finally, to interpret the final model, we overlapped the best binarized model (i.e., suitable/unsuitable) with the uncertainty raster and considered highly suitable areas to those with less than the third quartile of uncertainty values.

5.4 Results

A total of 1182 raw anthrax outbreak occurrences in domestic livestock, spanning from 2006 to 2021, were collated from various sources and used in the current study (S1 File. Table 1). Cattle, sheep, and goats outbreaks accounted for 80.7%, 14%, and 4% respectively, representing the majority of studied outbreaks (98.7%). The remaining occurrences represented outbreaks attributed to horses and swine (1.3%). Over the studied period, the cumulative frequency of anthrax occurrences started increasing in July, peaked in September (n=193) at three times the mean for the first six months of the year (n=65), and gradually decreased until December (n=62, S2 Fig).

Each of the three explored approaches resulted in 15 candidate models, reflecting combinations of three feature classes and five regularization multiplier values. The three best-fitting models were identified through the described three-step framework (Table 1).

Table 4. Parameters of ecological niche models categorized by principal component analysis (PCA) approach. The best model for each approach was selected using a three-step selection framework (i.e., pROC, omission rates, and AICc). AICc: Akaike information criterion corrected for sample; dem variable: demographic variable; Features: L=linear, LQ=linear+quadratic, LQP=linear+quadratic+product; PCA: principal component analysis; pROC: partial area under the Receiver Operating Characteristic; OR: omission rate; RM: regularization multiplier.

Approach	Qcjcarcb dc_rs pcq	Qcjcarcb PK	No. of predicted pixels	pROC significance	OR-5%	AICc	No. of parameters
? nnpm_af / 8 ? jj t_pg_`jcq NA?	J ON	. ,/	34,917	: . ,. 3	0.0294	4,732.26	20
? nnpm_af 08 NA? `wbnk _gl &l t ml jw'	J ON	. ,3	25,895	: . ,. 3	0.0441	4,634.63	41
? nnpm_af 18 NA? `w bnk _gl ) bck , t_pg_`jc	J O	. ,3	34,323	: . ,. 3	0.0147	4,715.51	18

The model output for *B. anthracis* developed using a PCA per environmental domain plus the variable representing ruminant abundance in the studied area were selected as the best overall model (i.e., approach 3; Table 1). This model yielded a wider prediction with lower uncertainty and presented a lower OR with a lower number of parameters than the two other approaches (Table 1). To generate this ENM approach, we retained the first three PCs for temperature and soil, explaining 98.83% and 95.77% of their respective domains, the first two PCs explaining 99.44% of the moisture domain, and one PC each for EVI and ruminant abundance. Models' median, uncertainty, and areas suitable and non-suitable for *B. anthracis* at 5% threshold are illustrated in Fig 2. Outputs for the other two approaches can be found in the S2 File Fig 1. We highlight that the temperature and soil domains had the highest contribution to the final selected model accounting for 38.2 and 32.9%, whereas similar contributions were attributed to EVI and ruminant abundance, at 10.3% and 9.9%, respectively (S2 File Table1).

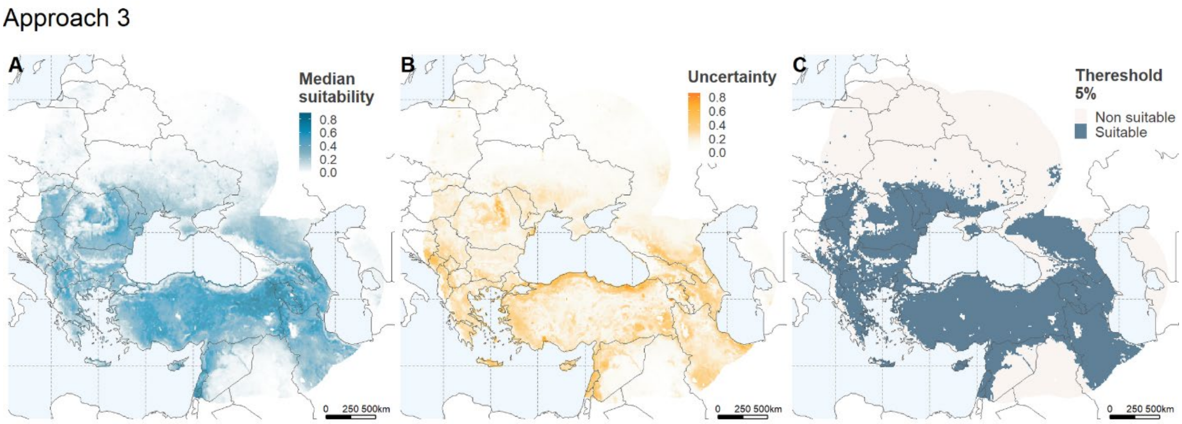

Fig 2: Ecological niche model outputs for *Bacillus anthracis* in the Black Sea basin. Model outputs for the selected best model for *B. anthracis* using principal components (PCs) by domain plus the demographic variable based on ruminant abundance (i.e., approach 3; Table 1). Maps depict (A) continuous suitability, (B) uncertainty, and (C) a binary map of suitability using a 5% threshold. Maps were developed using R Statistical Software (v4.2.1) [17].

We contrasted suitable areas for anthrax in the overall best model binary map with varying levels of model uncertainty. Low uncertainty was defined here as those pixels with values below the third quartile of the uncertainty range (i.e., Q3= 0.23; Fig 3A). Regions identified as highly suitable with low uncertainty (Fig 3B) span western to central Armenia, extending into the southwest of Azerbaijan; they include a limited area in the northeast of Azerbaijan and the southern border region of the Russian Federation; the interior regions of the Islamic Republic of Iran and southern Russian Federation; as well as the interior eastern, central and central-south areas of Türkiye (Fig 3B). Additionally, anthrax suitability is also observed in centre south and north Bulgaria and south and east Romania, centre east of North Macedonia, north of Serbia, southeast of Hungary, centre to south of Moldova, and the south coast of Ukraine with the Black Sea (Fig 3B).

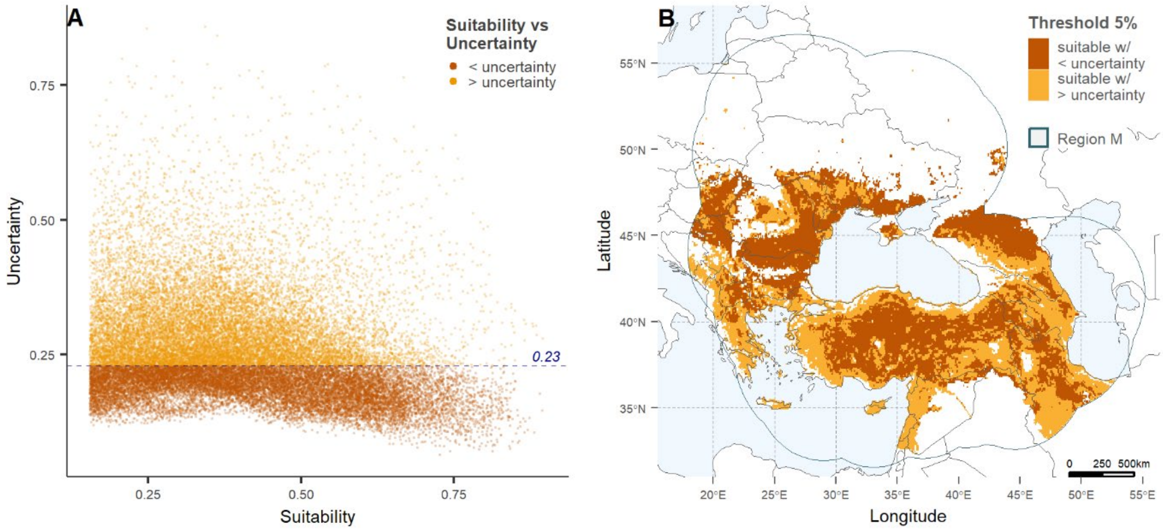

Fig 3. Suitability versus uncertainty regions for the best-selected model of the potential distribution of *Bacillus anthracis*. (A) Illustrates the correlation between continuous anthrax suitability and uncertainty for the best model (Table 1, Fig 2). High uncertainty was defined by a cut-off set as the third quartile across all uncertainty values (>=0.23). (B) Depicts the 5% binary output of anthrax suitability with higher (orange) and lower (ochre) uncertainty. Graph and map were developed using R Statistical Software (v4.2.1) [16].

Regions with high suitability with low uncertainty where no anthrax occurrences have been reported (Fig 1 and Fig 3B) can be found in the southern interior of the Russian Federation, the interior of the Islamic Republic of Iran, the central southern region of Bulgaria, central-east of North Macedonia, northern Serbia and centre to east of Hungary. Conversely, regions where anthrax cases have been reported, yet are depicted in our models as areas of low anthrax suitability, are primarily seen in central to northern regions of Ukraine and southern regions of Belarus. High suitability areas with high uncertainty are observed along the coast of southern Türkiye with the Black Sea, the west coastal area of Türkiye with the Mediterranean Sea, and the southern-east region of Türkiye along the border of the Republic of Iraq and the Islamic Republic of Iran.

5.5 Discussion

Through the scope of distribution modelling, we found highly suitable regions for *B. anthracis* survival in the Black Sea basin; these areas might well benefit from investment and resource allocation for the control and prevention of anthrax outbreaks. Our model's predictions agreed with findings from previous studies conducted at various geographical scales. Suitable areas identified for anthrax spanned from central to eastern Türkiye, Armenia, southern Georgia, the southern Russian Federation, Bulgaria, southern and eastern Romania, Hungary, Moldova, and southern Ukraine. These areas are similar to those found by recent studies exploring the ecological niche of *B. anthracis* at a global scale [6,16], as well as a study specifically focused on northern latitudes [47]. Additionally, our model found anthrax-suitable areas with low uncertainty in northeast Azerbaijan, consistent with anthrax spatial clusters observed between 2000 and 2010 [48]; and the Odesa region in Ukraine, converging with a publication reporting *B. anthracis* in environmental samples and animal anthrax cases in this area [49]. Finally, we should highlight that although our model did not include anthrax occurrences from Georgia, it accurately predicted the southeastern region of this country as suitable for anthrax, corroborating previous reports (Pers. Comm. T. Chaligava). However, it was unable to predict similar suitability in central to northern regions of Georgia, where both livestock (Pers. Comm. T. Chaligava) and human anthrax cases [50] have been documented.

There is a well-established spatio-temporal link between human and livestock anthrax cases due to the high occupational nature of anthrax in humans [1]. In this regard, our model corroborates the high incidence of human and livestock anthrax cases found in eastern provinces of Türkiye, clustering around animal trade centres and large international commercial roads [51,52] and linked with livestock trade routes between eastern and western Türkiye and from the centre Anatolia to the southern and northern parts of the country [52].

Upon comparing Maxent ENMs assessing various variable combinations, we found that the inclusion of the ruminant abundance (biotic variable)—which PC ranked fourth in the final model (S2 File Table 1)—improved model performance and was an important parameter in selecting the best overall model of anthrax suitability in this region. Livestock's abundance has previously been explored and seen as influential in anthrax distribution studies [26,47,53–56]. These results emphasize the importance of biotic interactions for disease systems [15]; ruminants are the most susceptible hosts to *B. anthracis* and play a key role in the maintenance and transmission of anthrax [57]. It is worth noting that ruminant production is a critical livestock subsector in the majority of the studied countries [58–67]. In addition, areas found as suitable for anthrax by our model largely match rural settings where pastoralism is widely practiced [68], and livestock is the main source of subsistence for these populations [4,68]. Similarly, Carlson *et al* [6] suggested higher human anthrax risk in rural areas, and observed increased human and livestock anthrax vulnerability in rainfed systems across arid and temperate landscapes in the same region (Eurasia).

Soils and temperature had the highest contribution percentage to our model (S2 File Table 1). Chernozem or black steppe-type soils, prevalent in eastern Europe [69] and partly covering our M region, are known to create favourable conditions for anthrax sporulation [70] and have been associated with anthrax epidemics [7]. At the same time, the southern part of the M region, where the mean annual temperature is higher, was identified as suitable for anthrax by our model. This result aligns with established knowledge regarding favourable conditions for anthrax viability in areas with temperatures exceeding 15 ^{0}C [3] and is further supported by results from Carlson *et al.* and Walsh *et al.* [6,47]. Furthermore, cumulative anthrax occurrences were higher between July and October. This period corresponds to high temperatures and dry conditions across the region [71], which facilitate the mechanical dispersion of anthrax spores [8]. Additionally, this period coincides with the time when ruminants graze in local pastures or migrate to summer pastures. As the grass gradually becomes shorter during this season, ruminants tend to graze closer to the soil, heightening their risk of exposure to the *B. anthracis* spores [72]. Moreover, the high temperatures during this time may also lead to ruminants' nutritional stress and compromise their immunocompetence, making them more susceptible to the disease [73]. Such temporal pattern was previously observed in Azerbaijan [74], Türkiye [75] and Kyrgyzstan [72].

Some of the few anthrax occurrences in the northern M region were missed by our final model (Fig 3). This discrepancy may be attributed to the low mean annual temperature at these latitudes, which theoretically hinders anthrax viability [3]. However, it is worth noting that during summer months, temperatures may still enable significant sporulation of *B. anthracis* [3]. In contrast, Deka *et al.* [16] showed "very high" and "high" suitability for anthrax in parts of our northern region M, diverging from our findings. Additionally, anthrax cases in Ukraine and Belarus were reported sparingly, likely due to rigorous documentation of biothermal pits and infected burial grounds [49]. These areas are subject to strict legislation prohibiting any construction as well as agricultural and pastoral practices without prior disinfection at these sites. Furthermore, the lack of cases in these countries may be also explained by the prevalence of intensive livestock production systems where ruminants are often confined, and pastoral practices are uncommon, reducing opportunities for exposure to anthrax spores. Nevertheless, despite the current suboptimal environmental conditions for anthrax viability in this region, climate change-led extreme weather events, such as warmer temperatures, high precipitation and droughts [76] are expected to increase anthrax risk in these areas [16,47].

Besides local climate, soil characteristics, host demography, and wildlife interactions, anthrax outbreaks are associated with a range of socio-economic factors. These factors encompass food security, disease awareness, cultural and religious events, as well as access to veterinary services and healthcare. These factors are directly linked with livestock production practices, including production systems, pastoralism, seasonal movements, veterinary surveillance and control capacity, vaccination use and coverage, and the application of biosecurity measures [77]. Further research into the impact of these factors on the risk of anthrax outbreaks among livestock and humans in the region would complement the findings of the current study.

Our regional-scale map illustrating anthrax suitability complements existing studies targeting this region at broader scales [6,16,47,56]. In our study, we explicitly incorporated uncertainty measures into our final predictions, aiming to highlight and define more accurately potential anthrax-suitable. The inclusion of uncertainty in the final outputs of ENMs is seldom implemented [6,16,19,26], and we advocate for its consideration, especially in ENM studies exploring pathogens.

As an evidence-based map of anthrax distribution, the areas highlighted by our model should guide future research efforts aimed at anticipating future outbreaks. They should facilitate resource allocation to improve the cost-efficiency of surveillance and control activities, as well as disease awareness and educational campaigns promoting appropriate quarantine, carcass handling, and disposal. For the success of such preventative measures, we stress the importance of coordinated efforts between the veterinary and public health sectors at both national and international levels.

5.6 Conclusions

Our study identified high-risk areas for anthrax across central and eastern Türkiye, Armenia, southern Georgia, southern Russia, Bulgaria, southern and eastern Romania, Hungary, Moldova, and southern Ukraine. These findings are critical for prioritizing resource allocation and implementing anthrax management interventions in the region.

Leveraging uncertainty levels and explicitly including them in our modelling approach improved the reliability of the potential suitable and non-suitable regions for anthrax identified in our final maps. We believe this approach also facilitates the interpretability of our results and enhances their utility for decision-makers and stakeholders.

The inclusion of ruminant abundance as a biotic variable in our modelling framework significantly improved model performance, highlighting the importance of host-pathogen interactions in the study region.

Overall, anthrax poses a significant threat to livestock, particularly ruminants, whose production sector is essential for the economies and subsistence of rural populations in the Black Sea region. We anticipate that the risk maps generated in this work offer comprehensive insights into anthrax distribution in this region, providing valuable guidance for targeted interventions to mitigate the impacts of this disease.

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Supporting Information Captions

S1 File. Anthrax occurrences data sources, environmental domains, and R packages used in the current study. (PDF)

S2 Fig. Seasonal trend of Bacillus anthracis georeferenced occurrences during our study period. (TIFF)

S2 File. Description of model outputs for non-selected models and Maxent output for selected approach. (PDF)

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5.8 Supplementary materials

S1 File: Anthrax occurrences data sources, environmental domains, and R packages used in the current study.

- Data sources used to extract anthrax occurrences in the study.
- S1 File Table 1. Anthrax outbreaks in domestic animals (2006 to 2021).
- S1 File Table 2. Selected variable domains and respective sources.
- S1 File Table 3. Packages used in R programming language across this manuscript.
- S1 References

Data sources used to extract anthrax occurrences in study.

Bacillus anthracis confirmed occurrences from 2006 to 2021 were compiled from various sources, including international and regional notification information systems, national datasets, and a scientific article. These databases are further detailed in the subsections below and S1, Table 1.

Global datasets

The Global Animal Disease Information System from the Food and Agriculture Organization (FAO), known as EMPRES-i+, is an online platform available at https://empres-i.apps.fao.org/diseases. It consolidates worldwide animal disease events information received from official and unofficial sources that are then verified and validated by FAO in coordination with the World Organisation for Animal Health (WOAH) and the World Health Organization (WHO). From this data source, our final dataset comprised a total of 52 anthrax outbreaks recorded between 2006 and 2021 [1].

The WAHIS (World Animal Health Information System) is the reference database of the WOAH. Anthrax cases for countries classified as free or sporadic are reported to WOAH as immediate notifications or follow-up reports and can be accessed through WAHIS Reports—animal disease events, which are available at https://wahis.woah.org/#/event-management. Anthrax outbreak locations from 2006 to 2021 for participating countries following these criteria include Armenia, Azerbaijan, Romania, and Ukraine [2].

Regional datasets

The Animal Disease Information System (ADIS) is a disease management tool from the European Commission that was designed to document the evolution of the status of important infectious animal diseases (identified in the Animal Health Law (AHL)). This tool has the objective to ensure a rapid exchange of notifications between competent responsible authorities of EU member countries. Anthrax event notification data were obtained by FAO and was available for Bulgaria, Romania, Turkey, and Ukraine, a total of 563 outbreak points ranging from 2015 to 2021 were included in our original database [3].

National Datasets

National datasets for georeferenced anthrax events were obtained from Moldova and Türkiye through national focal points. These data ranged from 2010 to 2016 for Moldova, and from2016 to 2021 to Türkiye.

Other

A subset for our study region and species of the global database for naturally occurring anthrax compiled by Deka et al. [4] was used to complete our database.

S1 File Table 1. Anthrax outbreaks in domestic animals (2006 to 2021). Number of outbreaks extracted from each data source.

	Armenia	Azerbaijan	Belarus	Bulgaria	Moldova	Romania	Türkiye	Ukraine	Total
ADNS	-	-	-	8	-	10	541	3	562
EMPRES-i+	9	15	1	-	1	16	1	8	51
Focal point	-	-	-	-	12	-	504	-	516
WAHIS-events	8	15	-	-	-	13	-	8	44
Publication [4]	2	2	-	2	-	2	-	1	9
Total	19	32	1	10	13	41	1046	20	1182

S1 File Table 2. Selected variable domains and respective sources. Details on resolution, source and availability of the four environmental domains: temperature, moisture, vegetation index, and soil; and one demographic variable: ruminant abundance, used in study.

Data domains & variable description	**Variable short name**	**Spatial and temporal resolution**	**Source**	**Availability**
TEMPERATURE (9 layers) *		**5 arc minutes / 2000-2010**	MERRAclim [5]	https://datadryad.org//resource/doi:10.5061/dryad.s2v81
Annual mean temperature	BIO1			
Mean diurnal range temperature	BIO2			
Isothermality	BIO3			
Temperature seasonality	BIO4			
Maximum temperature of the warmest month	BIO5			
Minimum temperature of the coldest month	BIO6			
Temperature annual range	BIO7			
Mean temperature of warmest quarter	BIO10			
Mean temperature of coldest quarter	BIO11			
HUMIDITY/MOISTURE (6 layers) *		**5 arc minutes / 2000-2010**	MERRAclim [5]	https://datadryad.org//resource/doi:10.5061/dryad.s2v81
Annual mean specific humidity	BIO12			
Specific humidity of most humid month	BIO13			
Specific humidity of least humid month	BIO14			
Specific humidity seasonality	BIO15			
Specific humidity mean of most humid quarter	BIO16			
Specific humidity mean of least humid quarter	BIO17			
VEGETATION INDEX (299 layers)		**250 m / 2005-2021**	Moderate Resolution Imaging Spectroradiometer (MODIS)[6]	https://lpdaac.usgs.gov/products/mod13q1v061/
Enhanced Vegetation Index MOD13Q1 product Version 6.1	EVI			

SOILS (4 layers)		**250 m / 2012-2016**	SoilGrids [7,8]	https://soilgrids.org/#!/?layer=TAXNWRB_250m&vector=1
Cation exchange capacity of soils at two depths	CECSOL†			
Soil organic carbon content at two depths	ORCDRA†			
Soil pH x 10 in H_2O at two depths	PHIHOX†			
Nitrogen	Nitrogen†			
RUMINANTS' ABUNDANCE** - Sum of raster layers for domestic ruminants' distribution GLW4		**5 arc minutes/ 2015**	Gridded Livestock of the world – 2015 (GLW4)[9]	
Global cattle distribution in 2015 (5 minutes of arc)	5_Ct_2015_Da.tif		[10]	https://dataverse.harvard.edu/file.xhtml?fileId=6769711&version=1.0
Global goats distribution in 2015 (5 minutes of arc)	5_Gt_2015_Da.tif		[11]	https://dataverse.harvard.edu/file.xhtml?fileId=6769696&version=1.0
Global sheep distribution in 2015 (5 minutes of arc)	5_Sh_2015_Da.tif		[12]	https://dataverse.harvard.edu/file.xhtml?fileId=6769626&version=1.0

*Bioclimatic variables combining information from temperature and humidity (BIO-8, BIO-9, BIO-18 and BIO-19) were not included in the analysis [13].
**Excluded global buffalo distribution.
†Depths considered for each variable: 0-5 cm.

S1 File Table 3: Packages used in R programming language across this manuscript.

Package	Application	Reference	Availability
kuenm	Principal component analysis (PCA), model calibration, selection, and calculation of evaluation metrics for *B. anthracis*.	[14]	https://github.com/manubio13/ku.enm
raster	Manipulation of raster files: crop, resample, mask, etc.	[15]	https://cran.r-project.org/web/packages/raster/vignettes/Raster.pdf
SpThin	Spatial thinning of *B. anthracis* occurrence records	[16]	https://cran.r-project.org/web/packages/spThin/spThin.pdf

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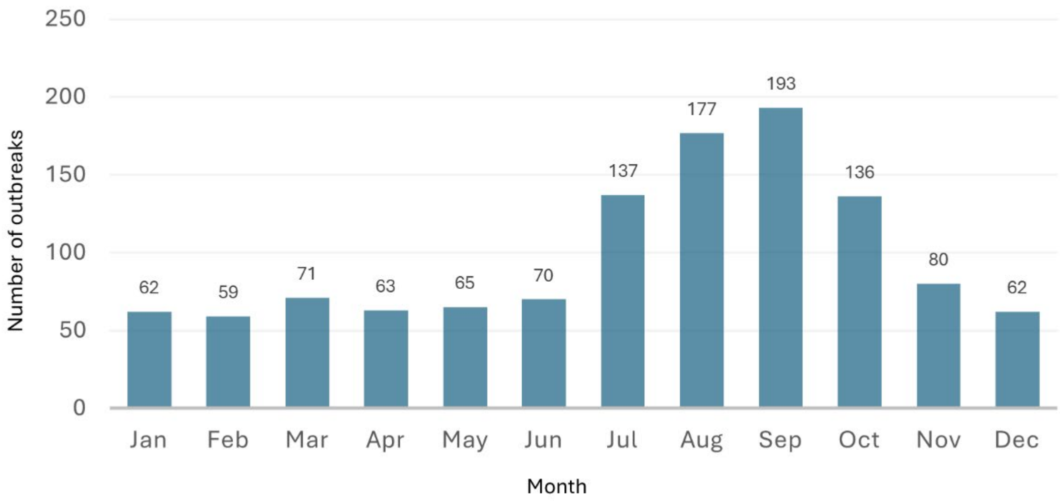


S2 Fig. Seasonal trend of Bacillus anthracis georeferenced occurrences during our study period.

S2 File: Description of model outputs for non-selected models and Maxent output for selected approach.

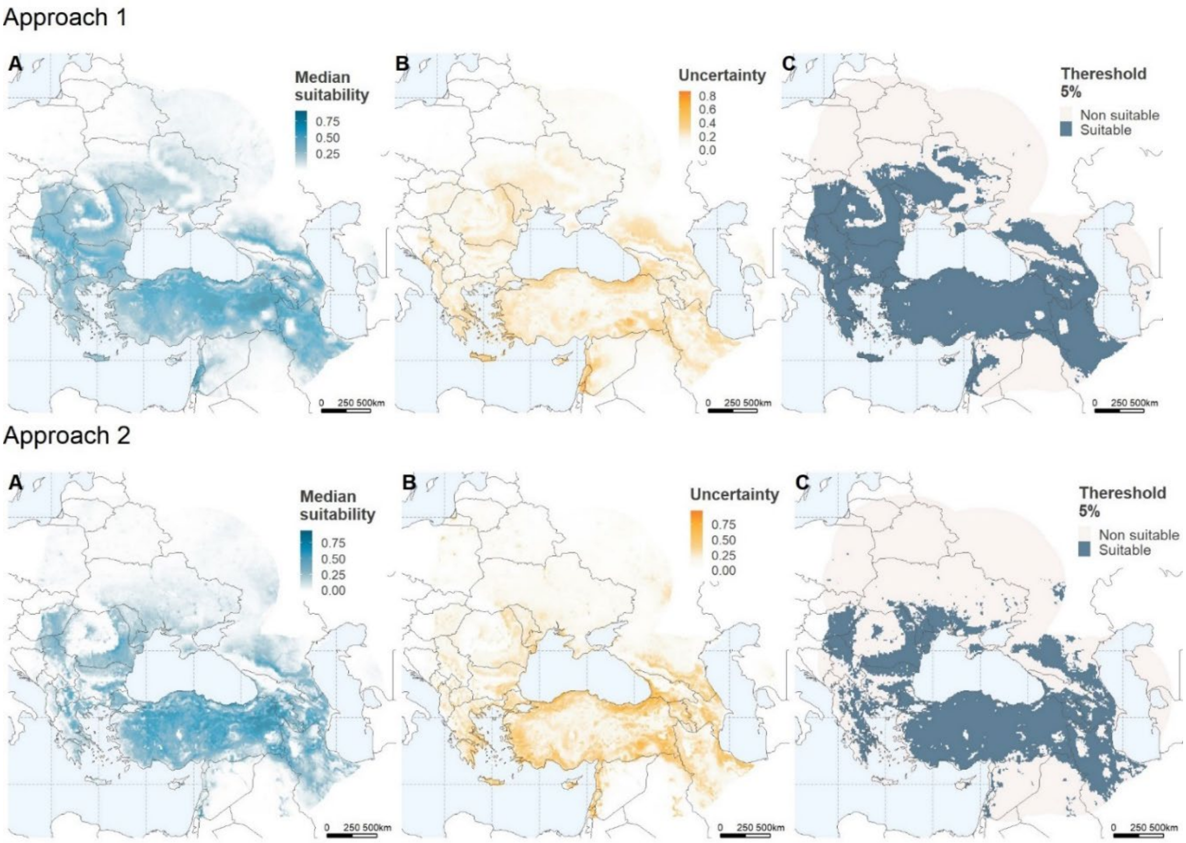
- Model outputs for non-selected approaches.
- S2 File Fig 1. Ecological niche modelling outputs for *Bacillus anthracis*.
- S2 File Table 1. Maxent output for approach 3.
- S2 References

Model outputs for non-selected approaches

The two approaches based on variable combinations with only abiotic variables resulted in lower model performances. Model parameters and outputs for the two approaches that were not selected are presented in Table 1 (main text) and Figure 5, respectively.

The first approach used a PCA including all environmental variables. We kept the first five principal components (PCs) explaining 91.14% of the variance among all variables. This approach had a larger area predicted as suitable but a slightly higher omission rate and two additional parameters (Table 1, main text).

The second approach used PCAs in the environmental domain. We retained the first three PCs explaining 99.78% of the variance for humidity, 95.73% for soil, 98.87% for temperature, and one PC explaining 100% of the variance for vegetation greenness. The binary model (E=5%) for this approach (seen in Supplementary Material, Figure 5, approach 2, panel C) yielded a smaller predicted area, using more than the double number of parameters compared with the other two approaches.



S2 File Fig 1. Ecological niche modelling outputs for *Bacillus anthracis*. Model outputs for *B. anthracis* using approach 1 (PCA for all selected variables) and approach 2 (PCA by domain). For both approaches, maps depict continuous suitability (A), uncertainty (B), and binary map of suitability using a 5% threshold (C). Maps were developed using R Statistical Software (v4.2.1) [195].

S2 File Table 1. Maxent output for approach 3. Percent contribution and permutation importance (Maxent's automated output) for approach 3 (selected approach) in descending contribution order. The principal component (PC) three (PC3) from the temperature domain and the PC1 from the soil domain have the highest contribution for the selected model.

Variable	Percent contribution (%)	Permutation importance
Temperature PC 3	35.5	12
Soil PC 1	21.1	35.2
EVI PC 1	10.3	7.5
Ruminant abundance PC 1	9.9	1.1
Soil PC 2	6.5	16.8
Soil PC 3	5.3	13.6
Humidity PC 2	5	2.8
Humidity PC 1	3.7	1.8
Temperature PC 2	1.4	3.9
Temperature PC 1	1.3	5.2

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General discussion

Chapter VI

Ruminant production in the Black Sea basin is rooted in ancient shepherding traditions, shaped by transient populations and evolving geographical and political landscapes. In this region, where smallholders and family farms are predominant, animals are crucial for improving living standards (1,2). Ruminants provide not only food and income but also act as wealth reserves during crises. They supply wool and leather for clothing, manure for energy and fertilizer, draught power, and transportation (3). However, the sector is threatened by the emergence and spread of diseases which can negatively impact national economies, rural food security, and public health.

This PhD thesis addressed these challenges through two main lines of research. Firstly, it identified factors influencing the spread of six ruminant diseases (anthrax, brucellosis, Crimean Congo haemorrhagic fever (CCHF), foot-and-mouth disease (FMD), lumpy skin disease (LSD), and peste des petits ruminants (PPR)) in nine countries of the Black Sea basin (Armenia, Azerbaijan, Belarus, Bulgaria, Georgia, Moldova, Romania, Türkiye, and Ukraine). This involved describing the ruminant production and sanitary status for the selected diseases, and examining associated surveillance and control measures. Secondly, the thesis aimed to spatially quantify the suitability of PPR and anthrax in the region.

This thesis presents the first collection of studies on ruminant diseases in the Black Sea basin as a whole, marking a significant advance in our understanding of the epidemiology of priority ruminant diseases in the region. By addressing existing knowledge gaps in disease dynamics, this research offers new insights. Furthermore, the risk maps developed for PPR and anthrax provide national authorities with valuable tools for guiding risk-based disease prevention and control interventions in this resource-limited region.

Study 1 (4) explored the connections between ruminant production, socio-economic levels, veterinary capacity, cultural and religious traditions, political history, countries' affiliations, and current conflicts to understand sanitary status, disease emergence, and potential threats. Due to time constraints, the study provided an overview rather than an in-depth analysis, leading to some over-generalizations. Consequently, it grouped some countries together and briefly touched on others with minimal disease presence.

In some countries, post-Soviet reforms aimed at increasing farm efficiency and land access (5) led to significant political instability, removal of subsidies, closure of large slaughterhouses, and depletion of veterinary services. These changes caused dramatic declines in ruminant populations, agricultural production, and rural employment, along with increased disease incidence and rising poverty rates in rural areas (5–7). Despite some recovery in the 2000s, poverty remains widespread in rural areas. To sustain this recovery, it is essential to modernize market infrastructures by ensuring market access, providing access to agricultural inputs and modern machinery, and implementing policies that support smallholders (8–10).

Building on this context, study 1 examined other socioeconomic factors. More than half of the population in lower and middle income countries (LMICs) like the study region, live in rural areas and rely on agriculture and livestock for their subsistence (11,12). The emergence of TADs and zoonoses impacts these countries more significantly due to increased population growth rate, high market demand for animal products, shifts in livestock production systems and land usage, inadequate infrastructures, shortage of skilled workforce, social inequality, poverty, and ongoing conflicts (12,13).

The increasing risk of livestock disease emergence in LMICs poses a significant threat to neighbouring countries. This risk is underscored in the study region by recent disease outbreaks in EU bordering countries: LSD in Türkiye, the Balkans, and the Caucasus in 2012 (14), FMD in Bulgaria in 2011 (15), and PPR in Georgia in 2016 (16) and Bulgaria in 2018 (17). These outbreaks raise concerns about the reemergence and spread of TADs and zoonoses, such as brucellosis, FMD, LSD, and PPR, from Türkiye to the EU with potentially severe economic impacts. In response, the EU supports disease management in Bulgaria and Romania through coordinated vaccination programmes, animal movement restrictions, and test-and-slaughter strategies in the event of an outbreak.

Conversely, in LMICs, the improvement of animal health surveillance must consider additional factors, including the availability of effective control measures, cultural acceptability, trained personnel, financial resources, and logistical support (18). In these regions, such efforts are often unaffordable without external support.

Various regional and international initiatives aim to mitigate these constraints. The European Commission for the Control of Foot-and-Mouth Disease (EuFMD) focuses on reducing the threat of FMD and similar TADs in Europe and neighbouring countries through risk monitoring and mitigation strategies, capacity building for enhanced response to crises, and improving overall control measures, such as global FMD control, FAST control, and vaccine security (19). Study 1 also discusses other ongoing actions aimed at improving animal health in the region, including the GF-TADs (20), the implementation of national animal identification and traceability systems (NAITSs) in the Caucasus, and the establishment of veterinary surveillance points (VSPs) along migration routes to pastures in Georgia, Azerbaijan, and Türkiye.

Furthermore, community-based (i.e. participatory) disease surveillance could complement formal methods. This approach has proven to be a useful tool in improving disease surveillance among small-scale and remote rural farmers and pastoral communities in LMICs. It enables rapid and efficient data collection with minimal resource use, aiding in disease detection (21), while it connects rural communities with local authorities, promoting dialogue and trust between different parties (12). This method leverages the rural communities' rich knowledge about their livestock, the diseases affecting them, and the potential impacts they have on their livelihoods (22).

Nevertheless, the incomplete operability of NAITSs in the Caucasus, combined with the high proportion of unregistered backyard and remote farms, especially in Anatolia, hinders the implementation of effective disease management activities. Low government prioritization of rural areas results in insufficient resource allocation for surveillance, leading to limited diagnostic capacity and inefficient monitoring systems (21). Despite infrastructure development in the region (e.g. laboratory system in Azerbaijan (23)), there is a significant shortage of human resources. This includes veterinarians capable of reaching remote locations and specialized staff to regularly maintain NAITSs and associated disease monitoring systems (24). Additionally, a lack of disease awareness, widespread social stigma, and mistrust of government interventions contribute to high levels of underreporting (25,26). As a result, disease outbreaks in these areas may go undetected and potentially spread further.

Employing risk-based methods for surveillance and control is especially important in resource-limited settings. Disease risk maps are highly useful tools to identify areas that require targeted management activities (27). However, surveillance data in these regions is often sparse or incomplete, making it challenging to apply statistically robust, traditional risk-based models for disease mapping. Despite these limitations, there is a high demand for such maps to guide policy-making and resource allocation (28).

To address data limitations, this thesis applied alternative methods in study 2 (29) and study 3 (30). Spatial multicriteria decision analysis (GIS-MCDA) was used for risk mapping the suitability for the spread of peste des petits ruminants (PPR), and the Maxent algorithm was applied to explore anthrax suitability in the study region.

The risk map of PPR spread (study 2) was generated using a knowledge-driven method. Unlike data-driven approaches that require the georeferenced location of disease events (and often presence and absence data), this method can be used in the absence of disease reporting, and when field-based disease surveillance is unavailable or unreliable (31). Our study region combined various of these issues: regions where the disease was endemic but not reported (e.g. rural settings in Anatolia); areas with low surveillance reliability (e.g. the Caucasus); and countries free of PPR including Belarus, Moldova, Romania, and Ukraine.

Despite the acknowledged subjective nature of the expert elicitation step and quality limitations of risk factor data further discussed in study 2, this method offers a quick and inexpensive approach to mapping disease risk. The preliminary estimates of disease risk generated by this method can help authorities prioritize and plan disease control programmes (32). National authorities and international colleagues involved in the global programme for the control and eradication of PPR will be able to use the risk map information for closer assessments with local veterinary services. This includes evaluating vaccination programmes in high-risk areas, implementing training activitivies for veterinary professionals and disease awareness campaigns linked to community-based surveillance in remote locations.

The anthrax suitability risk map generated in study 3 employed the Maxent algorithm, a method traditionally used in ecological niche modelling (ENM) that in recent decades was proposed to study disease distribution (33). ENM methods are often applied when only presence data is available and are frequently used for data-poor settings, such as the study region (25,34).

The anthrax distribution model had better predictive ability when ruminant abundance was included as one of the explanatory variables. This emphasizes the importance and predominance of rural and pastoral practices in the study region, as they promote a closer link between the hosts, the pathogen, and the environment, facilitating the exposure of ruminants to anthrax spores while grazing.

Furthermore, disease risk maps aiming to inform surveillance and control activities, need to be interpreted with caution, recognising model uncertainty, and potential sampling bias. Risk estimates should always be accompanied by clear statements regarding their uncertainty and the possible influence of biases, and whenever possible, a map of statistical uncertainty should be included, as presented in both study 2 and study 3. In study 3, we explicitly incorporated uncertainty measures into our final predictions, to more accurately highlight and define potential anthrax-suitable areas, thereby facilitating the interpretation of the suitability map.

Risk management procedures should align with the political context, societal values, and cultural acceptability of the community they aim to serve (35). To achieve this, it is important to first translate complex risk-related knowledge into actionable insights, and then effectively communicate these insights to both decision-makers and the public. This facilitates the understanding of findings and the definition of tailored management strategies for different settings (36). In today's post-truth era, where misinformation is widespread and trust in experts is low, conveying accurate disease risk information is particularly difficult. Using maps as tools to visually disseminate this information has proven to be effective for informing both parties—policymakers and the general public (37).

Given the ongoing climate change impact on the region, more research is necessary to assess the potential effects of environmental changes. Increasing drought conditions, already evident today, directly affect ruminants by causing heat stress, and indirectly by reducing the availability of water and pastoral lands, and the quantity and quality of forage and crops (38). This is particularly concerning for these countries where rural ruminant production depends on natural resources and operates with a very low-profit margin, leading to increased production costs and higher market prices (39,40).

Additionally, species distribution models, like Maxent, are powerful tools for predicting the potential distribution of disease under future climate scenarios (35). These methods are especially useful when studying diseases influenced by environmental factors (e.g. anthrax), or those with vectors affected by climatic conditions (e.g. CCHF and LSD). Stevens & Pfeiffer (35) described the unexpected emergence of Bluetongue, a vector-borne disease affecting ruminants, in Europe in 1998. This emergence was linked to the northward range expansion of its vector, *Culicoides imicola*, and the long-distance spread of the disease into new territories, where northern *Culicoides* species were found to be competent vectors for viral transmission. Since then, bluetongue has become a sporadic disease in central and western Europe (41). This example shows that the introduction of new species to areas with suitable conditions can lead to their establishment and spread. Therefore, active surveillance aimed at detecting introduction into areas highlighted by risk maps is the best first line of action (42).

While our studies offer valuable insights into PPR and anthrax risk distribution in the region, they are constrained by data limitations. Future research should focus on replicating such risk maps with updated and quality-assessed data, by applying community-based surveillance to improve data collection, reduce underreporting in rural and remote regions, and integrate socio-economic variables for more robust predictions. Moreover, to facilitate the effective implementation of disease management strategies further efforts are needed to understand their acceptability, as well as the motivations, and constraints for the implementation of biosecurity measures.

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Conclusions

Chapter VII

1. In the Black Sea basin, countries' political affiliations and the status of ruminant disease influenced disease management practices. EU countries like Bulgaria and Romania focused on maintaining their disease-free status through strict prevention strategies and no vaccination to maintain trade. In contrast, the Caucasus and Türkiye, which were endemic for some of the studied diseases, worked on improving their sanitary status.

2. Despite improvements in veterinary infrastructure in the Caucasus and Türkiye, including the implementation of NAITSs, veterinary surveillance points to support pastoralism, enhanced border control, and international initiatives for capacity building, disease management still presents limitations, particularly in rural and remote areas.

3. Incorporating expert opinion through GIS-MCDA has proven to be a valuable tool for risk mapping the spread of PPR in the study region. The generated risk map can help authorities to strategically target interventions. These risk-based interventions can involve strengthening surveillance for early detection and conducting training and awareness campaigns.

4. The high suitability for PPR spread along the Bulgaria-Thrace border raises significant concerns about its potential reintroduction into the European Union. To prevent this threat, it is crucial to maintain enhanced surveillance of small ruminant farms in southern Bulgaria and enforce stricter border controls on informal animal trade, especially during cultural events.

5. High-risk areas for anthrax identified through ecological niche modelling will help authorities prioritize resources for targeted management interventions in ruminants. The objective is to reduce the risk of anthrax in livestock and prevent associated public health threats in these countries.

6. The inclusion of ruminant abundance as a biotic variable in ecological niche modelling of anthrax distribution significantly improved model performance. This highlights the importance of host-pathogen-environment interactions. Additionally, by leveraging uncertainty levels in the modelling approach, the reliability and interpretability of the results are enhanced, thereby supporting informed decision-making by stakeholders.