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Spatial clusters of human and livestock anthrax define high-risk areas requiring intervention in Lao Cai Province, Vietnam 1991-2022

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Abstract

Anthrax, a widespread zoonosis in low and middle-income countries with low disease awareness and insufficient livestock vaccination coverage, has been known in Lao Cai Province in northern Vietnam for years before its apparent absence in 2009, which requires investigation as this infection is frequently reported from neighbouring provinces and countries. We aimed to describe the seasonal patterns of anthrax (1991-2008), compare livestock anthrax vaccine coverage to disease occurrence (1991-2022), and delineate the high-risk areas to inform local disease surveillance in the province. We illustrated the seasonal pattern of anthrax and provided a comparison between livestock vaccine coverage and disease occurrence by purely spatial SaTScan (Poisson model, 25% population at risk) to detect spatial clusters of human and livestock anthrax using population derived from zonal statistics routines. The number of cases, crude cumulative incidence, and spatial clusters of human and livestock anthrax were mapped in QGIS. Results indicate peak anthrax incidence from May to October. Buffalo, domestic cattle, and horses accounted for 75% of total animal cases. Horse anthrax was more common in Lao Cai than in its neighbours and often occurred in years with human mortality. Vaccination covered less than 30% of the livestock population. We found an apparent pattern where anthrax was controlled from 1998-2003 with higher vaccine coverage (>20%) and identified spatial clusters of human and livestock anthrax in Muong Khuong, Bao Thang, and Bac Ha districts of Lao Cai. The local public health and veterinary agencies are recommended to revisit the high-risk areas and communicate with neighbouring provinces for a regional approach to anthrax surveillance and control.

Introduction

A meeting of the World Health Organization (WHO) with the participation of the Food and Agriculture Organization (FAO) and the World Organization for Animal Health (formerly OIE) in 2005 indicated the significance of zoonoses, including anthrax, in the poverty reduction agenda (WHO, 2006). Anthrax is widespread in low and middle-income countries where disease awareness may be low with insufficient livestock vaccination coverage *(WHO, 2008; Kracalik et al.*, 2017; Sitali *et al.*, 2017). *Bacillus anthracis*, the anthrax pathogen, is a Gram-positive, rod-shaped, spore-form-

ing bacterium. The spores can persist in the environment for many years, making it challenging for disease control and elimination efforts (Hugh-Jones & Blackburn, 2009). The disease primarily impacts herbivorous domestic livestock and wild animals (WHO 2008). Human infections often occur among people exposed to the pathogen when handling a sick/dead animal or butchering contaminated meat (Kisaakye *et al.*, 2018).

Anthrax occurs near globally, with frequent outbreaks in Central and Southeast Asia, North America, West and Sub-Saharan Africa, and many European countries (Carlson *et al.*, 2019). Anthrax is widespread across Eurasia with more frequent outbreaks reported in China, Mongolia, India, Bangladesh, Iran and countries of the former Soviet Union (Carlson *et al.*, 2019; Chen *et al.*, 2016; Shaheenur Islam *et al.*, 2018; Li *et al.*, 2017; Nayak *et al.*, 2019). Though evidence confirms anthrax is persistent in Vietnam, Laos and Cambodia, disease occurrence and epidemiology are poorly understood in Southeast Asia (Leuangvilay *et al.*, 2012; Tran *et al.*, 2015; Gideon Informatics Inc. & Berger, 2021). The infection is considered a neglected zoonotic disease (NZD) (Aya Pastrana *et al.*, 2020). In Vietnam, anthrax has only been prioritized for intersectoral (human and animal health) surveillance since 2013 and was not made nationally reportable until 2015 (Vietnam – Joint circular number 16/2013/TTLT-BYT-BNN&PTNT, 2013; Vietnam - Ministry of Health -Circular number 54/2015/TT-BYT guiding the infectious disease notification and report, 2015). A national-level study using anthrax data from 1990 to 2015 indicated persisting anthrax in six provinces in the Northern midlands and mountainous region of Vietnam (Walker *et al.*, 2022). In the country, the responsibility for implementing infectious disease surveillance and control is delegated to the local authorities. Specifically, a provincial authority makes policies and mobilizes resources for anthrax control within its jurisdiction (Viet Nam - Law No. 03/2007/QH12 on Infectious Diseases Prevention and Control, 2007). Therefore, a spatial analysis for each province is needed to guide the local disease control strategies and prioritize resources for high-risk areas.

Lao Cai Province is one of the six provinces in northern Vietnam where anthrax has persisted in the last two decades (Walker *et al.*, 2022). It is a remote and poor province where 73.6% population live in rural mountainous areas (Lao Cai Statistics Office 2021, 2022) and a large proportion of rural households live below the poverty line (~35.1% in 2016) (Lao Cai Statistics Office 2016, 2017). A large livestock is a significant source of income, provides savings for emergencies, and plays an important role in agriculture for a household in rural Vietnam (Vuong *et al.*, 2021; Ta, 2022). Therefore, an effective anthrax surveillance strategy guided by spatial analyses would help prioritize local resources for disease control, and subsequently contribute to preserving this important source of income regionally. According to Lao Cai provincial human and animal health agencies, anthrax has not been reported since 2009. This contrasts with neighbouring Dien Bien, Ha Giang and Son La provinces, which have all reported anthrax in recent years (Tan et al., 2022; Luong *et al.*, 2023; Metrailer *et al.*, 2023). Additionally, Lao Cai Province has an international border with Yunnan Province in China, which has also reported a high intensity of anthrax (Chen *et al.*, 2016). This border area is known for active trans-border livestock trading (Turner, 2010; Ta, 2022). Though improved surveillance and some livestock vaccination have reduced anthrax intensity in recent years, a spatial analysis indicate anthrax persistence in several southern districts of China that share borders with northern Vietnam (Li *et al.*, 2017). In short, the risk of anthrax circulation among the Vietnamese provinces and through the international border is plausible and probable. Analyses using historical anthrax data are needed to inform local authorities of measurable high-risk areas to prioritize intensive surveillance and control programmes.

Here, we investigated the seasonal pattern of anthrax and compared anthrax vaccine coverage in livestock to disease occurrence. We also mapped the disease distribution and employed spatial clustering analyses to delineate high-risk areas of the disease using historical human anthrax and livestock anthrax data from 1991 to 2022 in the northern Vietnamese province of Lao Cai.

Materials and Methods

Study site, population and livestock

The study included all of Lao Cai Province in the northern midlands and mountainous region of Vietnam. The province shares an international border with China in the North, with Ha Giang Province in the East, with Yen Bai Province in the South and with Lai Chau Province in the West (Figure 1). Lao Cai has three governmental administrative levels: provincial, district (nine), and commune (164). Within the province, public health, veterinary and livestock production are organized across three levels. However, while the commune health centre is the lowest level of human health system, animal health and livestock husbandry are limited to the district and province levels. The population of Lao Cai Province was 761,890 people in 2021, 73.6% of whom lived in rural areas (Lao Cai Statistics Office 2021, 2022). Kinh, Tay, H'Mong and Dao are the four most populated ethnic groups that account for 88% of the province population (General Statistics Office of Vietnam, 2020). Buffalo, cattle, horses, pigs and goats are the most common livestock that contribute significantly to the local economy (Lao Cai Statistics Office 2021, 2022). In 2022, there were approximately 105,000 buffalos, 23,000 cattle and 3,000 horses in Lao Cai. The provincial livestock production system comprised mainly small-scale farms and household-scale live-

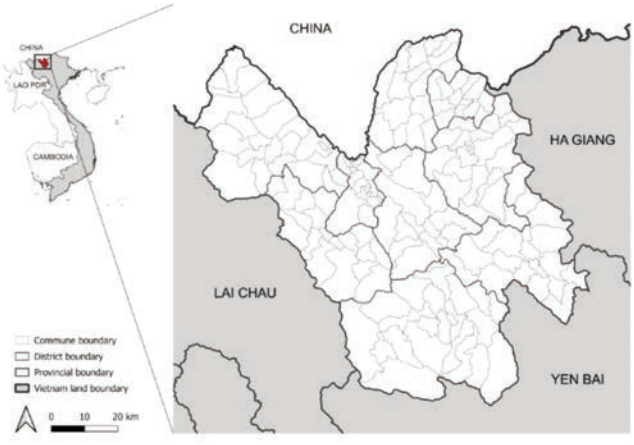

Figure 1. Lao Cai Province in northern Vietnam and three governmental administrative levels in the province. Produced in QGIS using shapefiles downloaded from https://gadm.org.

stock establishments; the latter predominant in Lao Cai. Small-scale farms are those with an annual production value of approximately one billion Vietnamese Dong (~$40,000 USD). A household-scale establishment is owned by a family and often has several domestic animals per household. Though the number of registered farms was reduced from ~300 farms in 2018 to 118 in 2022, the farm number in Lao Cai is measurably higher than in neighbouring provinces (Ha Giang, Dien Bien, Lai Chau) but lower than in Son La Province (257 farms in 2022). The farms are highly concentrated in Bao Thang District (almost 90% of the total farms) (Lao Cai Statistics Office 2021, 2022; General Statistics Office of Vietnam, 2023).

Data collection and management

Lao Cai Provincial Centre for Disease Control (PCDC) and the Sub-Department of Animal Husbandry and Animal Health (Sub-DAH) have collected historical anthrax data from 1991 to 2022 in both humans and livestock. The month and year of the outbreaks are available from Lao Cai Sub-DAH reports that also provide annual livestock vaccination information for the whole province.

The public health system of Lao Cai Province is managed across three administrative levels. Health facilities at each level (provincial hospitals, district hospitals and commune health centres) are involved in infectious disease surveillance and control. Any patient receiving a clinical diagnosis of anthrax based on clinical signs and/or symptoms in one of the health facilities are reported to the PCDC. Index case notification triggers field outbreak investigations to identify further human and/or animal cases in the community. Field veterinarians conduct livestock anthrax surveillance, identify animal cases during household visits or receive case notifications from animal owners. Patients with active infections are treated at public hospitals or commune health centres.

Public health officials, veterinarians and local law enforcement staff jointly conduct contact tracing and collect samples from potentially contaminated meat products including, burned and buried dead animals. In a remote area, such as Lao Cai Province, collecting clinical samples for laboratory diagnosis is challenging and this was particularly true in the 1990s. Therefore, we relied on the judgments of the physicians based on clinical symptoms (human anthrax) and/or clinical signs (human and livestock anthrax) plus epidemiological factors (*i.e.* being in close contact with a sick/dead animal). These clinical signs and symptoms were used as anthrax case definitions in Vietnam's infectious disease surveillance system (Tan *et al.*, 2022). We entered data into a Microsoft Excel spreadsheet and then aggregated into commune polygons in QGIS, version 3.32.3 for mapping and spatial analyses (QGIS Development Team 2022). This study used open source commune, district, province and country polygons from GADM, version 3.6 (https://gadm.org/) (Global Administrative Areas, 2021).

Human and livestock population estimation

Populations in each commune were used as denominators for calculating crude cumulative incidence rates of anthrax in either humans or livestock. They were also used as underlying populations in spatial cluster analyses. We employed a zonal statistic routine in QGIS to estimate human and livestock populations for each commune from 1991 to 2022. The methods have been described elsewhere (Barro *et al.*, 2015) and their accuracy has been demonstrated in other studies at multiple spatial scales in Vietnam (Walker *et al.*, 2022; Luong *et al.*, 2023). For human populations, gridded unconstrained individual country population counts (grid cell resolution ~ 100x100 meters at the equator) for each year from 2000 to 2020 came from Worldpop.org. These population data were adjusted towards the population estimates provided by the United Nations (Gaughan *et al*., 2013; Worldpop 2022;). A zonal statistic routine was performed in QGIS to estimate human populations for each commune each year for the same period. Given the population growth rates in Lao Cai Province ranging between 2-3% per year (Lao Cai Statistics Office 2021, 2022), missing populations in each commune from 1991-1999 were calculated backwards using the zonal estimated populations in 2000 and an annual population growth rate of -2%. Similarly, a growth rate of 2% and forward calculations were applied for the missing populations in 2021-2022 based on the zonal estimated population in 2020. There were several common livestock species in Lao Cai; however, buffalo, cattle and horses accounted for most of the large-size livestock populations in the province (based on Sub-DAH reports). Additionally, the provincial anthrax vaccination program was limited to these three species. Thus, we estimated populations of buffalo, cattle and horses for incidence calculation and spatial cluster analysis at the commune level. We utilized two livestock data sources to estimate each commune's population each year for 1991-2022. First, we could retrieve the total populations for each of these species in 2005 and each year from 2007 to 2021 in each district of Lao Cai Province from the local agency reports. These numbers allowed the calculation of annual growth rates of each species as well as the ratios between species in each district for each year (2005, 2007-2021). The annual growth rates and between-species ratios from 1991 to 2004, 2006 and 2022 were assigned the average annual growth rates and ratios of the known period (2007-2021) of the corresponding district. Second, we downloaded a gridded cattle population count in 2006 (with a grid cell resolution of one km^2 at the equator) from the Livestock Geo-Wiki website (https://geo-wiki.org) (Robinson *et al.*, 2014). The raster of cattle population counts in 2006 was clipped to the boundary of each district. The raster calculator in QGIS was employed to create new raster layers of cattle populations for each district each year for 1991-2005 and 2007-2022 using the above-mentioned annual growth rates of cattle and the gridded cattle population count in 2006. Next, new raster layers of buffalo and horses for each district by year were created by using the raster calculator with year-specific cattle population count and the corresponding buffalo-to-cattle/horse-to-cattle ratios. After creating raster layers for each species, each district and each year from 1991 to 2022, we used the merge function in QGIS to combine the district raster layers to create a gridded population count for each species and each year in the whole province (resolution = one km^2 at the equator). Then, the zonal statistic routine was conducted in QGIS to estimate each commune's annual population of cattle, buffalo and horses from 1991 to 2022. The annual zonal estimated populations of each of the three species (2007-2021) in the whole province were compared to local agency reports. It shows reasonably close estimates of zonal statistics compared to the local reports (1-3% higher for cattle and buffalo; 2-7% higher for horses) (*Figure S1in the Supplement)*.

Crude cumulative incidence calculation

The cumulative incidence (CI) indicated the number of anthrax cases per 10,000 population of humans or livestock in the province from 1991 to 2022. Here, livestock refers to buffalo, cattle and horses, which were included in Lao Cai Province's livestock anthrax vaccination programme. Inclusion of other animal species,

such as pigs would have biased the incidence and spatial analysis because pig cases were only reported in a single year and its populations were large. The crude CI of human anthrax was calculated by dividing the total number of human cases (1991-2022) by the median-year human population (the average of populations in 2006 and 2007). Similarly, crude CI of livestock anthrax was the quotient of the total number of anthrax cases in buffalo, cattle and horses divided by the total population of these three species in the median year. The total number of cases and crude CI of human and livestock anthrax were mapped in QGIS to illustrate the anthrax distribution at the commune level of Lao Cai Province.

Livestock anthrax vaccine coverage

Anthrax vaccine was administered as one dose per year for each individual buffalo, cattle or horse. Therefore, livestock anthrax vaccine coverage for the whole province was calculated for each year from 1991 to 2022 using the total number of vaccine doses administered divided by the total combine buffalo, cattle and horse population in a corresponding year. The vaccination timing was determined by the funding availability for purchasing vaccine from the provincial budget. It was not uncommon that the vaccine was only available for vaccine deployment from the middle of the year (June-July).

Purely spatial SaTScan

We performed spatial scan statistics using SaTScan version 9.6 to detect spatial clusters of anthrax in the whole study period (1991-2022) (Kulldorff, 2022). The method was recently used in a study using human anthrax data in a nearby province of Vietnam (Luong *et al.*, 2023). Briefly, purely spatial scan statistics impose a series of circular search windows varying in radii from zero to a user-defined maximum radius determined by a proportion of the population at risk in a discrete Poisson model. The spatial clusters of anthrax were detected by comparing the risk inside versus outside each search window. The alternative hypothesis was that the anthrax risk inside the search window would be higher than that outside (Kulldorff, 1997). The likelihood ratio test was used to determine the most likely cluster with a maximum likelihood function and secondary clusters with lower likelihood values. The spatial clusters were determined at $p \leq 0.05$, which was calculated through 999 permutations using Monte Carlo simulations. Each cluster's relative risk (RR) was calculated using the observed and expected number of cases and the likelihood function (Kulldorff, 1997). Here, the centroid of each commune was used as a centre for each search window. The commune centroids (latitude/longitude) were extracted using the field calculator tool in QGIS. The purely spatial SaTScan was conducted for human anthrax and livestock anthrax in separate experiments, the specified window maximum radius of which was set at 15%, 25%, and 50% of the population at risk. These experiments required no geographical overlap among the identified spatial clusters. The centre of each detected cluster was a commune where its centroid was used as the centre for a search window and the cluster members were those included in a corresponding search window. The SaTScan results were aggregated to commune shapefiles and the spatial clusters were mapped in QGIS.

Results

Number of anthrax cases

A total of 106 human cases (9 deaths) and 91 animal cases were reported from 1991 to 2022 in Lao Cai Province. Most anthrax cases in both humans and animals were reported from 1991 to 1998, while sporadic outbreaks occurred in 2005 and 2008. The province reported zero cases from 2009 to 2022 (Figure 2). Buffalo, cattle, and horses accounted for 75% of animal anthrax cases, often

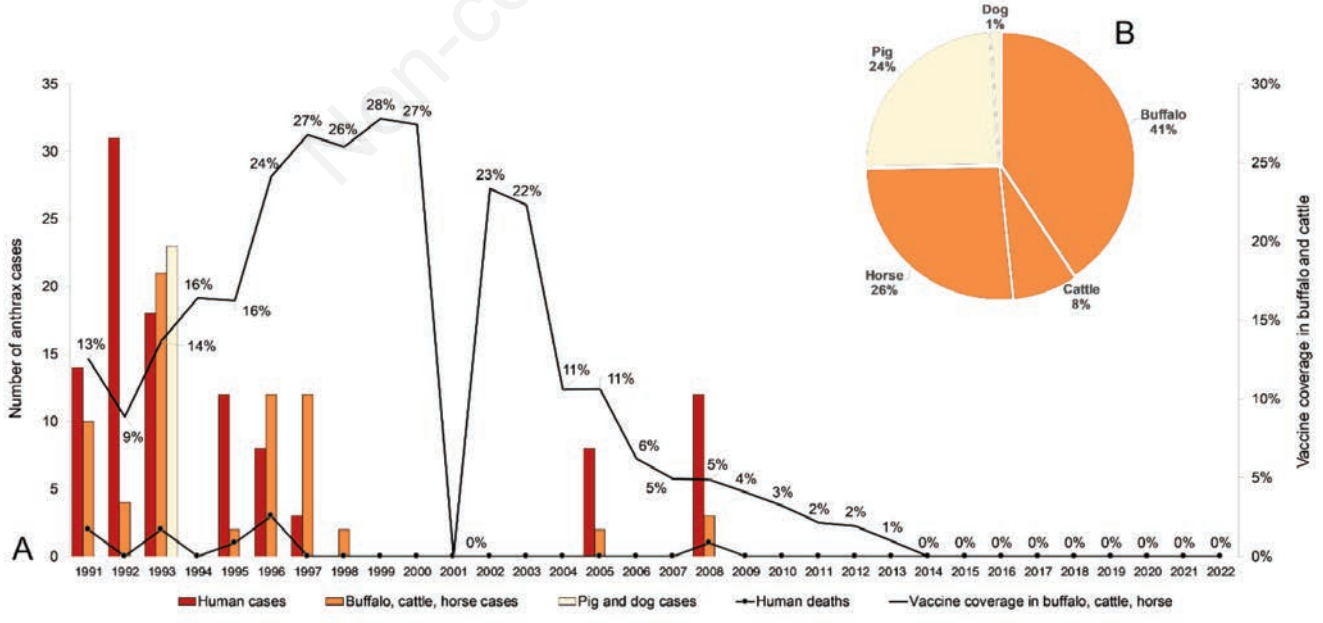

Figure 2. Seasonal pattern of human and animal anthrax in Lao Cai Province, Vietnam 1991-2022. Anthrax vaccine coverage in buffalo/cattle/horse and the number of human and animal anthrax cases.

accompanied with a rise in human cases. Cases in other animals, including pigs and dogs, were only reported in 1993. Higher numbers of horse cases were also reported in 1993, 1995, 1996, and 2008, all years with human mortality due to anthrax.

Figure 2 compares the number of anthrax cases and anthrax vaccine coverage in buffalo, cattle and horses for the whole province. The provincial anthrax vaccination programme covered less than 30% of these populations. Higher vaccination rates were seen from 1998 to 2003 (probably caused by a missing report rather than a true drop in vaccine coverage in 2001), where lower or zero anthrax cases in both humans and livestock were reported. In contrast, outbreaks occurred when vaccine coverage dropped to lower percentages in the periods 1991-1997 and 2004-2008. The vaccination programme was stopped in 2014 due to a lower disease priority in the local health plans (Figure 3).

Figure 4 depicts the spatial distribution of human anthrax and livestock anthrax in Lao Cai Province using the number of cases and crude CI per 10,000 population. Human anthrax was reported in 12 communes of four districts, including Bao Thang, Bac Ha, Muong Khuong and Si Ma Cai (Figure 4A). The crude CI per 10,000 people indicates a higher burden of anthrax in northern communes of Muong Khuong District (up to 173 cases per 10,000 people) in the study period (Figure 4B). Animal anthrax was reported in 12 communes where also human anthrax occurred. Additionally, livestock anthrax was present in three other communes where zero human cases were reported (Figure 4C). The crude CI of livestock anthrax shows the spread out of livestock anthrax in which many communes had a crude CI higher than 20 cases per 10,000 livestock heads. Particularly, two adjacent communes in the districts of Bac Ha and Bao Thang (centre of Figure 4D) and one commune in north-eastern Bac Ha District had crude CIs ranging from 147 to 894 cases per 10,000 livestock population.

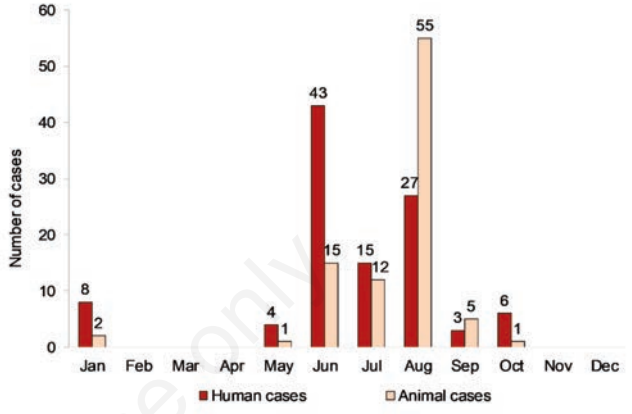

Figure 3. Spatial distributions of human and livestock anthrax in Lao Cai Province, Vietnam 1991-2022. The monthly distribution of anthrax in humans and all animal species (buffalo, cattle, horses, pigs, dogs) based on the cases reported. Most outbreaks occurred from May to October, except for an outbreak in January 2008.

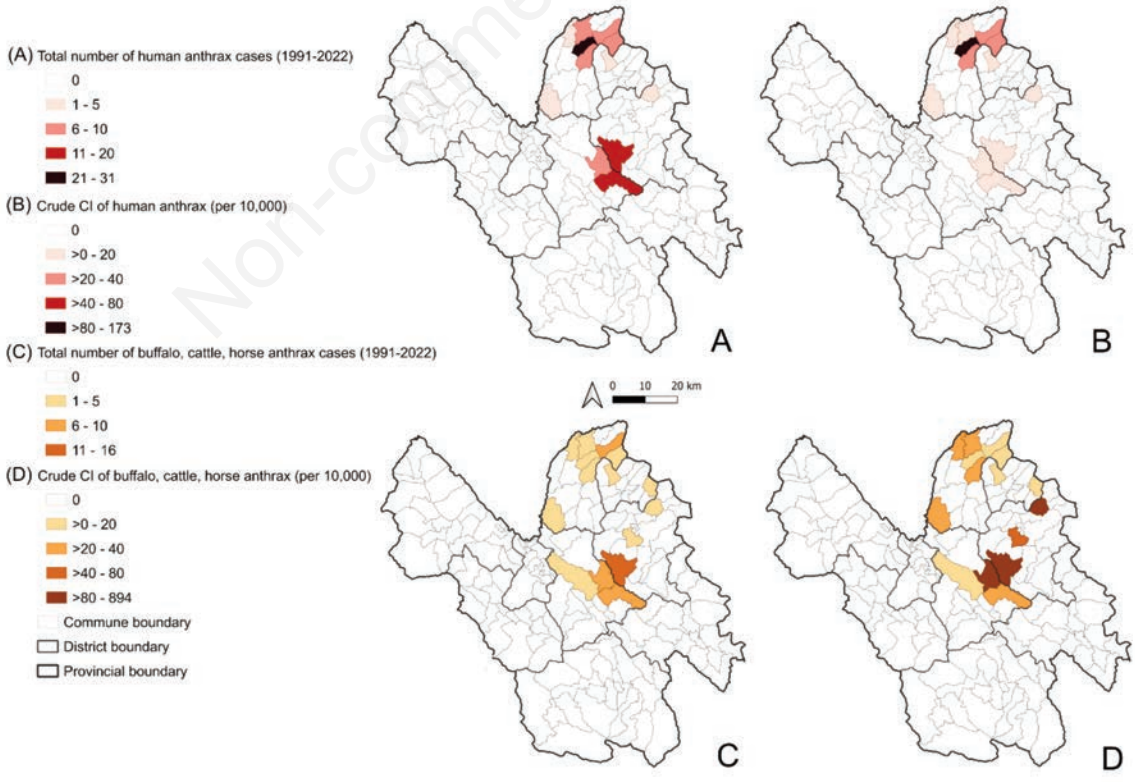

Figure 4. Total cases and crude cumulative incidence rates of anthrax in Lao Cai Province, Vietnam in 1991-2022. Human anthrax (**A, B**) and livestock anthrax (**C, D**).

Spatial clusters of human and livestock anthrax 1991-2022

The purely spatial SaTScan identified two spatial clusters of human anthrax (Figure 5A). The primary cluster with the highest likelihood value was centred in a northern commune of Muong Khuong District and expanded to cover seven communes of this district and two communes of Si Ma Cai District (RR=33.6). The secondary cluster was detected in one commune of Bao Thang District and two from the districts Bao Thang and Bac Ha (RR=13.6). For livestock anthrax, three spatial clusters were detected (Figure 5B). The primary cluster of livestock anthrax (buffalo, cattle, horses) was identified in the same area as the secondary cluster of human anthrax (RR=129.9). A secondary cluster was found near the primary human anthrax cluster (RR=6.8). An additional secondary cluster of livestock anthrax was identified in a single north-eastern commune of Bac Ha District (RR=45.6).

Discussion

There are two plausible hypotheses for the absence of anthrax from 2009 to 2022. Firstly, as it has been declared recently by local media news, control measures, such as animal health quarantine and health education for improving disease awareness have been well implemented (Cong Information of Lao Cai Province, 2023). However, it has been challenging to implement an effective quarantine campaign for many years because trans-border animal trade (official and unofficial) has been documented in the area for a long time (Turner, 2010). Second, anthrax has been underreported due to the low disease control priority and low disease awareness among local public health and veterinary staff (Trang *et al.*, 2015). Low disease control priority in the local health plans was indicated by the termination of a routine anthrax vaccination programme in the province in 2014. The low disease awareness was possible as anthrax had been absent in local reports for over a decade. Additionally, household-scale livestock establishments were predominant in Lao Cai Province, which likely increased challenges in livestock vaccination, livestock trading management and disease surveillance; this is particularly true in the mountainous region. The household livestock establishments were often considered an informal sector and had limited access to necessary resources for disease control (Dang-Xuan *et al.*, 2016; Nguyen-Viet *et al.*, 2017). The underreporting was likely influenced by socio-economic factors as one third of the population in Lao Cai live under the poverty line (Lao Cai Statistics Office 2016, 2017). A buffalo or a cow is a monetarily valuable asset for a household, which could facilitate the risk of consuming dead animals without reporting to local authorities. The second hypothesis is more plausible in the context that persistent anthrax has been reported in neighbouring provinces, *i.e.* Dien Bien, Ha Giang and Son La, in recent years (Tan *et al.*, 2022; Luong *et al.*, 2023; Metrailer *et al.*, 2023). These observations should encourage local agencies to revisit and conduct intensive surveillance in the high-risk areas where anthrax was historically reported.

The total number of reported animal anthrax cases nearly

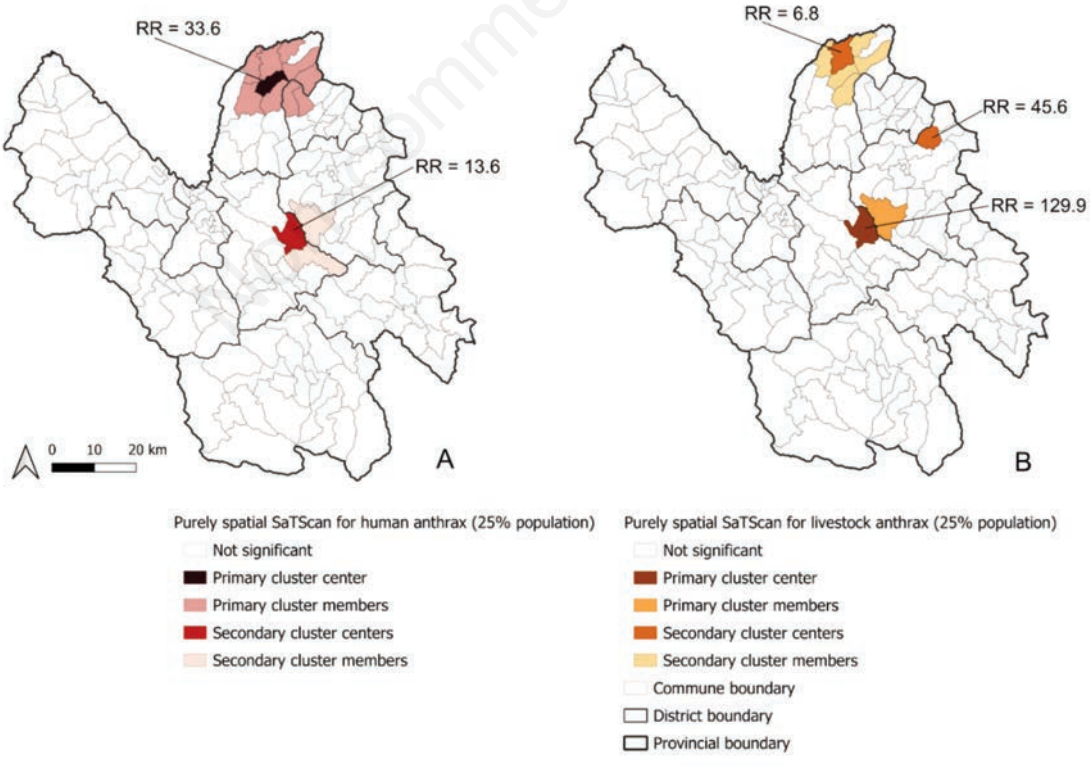

Figure 5. Spatial clusters of anthrax in humans and livestock in Lao Cai province, Vietnam 1991-2022. Human anthrax (**A**); livestock anthrax (**B**) detected by purely spatial SaTScan (Poisson, 999 permutations, 25% population at risk).

equalled the number of human ones indicating a different pattern compared to a recent study in nearby Son La Province, where a single animal death was associated with multiple human exposures and infections due to meat-sharing practices (Metrailer *et al.*, 2023). Buffalo, cattle and horses comprised 75% animal anthrax cases. Interestingly, horse anthrax was more common in Lao Cai Province compared to its neighbouring provinces (Tan *et al.*, 2022; Luong *et al.*, 2023; Luong *et al.*, 2023). Human mortality due to anthrax was observed when horse cases emerged (1993, 1995, 1996 and 2008) in Lao Cai Province. This could be associated with a traditional dish, namely "Thang co", a specialty of H'Mong people using horse meat and organs (Ta, 2022). However, we should be cautious with the interpretation and further anthropological and epidemiological investigations are needed to determine if ethnicity and culture can be associated with an elevated risk of anthrax. Local agencies are also recommended to pay attention to all animal species susceptible to *Bacillus anthracis* in their surveillance and control activities.

The seasonal pattern of anthrax in Lao Cai province suggests a timeframe for surveillance like the seasonal patterns in other provinces of northern Vietnam (Luong *et al.*, 2023). More surveillance efforts and resources for controlling the disease should be prepared before the anthrax season from May to October each year. Additionally, since the data in Lao Cai Province represent a pattern in the past (1991-2008), local agencies need to communicate with other neighbouring provinces that have recently reported anthrax to have a better understanding of the current anthrax season, and to collaborate in a trans-boundary/regional approach for anthrax surveillance and control. Though the available data did not allow a statistical evaluation of the role vaccination coverage, the patterns of livestock vaccination and disease occurrence clearly show the effective disease control of higher anthrax vaccine coverage, at least from 1998 to 2004 for buffalo, cattle and horses with respect to subsequent protection for humans. This finding aligns with studies conducted in other provinces of northern Vietnam (Tan *et al.*, 2022; Luong *et al.*, 2023) and a study in Georgia (Kracalik *et al.*, 2017). Although we observed spatial overlap, disease intensity showed an apparent spatial mismatch between crude CI of human and livestock anthrax. Human anthrax was more intense in the northern communes of Muong Khuong district, whereas livestock anthrax showed higher rates in the central communes of Bac Ha and Bao Thang districts. Two reasons could explain the mismatch. First, the population distribution would bias the crude CI where communes with higher populations as they would then have a lower rate, or vice versa. It is a fact that livestock was more populated in the northern communes of Muong Khuong District compared to the central communes of Bac Ha and Bao Thang *(Figure S2 in the Supplement*). In contrast, the human populations were higher in the central communes in Bac Ha and Bao Thang compared to the northern communes of Muong Khuong District. Second, the mismatch indicates a silo effect from a separation of anthrax reporting between the human and animal health sectors with irregular or no information sharing with one sector to the other. This is plausible since the data used in this study were dated long before the establishment of the first national guideline for intersectoral zoonotic disease surveillance in Vietnam (Vietnam - Joint circular number 16/2013/TTLT-BYT-BNN&PTNT, 2013). This silo effect has been described elsewhere in Vietnam and limits One Health efforts (McPake *et al.*, 2022).

The purely spatial SaTScan identified two human anthrax clusters and three livestock anthrax clusters in Lao Cai Province. The primary human anthrax and livestock anthrax clusters were detected in different areas, a mismatch that could be driven by the disease intensity under the influence of the population distribution explained above for crude CI. On the other hand, considering all significant spatial clusters, high-risk areas of anthrax both for humans and livestock existed in the northern communes of Muong Khuong District and the central and north-eastern communes belonging to the districts Bac Ha and Bao Thang. In the context of the limited disease surveillance and control resources, the province's human and animal health sectors are advised to first plan and implement future intersectoral anthrax surveillance strategies with the high-risk areas detected.

Our study faced limitations regarding data incompleteness as anthrax has not been reported in Lao Cao province since 2009. The incomplete case data did not allow statistical evaluations about the epidemiology of anthrax or to determine the roles of each livestock species with respect to human exposure. Additionally, the seasonal pattern relied on livestock anthrax data that could only be verified by prospective anthrax surveillance in the province.

Conclusions

The findings of seasonal pattern and spatial distribution of anthrax in Lao Cai Province, northern Vietnam should encourage the local agencies to revisit historical high-risk areas determined by the spatial cluster analysis and engage in an intersectoral approach involving both human and animal health sectors. The authorities should communicate with neighbouring provinces to join the regional anthrax surveillance and control efforts. We also observed a higher frequency of horse anthrax that suggests future studies investigating the association between horse-related cultural practices and anthrax risk.

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Online Supplementary Material

Figure S1. Difference between zonal estimated populations and local agencies' data (2007-2021) for Lao Cai Province, Vietnam. The percentage of difference indicates that populations estimated by zonal statistics are reasonably higher than in local reports.

Figure S2. Spatial distribution of the livestock population (buffalo, cattle, and horses) in Lao Cai Province, Vietnam in the median year (average of 2006 and 2007). The annual populations of each species were estimated by the Zonal statistic routine function of QGIS, using gridded cattle population count in 2006 (resolution one km^2 at the equator) from the Livestock Geo-Wiki website (https://geo-wiki.org) and the annual growth rates provided by the Provincial Sub-Department of Animal Health. The method for livestock population estimation is described in the Materials and Methods section of the paper.