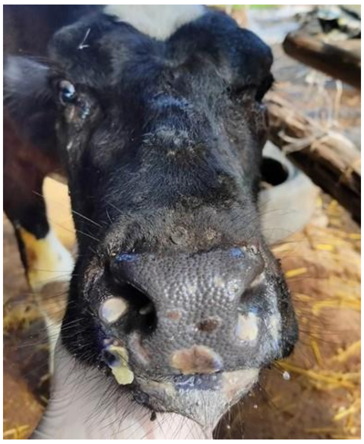
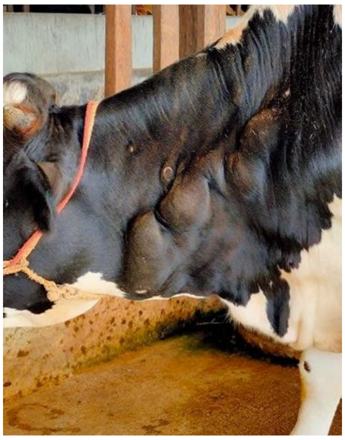
Final Report
Study to assess the impact of Lumpy Skin Disease (LSD) in Asia

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Abbreviation list

DLD	Department of Livestock Development, Thailand
EFSA	The European Food Safety Authority
FDG	Focus Group Discussion
GTPV	Goat pox virus
LSD	Lumpy skin disease
LSDV	Lumpy skin disease virus
MSCS	Maximum spatial cluster size
MTCS	Maximum temporal cluster size
SDE	Standard deviation ellipse
SEA	South East Asia
SPPV	Sheep pox virus
STP	Space time permutation
WAHIS	World Animal Health Information System
WOAH	The World Organisation for Animal Health

Executive summary of the overall study

A study to assess the impact of Lumpy skin disease (LSD) in Asia was commissioned by World Organisation for Animal Health (WOAH) and implemented by Chiang Mai University, (CMU), Thailand. The study was implemented from January 2023 to April 2024.

LSD has been geographically distributed from Africa to the Middle East and Asia. LSD was first reported in Asia and the Pacific region in 2019. LSD was first reported in Asia and the Pacific region in 2019 in north-west China, Bangladesh and India. During the northern summer of 2020, LSD has continued its spread across continental Asia with many members in South and South East Asia confirming outbreaks including eight out of 10 countries reported LSD outbreaks. Lumpy skin disease virus (LSDV) is highly host-specific causes disease only in bovine species such as cattle and water buffalo. However, LSDV affected a range of wildlife, including Gaur, Mainland serow, and Banteng LSD in the region and its implication on some of the endangered species of ungulates in SEA is not fully understood.

The estimated economic losses from these outbreaks have reached up to USD 1.45 billion. In this region, the animal trade is considered a significant driver of LSD spread, particularly in terms of long-distance transmission. Locally, short-distance transmission is likely facilitated by insect vectors. Molecular epidemiology reveals that LSD strains isolated from outbreaks in various countries share similarities, suggesting discernible patterns in their geographical distribution. Common practices to control LSD outbreaks across several countries include animal movement control and vaccination.

A phylogenetic analysis demonstrated that LSDV isolates in South Asia resemble those from Kenya, while those in Southeast and East Asia are recombinant viruses combining the Neethling vaccine strain and local field isolates. The recombinant LSDV predominating the LSD epidemic in South-East Asia due to insufficiently controlled LSDV vaccine was responsible for the release of recombinant LSDV strains in the field. This highlights the importance of using vaccine quality control to prevent future emergence of recombinant LSDV strains.

The spatio-temporal models identified that the clusters of LSD outbreaks in Asia were primarily concentrated in the southern and southeastern regions of the continent. The southeastern region was particularly notable for the high concentration of outbreak clusters. From 2006 to 2023, LSD outbreaks in Asia generally followed a west-to-east trend, as indicated by directional analysis. Nevertheless, an analysis of the data from 2021 to 2023 revealed that the distribution direction in Southeast Asia was from the northeast to the southwest. This pattern is associated with the significant increase in LSD outbreaks in the southeastern region.

The spread of LSDV between countries or regions is primarily associated with introduction of new livestock or illegal animal transportation. On the other hand, the transmission of LSDV within countries is likely facilitated by both animal movement and insect vectors. Studies within countries have suggested that the absence or ineffective of insect control poses a risk for LSD outbreaks in naïve cattle herds.

Prevention and control measures implemented in several countries include animal movement control, insect vector control, vaccination, and raising awareness among farmers and stakeholders about the disease. However, the specific details of these strategies vary from country to country. LSD Vaccines successfully used for LSD control are largely homologous live attenuated, in Southeast Asia countries are using commercially available live attenuated Neethling strain vaccines. Safe and efficacious LSDV vaccines are available against classical and recombinant LSDV strains.

The nationwide vaccination campaign and various control measures implemented in Thailand such as restriction on animal movements and control of potential insect vectors plays a crucial role in controlling LSD, while the study in Bangladesh highlights the importance of vaccination coverage to combat the disease.

Comprehending the intricacies of cattle production value chains and the roles of stakeholders is important for effective management. LSD outbreaks exert a detrimental impact along the cattle value chain, leading to reductions in milk production and carcass quality, hindrances in animal trading, and escalated operational costs. According to value chain analysis from the in-country study, LSD outbreaks cause significant economic losses in both dairy and beef production. In Thailand, the average total economic losses on the study farms were $2,461 USD, primarily due to the costs of treating LSD-infected cattle and losses in milk production. In Bangladesh, the losses averaged $283 USD, with the major losses attributed to cattle mortality and decreased milk production. The disparity in economic losses between the two countries is mainly due to the significantly larger herd sizes in Thailand compared to Bangladesh. From a sociological perspective, in small-holder cattle herds, the mortality or sickness of cattle negatively affects farmers, as cattle not only represent valuable assets but also integral parts of their families.

Given the extensive presence of LSD in Southeast Asia and the coexistence of other transboundary animal diseases (TADs) in the region, prioritizing resource mobilization efforts becomes imperative. Similar to other TADs, LSD can be effectively controlled through coordinated efforts among countries with similar epidemiological characteristics. Prevention and control strategies for LSD can be developed in alignment with the GF-TADs Strategy for 2021-2025.

Prevention and control of LSD in Asia require a comprehensive strategy that addresses various key aspects. It is imperative to strengthen coordination among stakeholders, including farmers, animal traders, and authorities, with support from WOAH as an international partner. Moreover, because the LSDV has been expanding its geographic coverage in non-endemic countries, sustaining its infection cycle, and causing massive outbreaks. Thus, there is an urgent need to activate surveillance mainly early detection and high-level monitoring programs and response to control LSD outbreaks in the region. Furthermore, it is crucial to enhance vaccine adoption by improving vaccine availability, ensuring quality, meeting demand, and achieving optimal vaccination coverage. It is imperative to attain a vaccination coverage of at least 80% within the target population.

For LSD-free country, it is advantageous to establish contingency plans. Preparedness measures, including early disease detection systems and the availability of laboratory facilities for prompt disease identification should be also formulated. Furthermore, conducting epidemiological simulation modeling to identify high-risk areas and assess the effectiveness of planned prevention and control interventions can provide valuable information for authorities and stakeholders to allocate budgets and resources effectively.

Capacity building through training programs for veterinarians, animal health officers, Veterinary paraprofessionals as well as strengthening regional epidemiology and laboratory networks, will enhance LSD prevention and control. Additionally, facilitating better coordination, harmonized approaches, and enhance quality of information sharing among countries in the region are essential components.

A comprehensive understanding of the epidemiology of LSD is essential for establishing effective contingency plans and control strategies at both regional and national levels. National studies should prioritize the development and evaluation of control strategies that are well-suited to the specific context of each country. On a regional scale, studies should focus on prevention and control strategies at borders and the identification of transboundary disease transmission pathways.

Regional study component

Summary of a regional study

- The regional study comprises a literature review of lumpy skin disease and an epidemiological study focusing on the spatial, temporal, and spatio-temporal distributions of LSD outbreaks.
- The primary approach of the literature review involves analyzing existing research publications, reports, and presentations from multiple countries presented at LSD regional meetings facilitated by WOAH.
- The literature review covers several topics but primarily focuses on the epidemiology of LSD in Asia, its impact, and the prevention and control strategies among Southeast Asian countries (SEA).
- LSD outbreak data obtained from WOAH were analyzed to determine the temporal and spatio-temporal distributions of LSD outbreaks in Asia. The same approach was applied to data from Southeast Asian countries to specifically focus on the distribution of LSD outbreaks in this region.
- The study investigated sixteen spatio-temporal models to determine LSD outbreak clusters through spatio-temporal analyses, employing various scenarios to generate outputs for interpretation. The results revealed clusters of LSD outbreaks in various regions.
- A directional distribution analysis was conducted to determine the spatial direction of LSD outbreaks in Asia and SEA. From 2006 to 2023 data, it is revealed that LSD outbreaks generally followed a trajectory originating in the Middle East, moving towards South Asia, and eventually reaching Southeast Asia.
- The analytical techniques, such as spatio-temporal analyses and directional analysis, are adaptable and can be applied to individual countries or specific regions within a country. This enables the exploration of LSD outbreak patterns within areas of particular interest.

Objective 1.1 Review of literature

Assessing the impact of lumpy skin disease in Asia: A literature review

Summary

- The first LSD outbreak in Asia occurred in Bangladesh in July, 2019. Since 2020, LSD outbreaks have been reported across several countries in Southeast Asia (SEA). In 2021, Thailand reported the highest number of LSD outbreaks in the region.
- LSD coordination meetings for SEA, organized by WOAH, have provided updates on the current LSD situation in SEA, facilitating activities to prevent and control the disease at both country and regional levels.
- Studies on the spatio-temporal distribution of LSD outbreaks demonstrate the existence of LSD outbreak clusters in several regions of Asia.
- Phylogenetic analysis revealed that the LSDV strains responsible for outbreaks in Vietnam were similar to those isolated in China and Russia. Moreover, the LSDV strain responsible for outbreaks in Myanmar was found to be indistinguishable from that discovered in Bangladesh and India.
- Several risk factors, including animal movement, insect vectors, and low farm biosecurity levels, are considered associated with LSD outbreaks in Asia.
- Most studies assessing the economic impact of LSD are solely based on partial estimations of economic losses. For example, a report from Bangladesh indicates that the financial loss per LSD case was USD 110, while a report from Thailand estimates losses due to a reduction in milk sold for dairy farms ranging from USD 119 to USD 413.
- Prevention and control of LSD is Asian countries generally based on vaccination.
- Only Thailand has reported the implementation of a nationwide vaccination campaign, with the effectiveness of this intervention demonstrated in a research publication.
- Regional cooperation should be facilitated for the prevention and control of LSD.
- Numerous knowledge gaps regarding LSD in Asia remain to be addressed. Further studies should focus on areas such as risk assessment for LSD outbreaks, identification of risk factors contributing to LSD outbreaks, assessment of LSD's impact along the value chain, evaluation of the effectiveness of control and prevention strategies implemented in each country, and epidemiological modeling of LSD.

Introduction

Lumpy skin disease (LSD) caused by the lumpy skin disease virus (LSDV) is a highly contagious, transboundary disease of cattle, buffalo, and some wildlife. The disease is on the list of the World Organisation for Animal Health (WOAH) (WOAH, 2022a). LSD has a negative impact on the cattle industry. It causes significant income loss for farmers and stakeholders along the value chain. Restriction of animal movements and trade bans in affected countries are also negative consequences of LSD.

LSD was originally found in sub-Saharan Africa, spreading to Egypt and the Middle East in the 1980s. The disease continued to spread and was discovered in Russia in 2015. It then spread to Europe. LSD has emerged in Asia, where it was discovered for the first time in Bangladesh in 2019. Thereafter, LSD outbreaks were reported in countries such as China, India, Nepal, Pakistan, Sri Lanka, Bhutan, Vietnam, Myanmar, Thailand, Malaysia, Laos, Cambodia Hong Kong, Taiwan, and Indonesia (Anwar et al., 2022; Azeem et al., 2022). LSD is now a major problem for livestock management and food safety in several Asian countries (Roche et al., 2020).

The disease is primarily transmitted mechanically by arthropod vectors (Tuppurainen et al., 2015) and has the potential to spread across countries or even continents via the movement of live animals (Sprygin et al., 2019). Several factors in Asia, including both legal and illegal transportation of livestock carrying the LSDV across borders, as well as the abundance of LSD insect vectors in some areas, have influenced the transboundary spread of LSD from one country to another (Roche et al., 2020).

The LSDV has been expanding its geographic coverage in non-endemic countries, sustaining its infection cycle, and causing massive outbreaks. Thus, there is an urgent need to activate global surveillance and high-level monitoring programs to control LSD outbreaks in the region.

Epidemiology of lumpy skin disease

Virus and host

The LSDV is a DNA virus of the *Carpripoxvirus* genus in the Poxvirus family. This genus comprises three viruses: LSDV, sheep pox virus (SPPV), and goat pox virus (GTPV). The LSDV shares 97% of its nucleotide sequences with SPPV and GTPV genomes (Tulman et al., 2001). The LSDV is large (230–260 nm), measuring 151 kb in length with 156 putative genes (Liang et al., 2022). Cattle and water buffalo (*Bubalus bubalis*) are the main hosts for the LSDV. Nevertheless, LSD infection has also been observed in some wildlife (Liang et al., 2022). In cattle, the morbidity varies from 2 to 45% and the mortality is usually less than 10% (Tuppurainen et al., 2021a). Nevertheless, LSD morbidity and mortality can vary considerably, depending on several factors such as the immunological status, age, and breed of cattle. The LSDV can survive for long periods at ambient temperatures, especially in dried scabs. It can persist in necrotic skin nodules for up to 33 days or longer. The virus can remain viable in a suitable environment for long periods (Mulatu and Feyisa, 2018).

Effects of LSD on animal health

The incubation period of LSD usually ranges from 4–7 days, as determined experimentally, but in natural conditions, this period is reported to range from 28–35 days (Ratyotha et al., 2022). The disease is characterized by large skin nodules, fever, enlarged lymph nodes, loss of appetite, and a reduction in milk production (Tuppurainen and Oura, 2011). It causes nasal discharge, reduced milk production, listlessness, and anorexia. Skin nodule lesions often appear on the head, limbs, neck, muzzle, eyelids, legs, perineum, udder, and genitalia (Molla et al., 2017a; Arjkumpa et al., 2022b). Lesions are usually exhibited as raised areas on the skin, measuring 2-7 cm in diameter (Namazi and Khodakaram Tafti, 2021). These lesions become necrotic after 2–3 weeks. A lesion that has sloughed off may leave a hole with a full thickness of skin and the “sit fast” necrosis lesion, which is an inverted conical zone of necrosis (Mulatu and Feyisa, 2018).

LSD-infected animals also have fever, hypersalivation, and enlargement of superficial lymph nodes. Mastitis or quarter loss due to teat lesions, pneumonia along with consolidation, abortion in the acute stage of the disease, and infertility in bulls are sequels of LSD (Namazi and Khodakaram Tafti, 2021).

According to a study conducted in Northeast Thailand in 2021, animals developed nodules on the flanks, legs, and neck. In some cattle, LSD complications like wounds with stable flies and maggots were observed (Arjkumpa et al., 2021). Furthermore, an investigation in Bangladesh showed that nodular lesions are the most common type of skin lesion, followed by laceration and nodular plus laceration lesions. Most lesions were seen on the whole body of animals, followed by the legs, neck, head, and lastly the neck plus leg region. More instances of swelling were observed in the joints than in any other part of the body (Parvin et al., 2022).

Transmission

The LSD virus is widely spread through blood-sucking insect vectors, which facilitate its mechanical transmission (Gupta et al., 2020). The most important LSDV vectors are biting flies such as *Stomoxys spp*., *Haematobia spp.,* and *Tabanidae spp.* Studies have shown that biting flies are highly prevalent in certain parts of Asia, and their presence is closely associated with the occurrence of LSD outbreaks (Jamil et al., 2022). In particular, *Stomoxys calcitrans* has been identified as a significant vector of LSDV in several Asian countries, including Pakistan, China, Egypt, and India. Moreover, multiple studies have implicated mosquitoes such as *Culicoides spp.* (biting midges) (Şevik and Doğan, 2017), *Culex spp.,* and *Aedes spp.* (Khan et al., 2021) as LSD insect vectors. Blood-sucking insects have been postulated to play a significant role in the spread of LSDV over a short distance. Most blood-feeding insects can fly up to 100 m without assistance from air currents (Greenberg et al., 2012), however viruses can be transmitted over considerably greater distances by flying insects with wind-assisted transmission (Chihota et al., 2001, 2003). Therefore, the spread of LSDV by flying insect vectors may not be restricted to a short distance.

Ticks also serve as vectors for the transmission of the LSDV. Several tick species have been identified as potential vectors of LSD in Asia, including the Asian blue tick (*Rhipicephalus microplus*), *Rhipicephalus annalatus* (El-Ansary et al., 2022), *Rhipicephalus decoloratus,* and the Asian long-horned tick (*Haemaphysalis longicornis*). For instance, a study conducted in India identified the presence of *Amblyomma hebraeum* and *Rhipicephalus appendiculatus* ticks on LSD-infected animals. According to another study, the ixodid was shown to play an important role in the transmission of the disease in the region (Sprygin et al., 2019).

Using uncertainty and sensitivity analyses, the basic reproduction number (R_0) is estimated for biting insects: *Stomoxys calcitrans* (stable fly), *Culicoides nubeculosus* (biting midge), and three mosquito species, namely *Aedes aegypti*, *Anopheles stephensi*, and *Culex quinquefasciatus* (Gubbins, 2019). The R_0 is interpreted as the average number of secondary cases arising from the introduction of a single individual, demonstrating its relationship to the underlying transmission process in insect vectors and cattle. The results suggest that *S. calcitrans* and *Ae. aegypti* are likely to be efficient vectors (Gubbins, 2019). In the experimental conditions, the reproduction numbers for important LSD insect vectors are identified. The results show that *S. calcitrans* has the highest R_0 (median R_0=19.1), confirming its significant transmission ability (Sanz-Bernardo et al., 2021).

The disease can also be transmitted by direct contact and through contaminated food and water. Direct contact is a less common way for the LSD virus to spread between animals. This can occur when infected animals come into contact with healthy animals through activities such as grazing, feeding, or mating. Infected animals shed the virus through their saliva, nasal discharge, and skin nodules (Aleksandr et al., 2020).

Spread of LSD

The movement of infected animals appears to be a major factor in the long-distance spread of the LSDV, but distinct seasonal patterns suggest that the disease is most likely to spread rapidly and aggressively over short distances by arthropods (Sprygin et al., 2019).

Animal movements play an important role in the spread of LSD. The virus may be spread through animal transport and movement since infected animals can spread the virus to other animals in new locations (Sprygin et al., 2019). A study in Turkey reveals that the trade in LSDV-carrying animals could explain the long geographical spread of the LSDV within the country (Şevik and Doğan, 2017). Likewise, according to a Russian study, vehicle-assisted transport of LSD-infected animals is associated with new LSD cases in locations more than 800 km away from the outbreak epicenter (Sprygin et al., 2018).

The complexity of the cattle and buffalo trade in Asia is well documented. The animal trade in this region is considered to be a driver of LSD introduction and spread (Roche et al., 2020). The informal animal trade of cattle and buffalo across the long porous borders between India, Nepal, and Bangladesh promoted the spread of LSD in July–August 2019 between Bangladesh and India (Roche et al., 2020). Similarly, the introduction of LSD to Nepal in June 2020 was most likely due to the ongoing flow of informal cross-border cattle movements from India to districts in Eastern Nepal. Since the LSDV that caused the outbreaks in Vietnam was similar to the strain endemic in Russia and China, it seems likely to have been introduced at the China-Vietnam border, subsequently spreading throughout all 27 provinces in Vietnam (Roche et al., 2020).

The control of animal movement is very challenging. Although Asian countries have control points and quarantine facilities, the presence of non-clinical animals and a potentially long incubation period for LSD in naturally infected animals (up to five weeks) may facilitate transnational spread through the trading of seemingly healthy animals harboring the virus during its incubation phase (Roche et al., 2020).

Spread and geographical distribution of LSD in Asia

Africa is endemic to LSD. The disease was first reported in Zambia in 1929 and later started to migrate from Africa to other continents (Tuppurainen and Oura, 2011). Prior to the discovery of LSD in Asian nations, the disease spread throughout the Middle East and surrounding countries.

LSD is transmitted through vectors and the first outbreak in Israel from Egypt in 1989 confirmed its aerial movement (Yeruham et al., 1995). Furthermore, Oman faced its first outbreak in 2009 (Kumar, 2011). Then from 2012–2013, the disease continued to be reported in Middle Eastern countries such as Syria, Lebanon, and Jordan. The disease spread to Jordan due to its close proximity to Israel and Syria, hence confirming the transboundary nature of LSD (Abutarbush et al., 2015). The disease was then propagated to Turkey through the Syrian border, further spreading to the Aegean, Mediterranean region, and Eastern, Central, and Southeastern Anatolia (Şevik and Doğan, 2017). Although the origin of LSD in Iraq in 2013 was unknown, the country shared extensive borders with many other nations, including Jordan, Turkey, Syria, Kuwait, Saudi Arabia, and Iran. LSD further spread to Cyprus and reappeared in Turkey in 2014 (Zeynalova et al., 2016; Şevik and Doğan, 2017; Saegerman et al., 2018). In the same year, due to the movement of animals through the Iranian border, the disease arrived in Azerbaijan (Zeynalova et al., 2016). The disease then covered almost all parts of the Middle East, with its presence reported in Armenia, Saudi Arabia, and Kuwait in 2015. Georgia was also documented to have an outbreak near the Russian border in 2016. The disease continued to occur in Azerbaijan during 2016 and 2017 (Saltykov et al., 2022). Epidemiological surveys indicate that the disease entered China via the Kazakh border (Kazakhstan) in 2019 (Khan et al., 2021).

The spread of LSD in Asia

Central Asia:

LSD further spread to Kazakhstan, with the first case being reported in 2016. Interestingly, phylogenetic analysis revealed that the strain bears a close resemblance to the one found in neighboring Russia (Orynbayev et al., 2021) Vaccine-like strains were found to be associated with LSD outbreaks in Russia which borders Kazakhstan (Kononov et al., 2019).

South Asia: Bangladesh reported its first LSD outbreak in July 2019 (Biswas et al., 2020). Subsequently, India reported it first outbreak in August of the same year (Sudhakar et al., 2020). Bhutan reported the occurrence of LSD in 2020 (WOAH, 2021d). In June 2020, Nepal reported the first outbreak of LSD in the eastern part of the country (Roche et al., 2020). The first outbreak in Pakistan occurred in 2021 (Imran et al., 2022). The results of the phylogenetic analysis conducted on the virus extracted from animal samples in India indicate a higher degree of genetic similarity with strains found in South Africa (Sudhakar et al., 2020). Moreover, the LSDVs obtained from confirmed cases in Nepal exhibit a close relationship to the virus originating from Kenya, as well as a resemblance to those identified in neighboring countries such as India and Bangladesh (Koirala et al., 2022).

East Asia:

In this region, China reported the first LSD outbreak in 2019. Additionally, the LSD outbreak in the Hong Kong territory was first documented in November 2020. The Hong Kong LSDV strain was strongly linked with live attenuated Neethling vaccine strains (Flannery et al., 2022). In 2021, Mongolia reported its first LSD outbreak (Odonchimeg et al., 2022). By July 2020, eight outbreaks had occurred in seven provinces of China, resulting in the infection of 156 cattle (Lu et al., 2021).

Southeast Asia:

From China, LSD spread to Southeast Asia, and by 2020, Vietnam faced LSD outbreaks. Phylogenetic analysis revealed that the LSDV strains responsible for outbreaks in Vietnam were similar to those isolated in China and Russia (Tran et al., 2021). Myanmar first reported LSD in 2020, and the LSDV strain associated with the outbreaks was identical to that found in Bangladesh and India (Maw et al., 2022). The year 2021 was critical for Southeast Asia due to the massive outbreaks there. Thailand contributed the most to these outbreaks, with LSD outbreaks being found across the country (Suwankitwat et al., 2022). Malaysia reported the first LSD outbreak in 2021 (WOAH, 2022c), as did Cambodia and Laos (WOAH, 2021j, h). In 2022, Singapore reported the first occurrence of LSD (WAHIS, 2022).

Outbreak reports from countries in South and Southeast Asia

Based on research publications and reports submitted to WOAH via World Animal Health Information System (WAHIS) and country presentations by the Members during the coordination meetings organized by WOAH (WOAH, 2021a, e, 2022f), the past status of LSD outbreaks in South and Southeast Asia are briefly described below.

South Asia

Bangladesh

In mid-July 2019, the first LSD outbreak in Asia occurred in Bangladesh, infecting 66 cattle in Chattogram District (Badhy et al., 2021). In October, the second LSD outbreak occurred in Dhaka, affecting 16 cattle. In March 2020, the third outbreak in Khulna affected 33 cattle, while a fourth outbreak occurred in Rajshahi, affecting 60 cattle (Azeem et al., 2022). From April 2020 to December 2021, LSD cases were reported in north Bangladesh (Parvin et al., 2022).

India

In the second week of August 2019, an outbreak occurred in India, affecting nine cattle in the state of Orissa/Odisha. Furthermore, two other outbreaks in the same state occurred later in August, affecting 79 cattle. In 2022, a massive outbreak began in May, infecting around 2.4 million animals and killing approximately 110,000 until October 2021. Phylogenetic analysis suggested that the LSDV isolates from Odisha and Ranchi were closely related to the Kenyan LSDV strain (Sudhakar et al., 2020).

Nepal

In June 2020, Nepal reported its first case of LSD in cattle farms [31], following outbreaks in South Asian nations including China, India, and Bangladesh. These cases occurred in a district close to the Indian border in Nepal. By the end of July 2020, the disease had infected 1,300 animals in three neighboring districts (Koirala et al., 2022). The LSDV isolates responsible for the outbreak in Nepal were closely related to historical LSDV strains from Kenya as well as those circulating in Bangladesh and India, implying that greater emphasis should be placed on LSD surveillance in the country (Koirala et al., 2022).

Southeast Asia

WOAH facilitated the following regional virtual coordination meetings to provide an update on the current LSD situation in Southeast Asia and to share experiences and lessons learned regarding the management of LSD outbreak:

1. A lumpy skin disease (LSD) coordination meeting for Southeast Asia in June 2021 (WOAH, 2021e). The presenters were from Cambodia, Lao PDR, Malaysia, Myanmar, Thailand, Vietnam, Indonesia, and the Philippines.
2. The second Lumpy skin disease (LSD) coordination meeting for Southeast Asia with focus on the implementation of LSD vaccination program in December 2021 (WOAH, 2021a). The presenters were representatives from Vietnam, Thailand, Malaysia, Lao PDR, the Philippines, and Indonesia.
3. A lumpy skin disease update meeting for Southeast Asia in December 2022 (WOAH, 2022f). The updated information was provided by presenters from Indonesia, Malaysia, Thailand, and Vietnam. There were also brief verbal updates by the Representatives from Myanmar, Singapore and Australia (WOAH, 2023a).

Based on the country presentations made by the Members during the coordination meetings organized by WOAH, the past status of LSD outbreaks in Southeast Asia are briefly described below. It should be noted that relevant information from research publications was also included.

Vietnam

LSD was discovered in Vietnam in 2020, affecting 65 districts and resulting in 137 reported cases. In 2021, more than 1,401 LSD outbreaks were reported in 190 districts of 27 provinces (WOAH, 2022e). The LSDV associated with the outbreaks was similar to the endemic in Russia and China, during 2017 and 2019, respectively. The updated report published in April 2022 showed that the total number of outbreaks was 4,712 with 211,266 animals being infected with the LSDV.

Myanmar

The first LSD outbreak was reported in November 2020. The index case was observed in Nyein Chan village. Later, more LSD cases were found in several villages (WOAH, 2021k).

Malaysia

In May 2021, Malaysia faced its first outbreak in Perak state (Khoo et al., 2022) with 600 infected animals being slaughtered and this incursion proved to indicate the transboundary spread of LSD. During 2021, both homologous and attenuated strains were implemented in the immunization program with a positive effect being observed in 2022 when the number of LSD drastically reduced and only two diseased animals had to be slaughtered (WOAH, 2022c).

Indonesia

Indonesia faced its first outbreak of LSD in Riau in February 2022, soon after the first outbreak in West Sumatera, Jambi, Aceh, and North Sumatera in March and April. The further spread of LSD to Central Java three months later also encompassed East Java, with a total of 3785 cases being reported. Since then, a vaccination program using the homologous attenuated Neethling strain has been implemented (WOAH, 2022b).

Laos

Laos reported its first outbreak in the Savannakhet Province in May 2021. Later, the disease spread to the capital of Vientiane, affecting five districts and infecting 369 cattle (WOAH, 2021f). To control the outbreak, the surveillance network was strengthened and farm biosecurity measures increased to control the LSD outbreak. There are no reports available on the current status of LSD in Laos.

Cambodia

Cambodia experienced its first outbreak in May 2021 in the provinces of Preah Vihear and Udor Meacnchey (WOAH, 2021j). Up to August 29, there were 39,000 infected animals from 158 districts. The LUMPIVAC vaccine containing the Neethling strain is available in Cambodia and used to control LSD.

Thailand

In April 2021, the first LSD outbreak occurred in the northeast region of Roi ET Province. Since then, the disease has spread across the country. More than 650,000 cattle have been affected by the disease (WOAH, 2022d). The reported morbidity and mortality during the first outbreak were 40.5% and 1.2%, respectively (Arjkumpa et al., 2022a). During this massive LSD outbreak in Thailand, the majority of cases were identified in June 2021 (Suwankitwat et al., 2022). LSD outbreaks continued to be reported in Thailand a year after the first outbreak. Most LSD cases were found during June and July 2021. The number of daily new LSD cases is depicted in Figure 1.

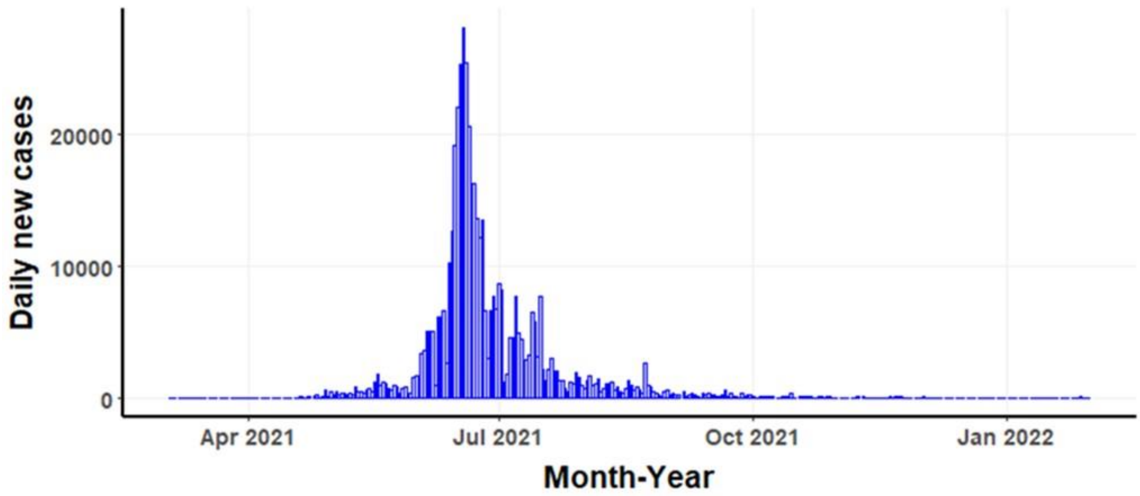

Figure 1: The number of daily new LSD cases in Thailand from April 2021 to January 2022.

Singapore

Singapore reported the first LSD outbreak in one dairy farms in March 2022. All of the affected animals have recovered, and none of them were culled. The primary focus of the control measures was on clinical surveillance, vector control, and monthly fogging. There was an attempt being made to prevent the transmission of diseases to captive wildlife species that are susceptible, such as giraffes and wild buffalo (WOAH, 2023a).

Geographical distribution of LSD in Asia

The geographical distribution of LSD outbreaks based on the available data from 2012 was obtained from WAHIS (WAHIS, 2024).

The maps show that several regions of Asia have a significant number of outbreaks, as denoted by red dots (Figure 2). The number of LSD outbreak reports increased from 2020 (Figure 3) to 2021 (Figure 4) and then decrease in 2022 (Figure 5).

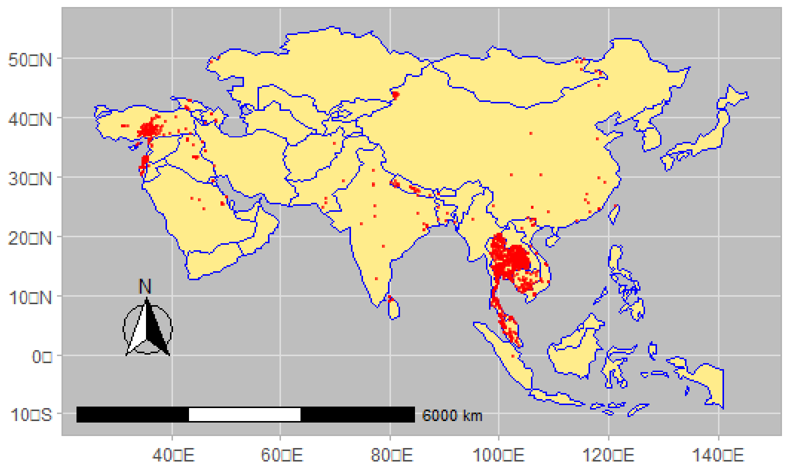

Figure 2: Overall distribution of LSD outbreaks from 2012–2022. The red dots depict the denser areas of outbreaks in the Asian region. The map was created based on the data from WAHIS.

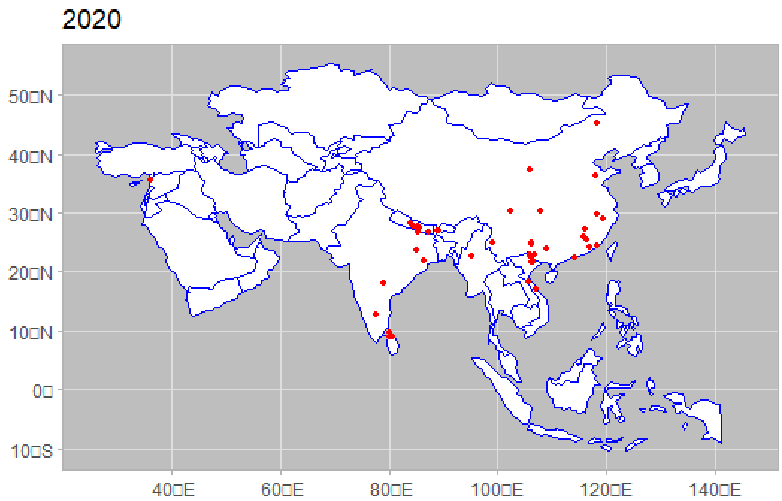

Figure 3: LSD outbreak report in 2020. Red dots indicate the outbreak points. The map was created based on the data from WAHIS.

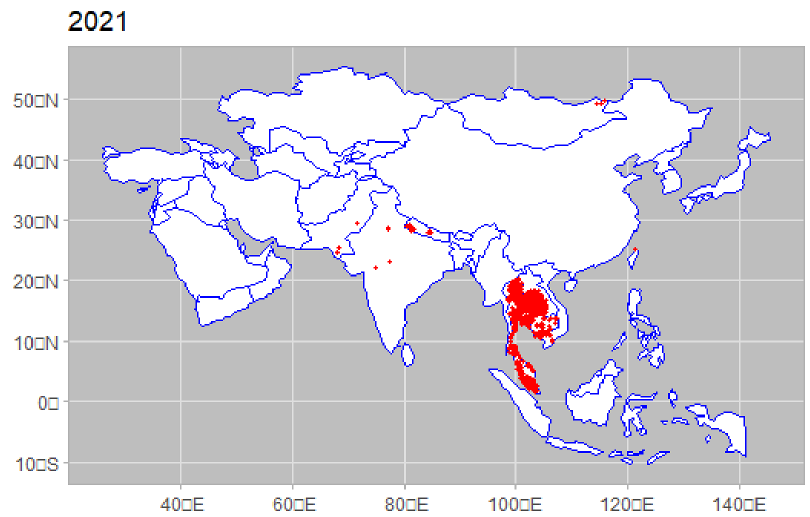

Figure 4: LSD outbreak report in 2021. Red dots indicate the outbreak points. The map was created based on the data from WAHIS.

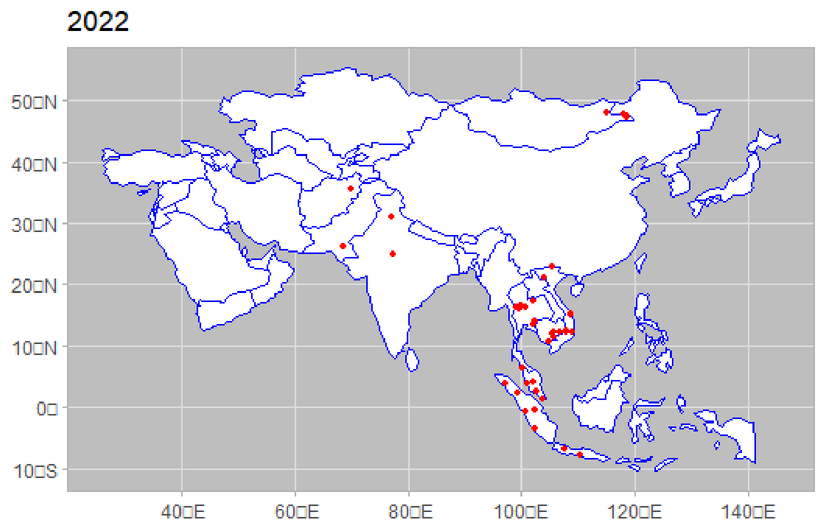

Figure 5: LSD outbreak report in 2022. Red dots indicate the outbreak points. The map was created based on the data from WAHIS.

Modelling LSD outbreaks and transmission

Despite numerous LSD outbreaks occurring in many Asian countries, there is still limited information on its spatial or spatio-temporal distribution and epidemiological dynamics. Therefore, it is crucial to completely comprehend the dynamics of LSD outbreaks to establish the baseline for subsequent epidemiological studies and long-term LSD control programs.

Spatial, temporal, and space-time scan statistics are used to find clusters of disease outbreaks or cases and determine whether these clusters can be explained by chance alone or have statistical importance. Clusters may appear as a result of common regional risk factors or local disease transmission. Many studies related to spatial distribution have been conducted around the globe, for instance in Zimbabwe (Swiswa et al., 2017), Eurasia (Allepuz et al., 2019), and Iran (Ardestani and Mokhtari, 2020). Similarly, the spatial and temporal distribution of LSD has been conducted in African and European countries such as Zimbabwe (Gomo et al., 2017), Uganda (Ochwo et al., 2018), the Balkan Peninsula (Stojmanovski, 2018), and Russia (Bouchemla et al., 2018; Byadovskaya et al., 2022). In addition, the mapping changes in the spatio-temporal distribution of the LSDV in Middle Eastern, Central Asian, and Eastern European countries between 2014 and 2016 were created using information from the OIE WAHIS interface (Machado et al., 2019)

Studies investigating the spatio-temporal distribution of LSD outbreaks have been carried out in Asia (Wang et al., 2022) and Southeast Asia (Arjkumpa et al., 2022b; Punyapornwithaya et al., 2022; Uddin et al., 2022; Modethed et al., 2023). However, the majority of these studies were focused solely on LSD outbreak data only from Thailand. Consequently, there are gaps in knowledge regarding the spatio-temporal distribution in other countries in the region.

The European guidelines recommend a protection zone of 20 km and a surveillance zone of 50 km for LSD. However, this recommendation may not be suitable for all countries in Asia. It has been suggested that each nation should make a decision based on its ecological and geographical characteristics, as well as existing production systems (Roche et al., 2020). Nevertheless, research on protection and surveillance zones in Asia is still very limited.

An understanding of within-herd transmission is required to evaluate the efficacy of intervention strategies and design effective monitoring programs. The transmission rate of LSD in some areas of Ethiopia has been estimated using a susceptible-infectious-recovered (SIR) epidemic model with environmental transmission (Molla et al., 2017b). However, based on the researcher’s knowledge, no similar studies have been conducted in Asia. In Turkey, the SIER (susceptible-exposed-infectious-recovered) model was used to assess the transmission and clinical dynamics of LSD such as mortality and recovery time (Mat et al., 2021).

For a better understanding of the LSD epidemic in Thailand, several mathematical models have been applied to daily new LSD cases and daily cumulative LSD cases in the country (Moonchai et al., 2023). The findings of such studies allow the progression of the LSD epidemic to be predicted. The predictive capability of forecasting daily new LSD cases at different time windows using various time series methods has been also investigated (Punyapornwithaya et al., 2023a). However, very little research has been carried out to estimate the rate of LSD transmission in Asia using mathematical models.

Risk factors

Poxviruses spread through a number of different routes, such as direct contact with aerosols, secondary dispersal through animal or insect vectors, reservoirs, fomites, and even semen although its transmission is still up for discussion (EFSA, 2015; Kumar et al., 2018). The transport of sick animals and vectors is likely to be the main reason for the disease spreading to infection-free areas.

Host

Cattle are the main natural hosts for the LSD (Tuppurainen and Oura, 2012). However, LSDV can infect other animals such as water buffaloes and yaks (Kumar et al., 2018). The buffalo is low risk compared to cattle due to its skin texture. Every breed and age group is vulnerable to LSD, yet some breeds showed more vulnerability than others. For instance, when comparing *Bos taurus* to zebu cattle and *Bos indicus,* the former is more prone to clinical illness (Abera et al., 2015). Exotic and crossbred cattle are more susceptible than indigenous cattle and buffaloes (Kiplagat et al., 2020). In addition, fine-skinned, high-yielding dairy Channel Island strains of *Bos taurus* are particularly vulnerable to the LSDV (EFSA, 2015).

Young calves and lactating cows are more vulnerable to infection (Kumar et al., 2018). Very young calves, lactating cows, and animals suffering from malnutrition generally develop the most severe infections, probably due to impaired cellular immunity (Hunter and Wallace, 2001). In certain circumstances, however, young animals may have a low risk of exposure if they were kept in separate barns from insects, thereby reducing their susceptibility to fly bites (Abera et al., 2015; Selim et al., 2021).

Male animals have a higher cumulative incidence than females due to stress factors such as exhaustion and fatigue rather than for biological reasons (Gammada et al., 2022). The majority of male cattle in Asia are draft oxen used for heavy labor, which might contribute to an increase in susceptibility (Gari et al., 2010). Furthermore, when employed, male cattle cannot protect themselves effectively from biting flies, and beat scratches on their skin caused by the ploughing equipment may attract biting flies, potentially capable of transmitting LSD infection (Abera et al., 2015).

Pathogen agent nature

Capripoxviruses can survive for a very long time on or off the animal host and are highly resistant to the environment. In a proper setting, such as a shaded animal house, they may last for up to six months. The virus can be extracted from skin nodules that have been preserved at -80 °C for 10 years (Gammada et al., 2022).

Environment

The environment influences the abundance of insects. An abundance of LSD insect-vectors found in some favorable environmental conditions is related with LSD outbreaks. For example, the abundance of insect-vectors found during the summer is linked to LSD outbreaks in Egypt. Also, in most Sub-Saharan Africa, the LSD has been usually observed following the rainy season when the population of insects increase (Mulatu and Feyisa, 2018). In Israeli dairy farms, the relative abundances of insect vectors in December and April were associated with the occurs of LSD outbreaks (Kahana-Sutin et al., 2017). Furthermore, during the rainy season (June to August) in various regions of Nepal, there were reported outbreaks of LSD. It is possible that these outbreaks are associated with the rise in population of arthropods in the area (Gautam et al., 2022).

In Africa, the middle East and Europe, LSD insect-vectors being less active during dry season or cold winters thus there is a seasonality in LSD incidence. Nevertheless, given the prevalent climatic conditions, some Asian countries may not have a vector-free season (Roche et al., 2020).

Management practices

Husbandry practices such as communal grazing and watering points and the introduction of new animals to a herd are also shown to be associated with the occurrence of LSD (Ochwo et al., 2019). The virus can be secreted in milk, nasal secretions, saliva, blood, and lachrymal secretions. Indirect transmission of the LSDV may occur when livestock exposed to saliva or nasal discharge from suspicious animals share water containers and feed troughs (Ochwo et al., 2019; Namazi and Khodakaram Tafti, 2021).

Animal movement

Uncontrolled cattle trafficking across borders for trading purposes is another potential means of LSD transmission. The first occurrence of LSD is frequently linked to the movement of cattle, whether legally or illegally, between farms, areas, or even nations (FAO, 2017).

The movement of cattle across Southeast Asia through the direction of traditional cattle trade flows is considered as the important mean in the spread of LSD in term of the long-distance transmission (Roche et al., 2020). However, it was observed that the common direction of the flow of LSD from the Middle East to India and China then south to Indonesia is in almost all cases opposite to the typical direction of the commercial live cattle trade across these regions. Thus, other means of spread may responsible for long distance transmission. In this aspect, it is hypothesized that the movement of infected insect vectors on prevailing winds is likely to be the mean for long distance transmission (Ainsworth, 2023).

Furthermore, some countries hold religious and cultural celebrations during which animal sacrifices are made. This increases the number of livestock moved prior to the festive season along with the risk of LSD transmission (Tuppurainen et al., 2021b).

Diagnosis of LSDV

LSDV can be diagnosed based on typical clinical signs such as presence of nodular lesion in the skin. The clinical symptoms of LSD are very distinct, and the distinctive skin lumps are typically noticeable from a distance (Roche et al., 2020). However, the occurrence of LSD should be confirmed by laboratory techniques. There are various laboratory methods for LSDV detection such as polymerase chain reaction (PCR), Viral isolation (VI) and electron microscopy (Beard, 2020; WOAH, 2021c; Liang et al., 2022).

Molecular techniques based on PCR has been considered as fast and sensitive method. Thus, PCR is widely used for LSDV diagnosis (Şevik and Doğan, 2017; Liang et al., 2022; Suwankitwat et al., 2022). A study comparing various diagnostic tests in experimentally infected cattle revealed that PCR was a rapid and reliable way to show viral DNA in blood and skin samples (Tuppurainen et al., 2005b). Notably, in order to confirm the disease, laboratory testing should be focused on those animals with skin lesions first due to the specificity of LSD skin nodules and also the fact that PCR is more sensitive in tissues (skin and ophthalmic/oral/nasal discharges). The gold standard for LSDV diagnosis is virus isolation. This method is a sensitive and reliable diagnostic test. However, it is a time-consuming technique as isolating LSDV takes several weeks (Tuppurainen et al., 2005a).

Various serological tests such as viral neutralisation, enzyme-linked immunosorbent assay (ELIZA), indirect fluorescent antibody test (IFAT) and immunological blotting (Western blotting) can be used for detecting antibody against LSDV. However, it is not possible to distinguish the three viruses in the *Capripoxvirus* genus using these techniques (WOAH, 2021c).

Other techniques such as real-time PCR (qPCR), Loop-mediated isothermal amplification (LAMP), Immunohistochemical (IHC), fluorescent antibody technology (FAT), Lateral flow immunoassay (LFIA), Immunoperoxidase Monolayer Assay (IPMA) and Triple E, are well-described and discussed in a previous review article (Liang et al., 2022). Some of these (e.g., IMPAM and Triple E) are newly developed methods.

Economic impact of LSD

The impacts of LSD on the domestic and international cattle trade are complex and extend beyond the immediately affected producers. Restrictions to the global trade in live animals and animal products, costly control measures, as well as indirect costs due to compulsory limitations on animal movement, can cause substantial financial losses at national level (Tuppurainen and Oura, 2011). Severe and permanent damage can occur to hides due to LSD lesions, thereby decreasing their commercial value (Gari et al., 2011). Moreover, infected animals experience a variety of negative effects, including sickness, a reduction in production, poor growth, infertility, and a loss of draft power (Gari et al., 2011). Additional expenditure is also incurred through vaccination of the herd, treatment of infected animals, removal of affected animals, and enhanced biosecurity (Babiuk et al., 2008; Tuppurainen and Oura, 2011).

Various studies have quantified the financial losses caused by LSD. According to an Ethiopian study, the cost per herd affected by LSD is USD6.43 for local zebu herds and USD58 for Holstein Friesians (Gari et al., 2011). This study also showed that milk production losses in LSD-infected herds could be as high as 50%. In addition, a questionnaire survey in Ethiopia indicated that the losses per affected lactating cow were USD141, with the median total economic loss of an LSD outbreak at the herd level being USD1,176 (Molla et al., 2017a). In Kenya, the economic impact of LSD was compared between indigenous pure-breed farms and exotic-breed farms to indicate a farm-level loss. The indirect losses from treatment and vaccination were proportionately much higher for indigenous breed farms (Kiplagat et al., 2020).

During an outbreak in Jordan, it was estimated that the supportive antibiotic treatment cost was GBP27.9 per head (Abutarbush et al., 2015). In Turkey, the total cost of the LSD outbreak based on 393 surveyed herds was GBP822 940 (Şevik and Doğan, 2017). Another study in Turkey shows that the production loss from LSD infection was estimated at USD886.34 per head of dairy cattle and USD1,066.61 for beef cattle (Mat et al., 2021). The cost of disease and control measures for LSD in Albania, Bulgaria, and Macedonia between 2016 and 2017 was EUR 20.9 million (USD25.45 million). The LSD-affected herds in these countries resulted in costs of EUR539 (USD656), EUR147 (USD179), and EUR258 (USD314) per head of cattle, respectively (Casal et al., 2018).

LSD has a negative economic impact on farmers as well as the country. Based on two scenarios, using the parameters obtained from Middle Eastern countries, it is estimated that the economic cost of LSD in South, East, and Southeast Asia could be as high as USD1.45 billion (Roche et al., 2020). This report represents an overall estimate; however, a study based on each country is still required. The production system, animal and product values, vaccine cost, and control strategy costs are all likely to vary from country to country. Therefore, it would be beneficial to conduct research using criteria pertinent to a particular nation.

Research has been conducted on the impact of LSD on the cattle industry in Asian nations. A research investigation was conducted in two districts of Bangladesh (Chouhan et al., 2022) wherein the average financial loss per case was approximated to be USD110.40. The study found that the monetary loss incurred in crossbred cattle was greater, amounting to USD114.23, as opposed to USD89.36 in indigenous cattle. The estimated annual loss due to LSD in the districts of Mymensingh and Gaibandha was USD91.33 million. In India, the LSD outbreaks resulted in the deaths of approximately 155,000 cows, leading to a direct economic loss of nearly 3 billion Indian Rupees (Kumar and Tripathi, 2022). Furthermore, according to a study conducted in Thailand, it has been approximated that the occurrence of LSD outbreaks leads to a reduction in farm milk production, thereby causing a decline in monthly revenue for farmers. The estimated losses range from USD 119.42 to USD 412.57 per farmer (Vinitchaikul et al., 2023).

In addition, socio-economic research on the negative effects of LSD is necessary because cattle in many regions of Asia are owned by small-holder farms or low-income families who are likely to be affected by LSD. A study on the impacts of LSD along the value chain should also be initiated to gain a better understanding of the issues involved. Value chain analysis (VCA) can also be applied to livestock production, enabling stakeholders to determine their behavior, risk perception, risk management, and response to disease control and prevention measures (Rushton, 2011). Risk analysis and VCA can be integrated to enhance the comprehension of disease risks, identify effective control measures, and inform disease surveillance. For example, risks of zoonosis through cross-border pig value chains between Lao PDR, Thailand, and Vietnam were assessed using VCA to reveal the interrelationships between market chains and zoonotic infection risks (Okello et al., 2017). Additionally, VCA can also support disease outbreak investigation, especially for Marek's disease, which has a strong association with animal movement. In Southern Thailand, VCA provided a better understanding of the layer and egg business and can be used as a guide to developing questionnaires for outbreak investigation (Dejyong et al., 2023). It is recommended that VCA be conducted before an outbreak occurs to facilitate and expedite an investigation once the disease has been detected (Rushton, 2011). Therefore, it would be advantageous to utilize VAC by incorporating various stakeholders along the value chain to gain information leading to a better understanding of the effects of LSD in Asian nations.

Prevention and control

LSD control is typically based on the following strategies: (i) vaccinating susceptible populations with more than 80% coverage; (ii) controlling the movement of cattle and buffalo and placing them in quarantine; (iii) ensuring biosecurity and controlling vectors; (iv) increasing both active and passive surveillance; (v) educating all parties involved on how to reduce risk; and (vi) establishing zoning, which includes extensive protection, surveillance, and vaccination zones (Roche et al., 2020). Nonetheless, several factors must be considered when developing LSD prevention and control strategies, including social, cultural and religious background, as well as national policies (Roche et al., 2020; Tuppurainen et al., 2021b) In the following sections, recommendations from WOAH (WOAH, 2023b), FAO (Roche et al., 2020), European Food Safety Authority (EFSA) (EFSA, 2016; EFSA Panel on Animal Health Welfare et al., 2022), and control strategies implemented by authorities from several Asian nations are presented.

WOAH recommendation

The Terrestrial Animal Health Code (Chapter 11.9: Infection with Lumpy Skin Disease Virus) (WOAH, 2023b) defines a country or zone as being free from LSD and describes the process of regaining that status. The requirements for importing cattle, water buffaloes, and other animal products (such as milk, semen, and embryos) from countries or zone free from LSD and from countries or zone free from LSD are also covered.

WOAH makes mention of surveillance, including clinical, viral, and serological, as well as high-risk area surveillance. It is highlight that a member country should justify the surveillance strategy chosen as being adequate to detect the presence of infection with LSDV. Also, the following practices should have in place (WOAH, 2023b):

a. a formal and ongoing system for detecting and investigating cases;
b. a procedure for the rapid collection and transport of samples from suspected cases to a laboratory for diagnosis;
c. a system for recording, managing and analysing diagnostic and surveillance data.

Prevention and control strategies recommended by FAO

The FAO paper (Roche et al., 2020) outlines the measures for LSD control, which include achieving vaccination coverage of over 80% in susceptible populations, implementing movement control and quarantine measures for cattle and buffalo, enhancing biosecurity and vector control efforts, strengthening both active and passive surveillance, raising awareness among all stakeholders on risk mitigation, and establishing large protection and surveillance zones as well as vaccination zones. Recommendations are made for both high-risk countries and those that currently have LSD. In this aspect, implementation should include the following for those at high risk of LSD introduction:

a. Strict border inspection of all susceptible animals
b. Pre-emptive vaccination of all susceptible animals in wide enough strips along the high-risk zone
c. Active clinical surveillance and awareness campaigns on clinical signs
d. Improved biosecurity at all levels of cattle production.

Countries categorized as having a moderate risk level are advised to adhere to all of the aforementioned measures, with the exception of pre-emptive vaccination. Conversely, countries that have already been affected by LSD are recommended to undertake the following actions.:

a. Control movement of susceptible animals and zoning/regionalization
b. Implement a mass immunization program for all susceptible animals
c. Apply humane slaughter procedures - if stamping out is permitted by law while adhering to animal welfare standards and providing compensation in accordance with national legislation
d. Enhance active surveillance in high-risk areas
e. Improve biosecurity at all levels of the cattle/buffalo production and value chain
f. In accordance with international laws, notify neighboring nations and pertinent international organizations in a timely manner.

EFSA recommendation

According to the publication in 2016, the EFSA advised the following strategies (EFSA, 2016):

a. Vaccination is recommended in areas at risk of LSDV introduction or where LSDV has already been introduced.

b. High within- and between-farm vaccination coverage is required to increase the likelihood of outbreak extinction.

c. Vaccination needs to be applied as uniformly as possible across the population to avoid areas where there are high densities of unvaccinated farms.

d. Farmers and veterinarians should be trained in the clinical identification of LSD in order to reduce underreporting.

Furthermore, based on a scientific assessment published in 2022, the EFSA Panel on Animal Health and Welfare (AHAW) makes the following recommendations for controlling LSD (EFSA Panel on Animal Health Welfare et al., 2022):

a. An epidemiological investigation should be carried out to perform vector surveillance, identify the virus, estimate its geographical origin, determine the duration of the disease and time of introduction, and estimate the prevalence of clinical signs.

b. Breeding sites and the larval population of vectors should be controlled using insecticide or repellent. Whenever possible, the animals should be maintained in a facility with vector protection to help lessen the risk of LSD spreading.

c. Surveillance of wildlife needs to be conducted due to the presence of cases in giraffes, African buffalos, impalas, and other antelope species.

d. The authorities should prioritize their visits at a certain distance (e.g., 4.5 km or 10 km) from the affected area and then gradually extend the visits outward beyond this distance up to the borders of the surveillance zone.

e. Animal movement restrictions should be implemented.

f. To prevent the disease from being reintroduced into new establishments, animals expected to repopulate should come from areas free of LSD. The importance of vectors in the spread of the disease should be taken into account during the repopulation process.

g. A protection zone within a minimum radius of 10 km and 30 km of the surveillance zone is recommended.

The EFSA has addressed the successful elimination of LSD in the south-eastern part of Europe (Saltykov et al., 2022). The ccontrol measures including mass vaccination campaigns with a live homologous vaccine against LSD, with sufficient livestock coverage were implemented at regional level in south-eastern Europe in all affected countries and Croatia (EFSA, 2017). Within a short period of time, these campaigns led to at least 90% of the animal population being immunized, demonstrating the high level of responsiveness and preparedness of the national authorities of those countries to control the epidemics.

Prevention and control of LSD in Southeast Asian countries

In general LSD control is based on vaccination (>80% coverage), movement control and quarantine, biosecurity and vector control, strengthening active and passive surveillance, raising awareness of risk mitigation among all stakeholders involved, and creating large protection and surveillance zones as well as vaccination zones (Tuppurainen and Oura, 2012; FAO, 2017). Although Southeast Asian countries such as Cambodia, Malaysia, Myanmar, Thailand, Vietnam, Lao PDR, and Indonesia are reported to use this approach (WOAH, 2021a), it is challenging in reality as mentioned in a previous report (Roche et al., 2020). Such challenges include: no procedures or strategy plans being in existence for the prevention, control, eradication, and monitoring of LSD, uncontrolled animal movement (cross-border illegal movement), lack of awareness and information among veterinarians and farmers in Southeast Asia due to LSD's recent discovery, poor hygiene and biosecurity practice in small-holder farms (backyard farms), the presence of a large number of vectors on a farm, vaccine stocks not always being readily accessible for rapid deployment and lack of laboratory capacity.

In some cases, farmers may be reluctant to inform veterinary officials about suspected LSD outbreaks due to their concerns of the negative consequences, such as a ban on trade and movement of cattle (Tuppurainen et al., 2021b). Delays in outbreak detection and reporting, therefore, make it more difficult to successfully manage LSD. Moreover, in countries such as India and Nepal where cattle slaughter is prohibited due to religious beliefs, implementing the necessary procedures may prove challenging (Tuppurainen et al., 2021b).

Countries such as Indonesia, the Philippines and Nepal are experiencing difficulties in diagnosing the disease due to the lack of technical capability and laboratory capacity. Previously, Indonesia only had one laboratory capable of performing diagnostic tests, but have now increased their laboratory capabilities and active training for officers (WOAH, 2021e).

Regarding the second LSD coordination meeting for Southeast Asia (WOAH, 2021a) and the related update meetings (WOAH, 2022f), representatives gave presentations on the prevention and control of LSD facilitated in their countries. Thailand has conducted a nationwide vaccination campaign, as well as a number of other preventative measures to limit the instances of LSD outbreaks and prevent further outbreaks (WOAH, 2021g, 2022d; Punyapornwithaya et al., 2024). Malaysia reported the use of a homologous vaccine against LSD (WOAH, 2022c). The following activities have also been carried out: establishing clinical surveillance, strengthening the control of illegal animal movement at international borders, implementing public awareness campaigns, and increasing knowledge and awareness among stakeholders (WOAH, 2022c). Vietnam formulated a national plan for LSD (2022–2030), approved by the prime minister in October 2021, and 9 million doses of the LSD vaccine were imported (WOAH, 2021i). Despite not using the LSD vaccination, Laos PDR has prioritized active surveillance, the regulation of animal movement, and the reporting of outbreaks (WOAH, 2021h).

Insect vector control

Insect vector control is considered to be a support measure (Roche et al., 2020). Nonetheless, for naive herds near regions with an outbreak, the use of insecticides would lessen the likelihood of insects spreading LSD from the infected herd to the naive ones. Therefore, several Asian countries experiencing the first LSD outbreak were observed to use insecticide to control the spread of LSD through insect vectors in outbreak areas (WOAH, 2022f).

In Thailand, veterinary authorities used insecticide to control the spread of LSD in 38,348 farms in outbreak and high-risk areas, with insecticide bottles distributed to 134,863 farms across the country (WOAH, 2022d). LSD outbreaks have been observed in Thailand in areas where animal movement is restricted and inter-farm animal contact is absent, indicating a high likelihood that insect vectors are primarily responsible for the spread of LSD in these areas. Therefore, using insecticides as advised by livestock authorities in cattle farms located in high-risk areas might help in reducing the spread of LSD via insect-vectors (Arjkumpa et al., 2022a; Punyapornwithaya et al., 2022).

Instead of using insecticides on a large scale, it is suggested that pour-on repellents can be used regularly to control vectors. In addition, barns should be cleaned regularly and manure removed to eliminate or limit vector breeding sites (Roche et al., 2020).

Public awareness and risk communication

Raising awareness among farmers, cattle traders, and other stakeholders is deemed necessary for the effective control and prevention of LSD transmission. The implementation of awareness campaigns aimed at farmers, veterinarians, cattle traders, artificial inseminators, and other relevant stakeholders is expected to facilitate early notification, rapid disease detection, and prompt response to LSD outbreaks by these stakeholders. (Kumar et al., 2018; Roche et al., 2020).

Risk communication between stakeholders is critical. A better understanding of LSD transmission and impact will raise awareness and facilitate effective collaboration. The risk communication also contributes to enhanced biosecurity, more readily disease detection, and more effective outbreak response (Roche et al., 2020). For instance, risk communication was implemented in the field, as well as in local and regional meetings, in response to LSD outbreaks in Thailand. Efforts were also implemented to promote cooperation and involvement among livestock authorities, neighbouring communities and the private sector. Furthermore, the web-based system was employed as a platform for the distribution of information and the provision of prompt updates pertaining to LSD (WOAH, 2022d; Punyapornwithaya et al., 2024). Nepal has taken proactive measures in response to outbreaks by providing education to veterinarians and animal health workers, as well as facilitating tentative diagnosis and treatment at the field level (Gautam et al., 2022).

Vaccination

Vaccination is the most effective tool for LSD control and its potential eradication, in countries with limited resources where the disease is endemic (Tuppurainen et al., 2021b). The following vaccines have been used in the protection of animals (WOAH, 2021b): homologous vaccine (for use on cattle with an LSDV-based vaccine, or sheep/goat with a sheep/goat pox virus-based vaccine) and heterologous vaccine (a sheeppox/goatpox virus-based vaccine to protect cattle against the LSDV).

The majority of commercially available LSD vaccines are live attenuated vaccines based on an LSDV strain, sheeppox virus (SPPV), or goatpox virus (GTPV) (Tuppurainen et al., 2021b). The live attenuated LSDV vaccines (Neethling vaccines) are used in cattle in several countries (Tuppurainen et al., 2021b; Suwankitwat et al., 2022). This type of vaccines provides good protection for cattle against virulent field LSDV strains (Tuppurainen et al., 2021b). The good efficacy of live attenuated LSD vaccines was demonstrated when the homologous Neethling strain vaccines were utilized as a mass vaccination to eliminate LSD in Southeastern Europe between 2016 and 2017 (EFSA et al., 2020). The heterologous goat pox virus (GTPV) vaccines like the Gorgan GTPV also provide good protection in cattle as demonstrated in several studies (Gari et al., 2015; Varshovi et al., 2017; Zhugunissov et al., 2020). The attenuated Gorgan GTPV is suggested to be used for the areas where outbreaks are caused by a combination of LSDV and SPPV (Roche et al., 2020). A field study shows that the Gorgan GTPV vaccinated cattle showed strong cellular immune responses (Gari et al., 2015). Unlike GTPV vaccine, SPPV vaccine does not provide a high immunity against LSD in animals compared to the SPPV vaccine (Brenner et al., 2009; Gari et al., 2015). A study shown that the Yugoslavian RM 65 SPPV vaccines used in Israel from 2006 to 2007 did not provide a complete immunological protection (Brenner et al., 2009). Several studies have also supported the findings that an attenuated SPPV vaccines provide partial protection provided by against field strain (Tageldin et al., 2014; Abdallah et al., 2018).

In terms of clinical reactions in cattle following vaccination, LSD live attenuated homologous vaccines can result in localized inflammation, a decrease in milk supply, and occasionally “Neethling disease,” a mild generalized condition with skin lesions (Bedeković et al., 2018), whereas GTPV vaccines are less likely to produce these signs. Moreover, the side effects from the SPPV vaccine in naive cattle are less common than those from attenuated LSD vaccines (Tuppurainen et al., 2021b). However, a study conducted under field and experiment conditions showed that the live attenuated LSD vaccine used in Vietnam and Egypt has insignificant post vaccination effects on the skin and health indices (Bazid et al., 2022) Concerns have been raised regarding the use of live attenuated vaccines (Neethling-based vaccine) since it was discovered that several vaccine-like recombinant strains were responsible for an LSD outbreak in Russia (Kononov et al., 2019; Sprygin et al., 2020). It was also found that vaccine-like recombinant strains carrying genetic signatures from both Neethling- and KSGP-based LSDV vaccines were involved with LSD outbreaks in several Asian countries such as China (Ma et al., 2022), Vietnam (Mathijs et al., 2021) and Taiwan (Tsai et al., 2022).

The European Food Safety Authority advised using a safe and effective inactivated vaccine for prevention in disease-free countries due to the elevated risk of the LSDV spreading to new areas (EFSA, 2015). Inactivated vaccines provide a shorter duration of immunity than live attenuated vaccines. The advantages of using inactivated vaccines include safety, lack of replication, lack of spread to nearby unvaccinated animals, and lack of reversion to virulence (Hamdi et al., 2020). The non-replicative characteristics of inactivated vaccines can prevent transmission of the vaccine virus to naïve animals and recombination with virulent virus strains (Hamdi et al., 2020; Tuppurainen et al., 2021b).

In the experimental setting, the live attenuated vaccine provides complete protection against LSD for at least 1.5 years, whereas the inactivated vaccine provides complete protection for six months, but cannot protect all vaccinated animals after one year. Therefore, a bi-annual vaccination with inactivated vaccines is advised (Haegeman et al., 2023).

In Southeast Asian region, Thailand has implemented nationwide vaccination as a measure to control the LSD outbreak and prevent new cases. According to a Bayesian structural time series analysis, the implementation of this mass vaccination campaign significantly reduced the number of new LSD cases. The relative effect of the mass vaccination led to a reduction of 78-119% in the incidence of LSD cases (Punyapornwithaya et al., 2024). The effectiveness of the approach aligns with findings from other regions, including studies conducted in South-Eastern Europe (EFSA, 2017) and the Balkans (Klement et al., 2020).

Type of LSD vaccine used in Asian countries

The live attenuated vaccine for LSD from MSD-Animal Health (LumpyVax®) is commercially available and has been used in many Asian countries including India, Thailand, Malaysia, and Indonesia. The other commercial LSD vaccines commonly used in Asia are Lumpyshield-N®, LumpyShield-G®, Jovivac Strong®, MEVAC®, Bovivax LSD-N and Lumpi-ProVacInd. In some countries where FMD exists, the LSD vaccination is combined with the FMD vaccine. In Malaysia, LSD vaccination is combined with FMD, Haemorrhagic Septicemia (HS), or the RB51 vaccine. Table 1 shows the type and trade names of vaccines for combating LSD outbreaks in some Asian countries (WOAH, 2021a).

Table 1: Type and trade name of vaccine used to combat LSD outbreaks in Asian countries.

Country	Control measures	Trade brand	Reference
Vietnam	Homologues Heterologous	LumpyShield-N® LumpyShield-G® JovivacStrong®	(WOAH, 2021a)
Thailand	Homologues	LUMPYVAX®, MEVAC®	(WOAH, 2021a)
Malaysia	Homologues	Bovivax LSD-N®, LUMPYVAX®, MEVAC®	(WOAH, 2021a)
Cambodia	Homologues	LUMPYVAX®,	(WOAH, 2021a)
Indonesia	Homologues	LUMPYVAX®, MEVAC®	(iSIKHNAS, 2023)
India	Homologues	Lumpi-ProVacInd®	(Ministry of Fisheries, 2022)
Bangladesh	Homologue or Heterologous	Unknown	(MOF, 2021)

The distribution of LSD has extended to various Asian nations with diverse geographical features. Thus, the implementation of control and eradication measures for LSD outbreaks must be tailored to the specific circumstances of each country and region. This involves considering factors such as the size of the susceptible cattle population, local cattle farming practices, LSD risk factors, and social and religious traditions and beliefs (Roche et al., 2020).

Research on the epidemiology of LSD in Asia

The majority of LSD research in Asia is focused on molecular epidemiology. In this context, numerous studies on the molecular epidemiology of LSD have been conducted in Asia. For instance, molecular characterizations and phylogenetic analysis of LSDV linked to LSD outbreaks were carried out in various countries such as China (Ma et al., 2022; Wang et al., 2022), Nepal (Koirala et al., 2022), Mongolia (Sprygin et al., 2022), Bangladesh (Badhy et al., 2021; Parvin et al., 2022), Pakistan (Manzoor et al., 2023), India (Kumar et al., 2021; Sethi et al., 2022; Sudhakar et al., 2022; Bhatt et al., 2023; Putty et al., 2023), Myanmar (Maw et al., 2022), Vietnam (Mathijs et al., 2021; Tran et al., 2021; Ngoc and Tam, 2022), Malaysia (Khoo et al., 2022), Taiwan (Tsai et al., 2022) and Hong Kong (Flannery et al., 2022).

Several studies have been conducted on the clinical manifestations of LSD in cattle, as well as the presence of LSD insect vectors in cattle farms. Studies conducted in Bangladesh comprehensively describes the clinical characteristics of LSD cattle (Parvin et al., 2022; Uddin et al., 2022). Clinical findings of LSD in native cattle and Asian buffaloes in India are comprehensively described (Pandey et al., 2022). In terms of LSD insect-vector research, a field survey conducted in Thailand revealed a high abundance of insects in cattle farms. The study also presents a summary of the techniques utilized by farmers in controlling these insects. (Arjkumpa et al., 2022b).

As previously mentioned, the economic impact of LSD has also been subject to investigation. There are at least three publications that report on the negative impacts resulting from LSD outbreaks (Chouhan et al., 2022; Kumar and Tripathi, 2022; Vinitchaikul et al., 2023).

Various studies have investigated the risk factors that may contribute to the outbreak of LSD (Odonchimeg et al., 2022; Uddin et al., 2022; Susanti et al., 2023; Arjkumpa et al., 2024). Nevertheless, the available literature on the development and efficacy assessment of vaccines for LSD is currently limited. One of these studies conducted in Vietnam has reported the effectiveness and potential adverse reactions of live attenuated vaccines (Bazid et al., 2022).

In 2021, Thailand had the highest number of LSD outbreaks (Anwar et al., 2022). It is noteworthy that numerous studies on various topics related to LSD have been carried out. These studies include LSDV molecular characterization and phylogenetics (Sariya et al., 2022; Seerintra et al., 2022; Singhla et al., 2022; Suwankitwat et al., 2022; Suwankitwat et al., 2023a; Suwankitwat et al., 2023b), spatio-temporal analysis of LSD outbreaks (Arjkumpa et al., 2022b; Punyapornwithaya et al., 2022; Modethed et al., 2023), identification of risk factors associated with LSD outbreaks (Arjkumpa et al., 2024), transmission kernel of LSDV (Punyapornwithaya et al., 2023b), epidemic growth modelling of LSD cases (Moonchai et al., 2023), forecasting of the new LSD cases (Punyapornwithaya et al., 2023a), economic losses due to LSD outbreaks (Vinitchaikul et al., 2023), and the impact of mass vaccination on the reduction of LSD new cases (Punyapornwithaya et al., 2024). Several of these studies were financially supported by the government with the expectation that their outcomes would enhance the comprehension of LSD and serve as a fundamental resource for livestock authorities to facilitate and develop effective prevention and control programs.

Notably, although some research topics may not be addressed within this particular section, references to several additional studies related to LSD are incorporated throughout this review.

To gain a better understanding of LSD epidemiology in Asia, it is essential to investigate other areas, such as assessing the consequences of LSD outbreaks, identifying risk factors relevant to production system and environmental conditions, identifying high-risk regions for LSD outbreaks, and evaluating the efficacy of vaccines used in the region.

Areas for further study

A better understanding of LSD epidemiology is essential for Asian countries since the disease has been widespread in the region. The disease may persist or become endemic in the area. Studies on various countries and regions would provide important information that may facilitate regional cooperation in disease control and prevention. The following topics are discussed elsewhere in this paper, and identified as existing knowledge gaps that require better understanding:

1. Spatial and spatio-temporal data analysis on LSD outbreaks in various countries.
2. Role of LSD insect vectors, interface between vectors and cattle, controlling vectors in various regions, and the distance and time span over which the vectors can transmit the disease.
3. Effectiveness of control and prevention strategies implemented in each country.

4. Economic losses due to LSD and the impact of LSD on the socio-economic status of farmers.
5. Impact of LSD on the various actors and stakeholders involved in the value chain.

It would be worthwhile examining the data already available from WOAH to obtain further knowledge that may ultimately lead to a better understanding of the epidemiology of LSD. Furthermore, additional research should be conducted to obtain knowledge relevant to the specific objective.

Conclusion

An overview of LSD epidemiology in Asia is provided in this paper. In order to offer a broader perspective regarding LSD, this review is based on research publications, country reports, and other sources. Based on the distribution of LSD both at regional and country levels, there is evidence to suggest that LSD poses a significant risk to cattle and buffalo production. Control strategies implemented by various countries are described in this study. How LSD affects actors and stakeholders economically in the value chain is one of the most important knowledge gaps addressed herein. Additionally, existing data from various agencies should be analyzed to provide a better understanding of LSD spatial epidemiology in preparation for LSD outbreaks. Furthermore, the lessons learned from various nations shared at the coordination meetings described in this paper can serve as baseline data for future regional cooperation.

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Objective 1.2 Spatio-temporal analyses and directional distribution analysis

Summary

- Clusters of LSD outbreaks were identified in the Western, Southern, and Southeastern regions of Asia, indicating a potential link between the outbreaks in these areas.
- The primary clusters of LSD outbreaks in Asia, as identified by several spatio-temporal models, were predominantly situated in two regions comprising countries in the southern and Southeastern parts of the continent. Specifically, within Southeast Asia, these clusters were primarily concentrated in Thailand and Indonesia.
- The outbreaks of LSD in Asia follow a west-to-east tend over an extended period. However, due to the high number of LSD outbreaks in Southeast Asia from 2021 to 2022, the trend shifted noticeably from northeast to southwest.
- Investigating LSD outbreak clusters based on spatial and temporal dimensions provides a better understanding of the epidemiology of LSD in the region. This facilitates authorities and stakeholders in identifying high-risk areas, particularly in settings with limited resources, to develop targeted control and prevention measures.

Spatio-temporal analysis

The objective of this analysis is to ascertain the existence of spatio-temporal clusters of LSD outbreaks in the Asian countries.

Introduction

Spatio-temporal analysis is a specialized analytical approach aimed at uncovering clusters of events or diseases that occur not only in specific geographical areas but also over specific time periods. This analysis can be performed using SaTScan™ software (Kulldorff, 2021). The analysis uses information about the locations and times of events or occurrences that varies both spatially and temporally. The data can be in the form of point data, aggregated data, or cases with specific coordinates and timestamps (Kulldorff et al., 2005; Kulldorff, 2021).

The SaTScan™ software systematically scans through various combinations of space and time to assess the statistical significance of observed clusters. This is achieved by comparing the actual data with simulated datasets in which events are distributed randomly. The determination of the statistical significance of identified clusters relies on p-values. The software provides a range of parameter settings, allowing the analysis to align with the investigators' study design. The results of the spatio-temporal analysis are usually visualized using maps. This visualization aids relevant stakeholders and decision-makers in comprehending the location and timing of significant clusters (Wang et al., 2022; Modethed et al., 2023)

One of the key applications of spatio-temporal analysis is resource allocation. By identifying clusters of events or diseases, results from the analysis helps decision-makers allocate resources more efficiently. For instance, in veterinary epidemiology, it can help direct interventions to areas and times with higher disease risks (Arjkumpa et al., 2020; González

Gordon et al., 2022). Additionally, it allows audiences to understand the underlying factors contributing to spatial and temporal variations in events, leading to more informed policy and decision-making (Alvarez et al., 2016; Kanankege et al., 2020).

Materials and Methods

Data

The dataset comprises 1,921 recorded instances of LSD outbreaks in various locations across Asia. This dataset is based on information sourced from WOAH. Each data point in the dataset is represented by geographical coordinates, specifying the locations of LSD outbreaks in the Asian continent. The dataset covers the LSD outbreaks from January, 2006 to August, 2023.

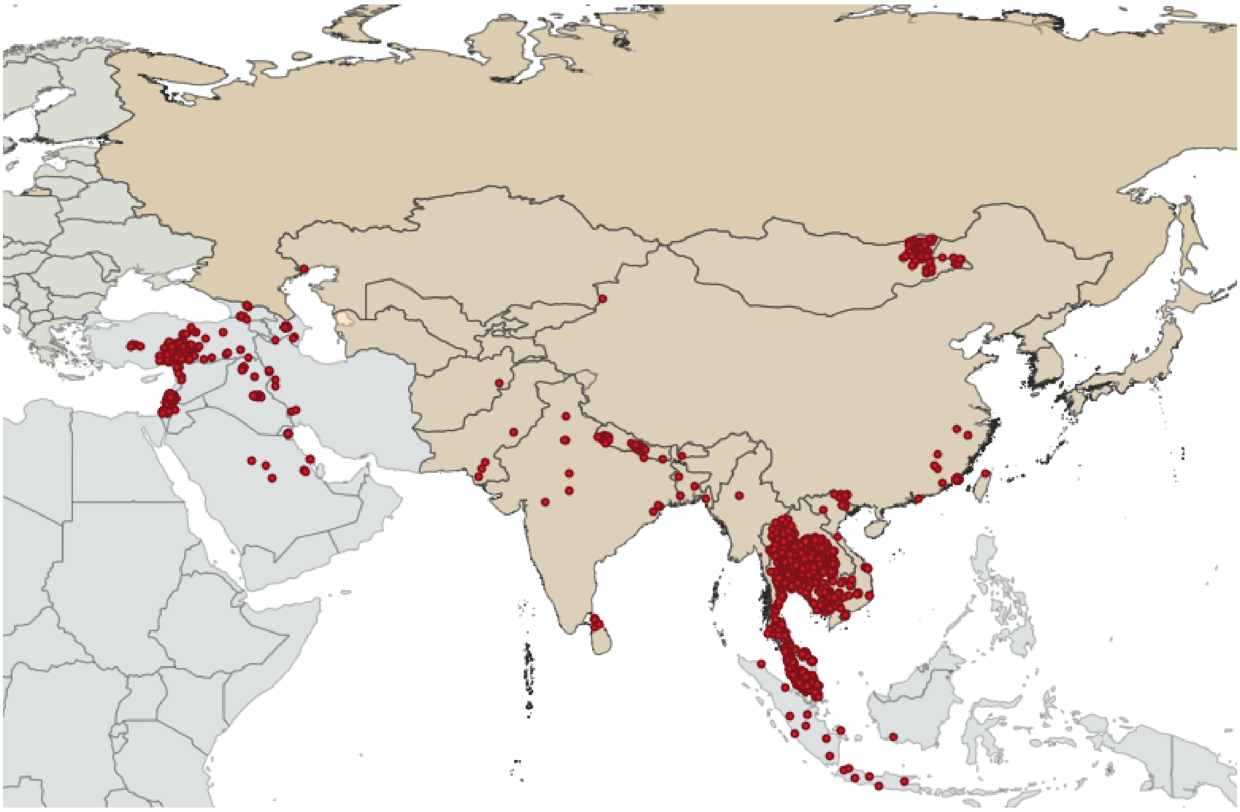

Figure A1. Locations (XY-coordinate: latitude and longitude) of lumpy skin disease outbreaks in Asia from January, 2006 to August, 2023

Space-time models

The scan statistics within the SaTScan™ software were utilized to detect and evaluate disease clusters. The scan statistics offers the opportunity to investigate the purely spatial, purely temporal, or spatio-temporal clusters.

In the spatio-temporal analysis, a scan statistic uses circular or elliptical scanning windows that traverse both space and time. These windows are tested against a null hypothesis, aiming to detect clusters with heightened event rates. Additionally, the analysis also considers temporal components, identifying when events are more likely to cluster during specific time periods.

The Spatio-Temporal Scan Statistic (STP) model (Kulldorff et al., 2005; Kulldorff, 2021) is a robust analytical tool used to identify clusters of outbreaks of diseases. This model is exclusively dependent on LSD case data that includes geographical coordinates and the onset date of the outbreaks. By analyzing this information, the STP model helps pinpoint spatial and temporal clusters, making it invaluable for disease surveillance and control efforts.

The Poisson model offers a slightly different approach. It not only considers the number of LSD cases but also takes into account the number of populations at risk within and outside specific time and space windows. The variables utilized in this model include the number of LSD cases, the total number of cattle in each farm, the coordinates of the farm, and the onset date of the outbreak (Kulldorff, 2021). This comprehensive approach allows for a more detailed analysis of the disease's spread, enabling more precise interventions and resource allocation.

In all of these spatio-temporal models, the identification of the most likely cluster and secondary clusters is accomplished through the log-likelihood ratio (Kulldorff, 2021). This statistical measure helps in quantifying the likelihood of observing the disease cluster. Specifically, in the STP and Poisson models, which operate under the Poisson assumption, the likelihood function for a specific space-time window is expressed as:

$$\left(\frac{c}{E[c]}\right)^{c}\left(\frac{C-c}{C-E[c]}\right)^{C-c} I\,(\,)$$

where C is the total number of LSD cases, c refers to the observed number of LSD cases within the space-time window and $E[c]$ denotes the covariate-adjusted expected number of LSD cases within the window under the null hypothesis while $C - E[c]$ is the expected number of cases outside the window. The term $I()$ is an indicator function, if the purpose is to scan only for clusters with high rate the $I()$ is set to 1.

For the analysis of LSD outbreak data, the spatio-temporal models, including the space-STP and Poisson models, were applied according to the availability of the data. The STP model requires the inclusion of geographical coordinates (latitude and longitude), along with the number of LSD cases at each coordinate. The Poisson model also demands information on the population at risk, in addition to geographical coordinates and the number of cases.

Furthermore, to gain more insights into the identification of LSD outbreaks, a total of 16 analyses were conducted based on different parameter settings.

Model parameter settings

The important parameter settings for both STP and Poisson models include the maximum spatial cluster size (MSCS), Maximum temporal cluster size (MTCS) and time aggregation. Typically, the MSCS and MTCS is configured to be 50% of the study period, while the time aggregation setting varies depending on the study's specific objectives.

The analysis aims to identify clusters of LSD cases in Asia using longitudinal data. If the MTCS and time aggregation intervals are set too small, there is a higher probability of identifying numerous clusters. However, these clusters are likely to be small and may lack meaningful significance. Therefore, a monthly and yearly time aggregation is chosen. Additionally, the MTCS is set at 50%, which is the default value and has been widely used in many previous studies.

Table A1. Details for spatio-temporal analysis

No	Type of analysis	Model	Area	Time aggregation	Maximum temporal cluster size
1	Space-time	Poisson	Asia	Year	50% of the study period
2	Space-time	Poisson	Asia	Year	1 year
3	Space-time	Poisson	Asia	Month	50% of the study period
4	Space-time	Poisson	Asia	Month	1 month
5	Space-time	STP	Asia	Year	50% of the study period
6	Space-time	STP	Asia	Year	1 year
7	Space-time	STP	Asia	Month	50% of the study period
8	Space-time	STP	Asia	Month	1 month
9	Space time	Poisson	SEA	Year	50% of the study period
10	Space time	Poisson	SEA	Year	1 year
11	Space-time	Poisson	SEA	Month	50% of the study period
12	Space-time	Poisson	SEA	Month	1 month
13	Space-time	STP	SEA	Year	50% of the study period
14	Space-time	STP	SEA	Year	1 year
15	Space-time	STP	SEA	Month	50% of the study period
16	Space-time	STP	SEA	Month	1 month

Table A1 provides information on different models and their parameters for spatial and temporal analysis in the Asia and Southeast Asia (SEA) regions. The key information in the table includes:

- Model Type: It specifies whether the analysis is purely spatial or space-time.
- Model: The model used for analysis, which is Poisson or STP.
- Area: The geographical area of analysis, which can be either Asia or SEA.
- Time Aggregation: The time interval used for data aggregation, either Year or Month.
- MTCS: This indicates the maximum duration of temporal clusters in the analysis, given as a percentage of the study period or in years or months.

Furthermore, the statistically significant clusters that were identified were mapped using QGIS (V3.32.2-Lima).

Results

Spatio-temporal clusters using data from Asian countries

The Poisson model results in Table 5 reveal that the model with a MTCS of 50% identified a cluster area that was similar but occurred in a different period. Most notably, the largest and most likely high-risk cluster was identified by the model with monthly time aggregation and a 50% MTCS setting. In contrast, the Poisson model with monthly time aggregation and a one-month MTCS displayed the lowest relative risk and a shorter duration when compared to the other models.

The results from each model were shown below. For all model, the first cluster is the most likely clusters (also known as the primary cluster). The cluster other than the primary cluster is defined as a secondary cluster. Notably, some models have more than one secondary clusters.

Table A2 summarizes the number of clusters generated by different models in two geographic areas, Asia and Southeast Asia (SEA). The models are categorized as purely spatial Poisson models, purely temporal Poisson models, and space-time Poisson or STP models.

Table A2. Model descriptions for spatio-temporal analysis applied to lumpy skin disease outbreak in Asia.

Model	**Description**	**Area**	**Number of clusters**	**Table number**	**Figure number**
1	Space time - Poisson model	ASIA	8	A3.1	A3.1
2	Space time - Poisson model	ASIA	8	A3.2	A3.2
3	Space time - Poisson model	ASIA	2	A3.3	A3.3
4	Space time - Poisson model	ASIA	4	A3.4	A3.4
5	Space time - STP model	ASIA	6	A3.5	A3.5
6	Space time - STP model	ASIA	7	A3.6	A3.6
7	Space time - STP model	ASIA	9	A3.7	A3.7
8	Space time - STP model	ASIA	9	A3.8	A3.8

Model 1

According to Model 1, the table displaying the primary and secondary clusters, along with the corresponding maps for these clusters, is presented below.

Table A3.1 presents an analysis of LSD outbreak clusters in Asia, employing the space-time Poisson model. Yearly time aggregation is applied, and the MTCS is set to 50% of the study period.

Clusters	**Cluster time**	**Coordinates/ radius**	**Observed cases**	**Expected cases**	**Relative risk**	**LLR**	**P-value**
Cluster 1(C1)	2021/1/1 to 2022/12/31	22.663549 N, 95.299698 E/ 1839.65	571088	90236.68	103.74	966342.77	<0.001
Cluster 2 (C2)	2012/1/1 to 2012/12/31	33.208958 N, 35.568854 E/ 17.06	2382	914.43	2.61	814.73	<0.001
Cluster 3 (C3)	2014/1/1 to 2014/12/31	40.545100 N, 47.461600 E/ 7.38	1765	618.16	2.86	706.00	< 0.001
Cluster 4 (C4)	2013/1/1 to 2013/12/31	32.348894 N, 35.271729 E/ 23.20	463	94.73	4.89	366.47	< 0.001
Cluster 5 (C5)	2013/1/1 to 2013/12/31	32.638526 N, 35.448236 E)/0	200	21.31	9.39	269.18	< 0.001
Cluster 6 (C6)	2014/1/1 to 2014/12/31	40.457000 N, 47.738800 E)/0	254	85.14	2.98	108.79	< 0.001
Cluster 7 (C7)	2013/1/1 to 2014/12/31	36.233900 N, 43.052520 E/ 353.05	120	49.24	2.44	36.13	< 0.001
Cluster 8 (C8)	2014/1/1 to 2014/12/31	34.909200 N, 36.484300 E/ 144.53	13	2.64	4.92	10.35	0.034

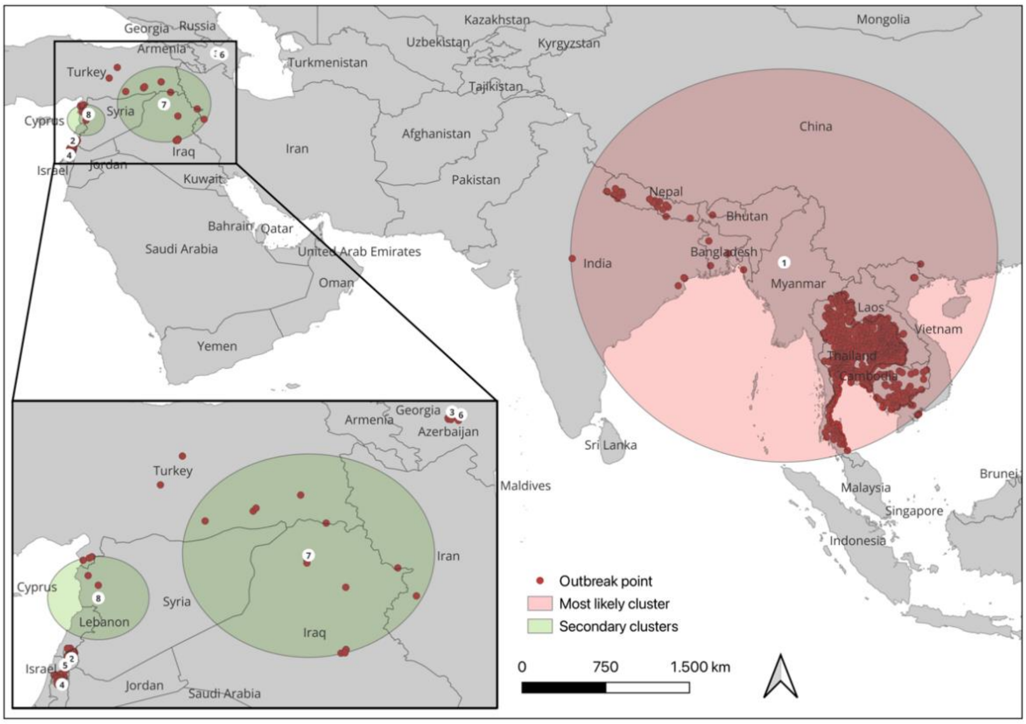

Figure A3.1 presents an analysis of LSD outbreak clusters in Asia, employing the space-time Poisson model. Yearly time aggregation is applied, and the MTCS is set to 50% of the study period. The model identifies one primary cluster and seven secondary clusters.

Model 2

According to Model 2, the table displaying the primary and secondary clusters, along with the corresponding maps for these clusters, is presented below.

Table A3.2 presents an analysis of LSD outbreak clusters in Asia, employing the space-time Poisson model. Yearly time aggregation is applied, and the MTCS is set to 1 year

Clusters	**Cluster time**	**Coordinates/ radius**	**Observed cases**	**Expected cases**	**Relative risk**	**LLR**	**P-value**
Cluster 1(C1)	2021/1/1 to 2021/12/31	20.230000 N, 100.160000 E / 2367.09	570266	90065.43	101.16	963611.03	<0.001
Cluster 2 (C2)	2012/1/1 to 2012/12/31	33.208958 N, 35.568854 E / 17.06	2382	914.43	2.61	814.73	<0.001
Cluster 3 (C3)	2014/1/1 to 2014/12/31	40.545100 N, 47.461600 E / 7.38	1765	618.16	2.86	706.00	< 0.001
Cluster 4 (C4)	2013/1/1 to 2013/12/31	32.348894 N, 35.271729 E / 23.20	463	94.73	4.89	366.47	< 0.001
Cluster 5 (C5)	2013/1/1 to 2013/12/31	32.638526 N, 35.448236 E / 0	200	21.31	9.39	269.18	< 0.001
Cluster 6 (C6)	2014/1/1 to 2014/12/31	40.457000 N, 47.738800 E / 0	254	85.14	2.98	108.79	< 0.001
Cluster 7 (C7)	2013/1/1 to 2013/12/31	36.233900 N, 43.052520 E / 353.05	97	36.97	2.62	33.53	< 0.001
Cluster 8 (C8)	2014/1/1 to 2014/12/31	34.909200 N, 36.484300 E / 144.53	13	2.64	4.92	10.35	0.034

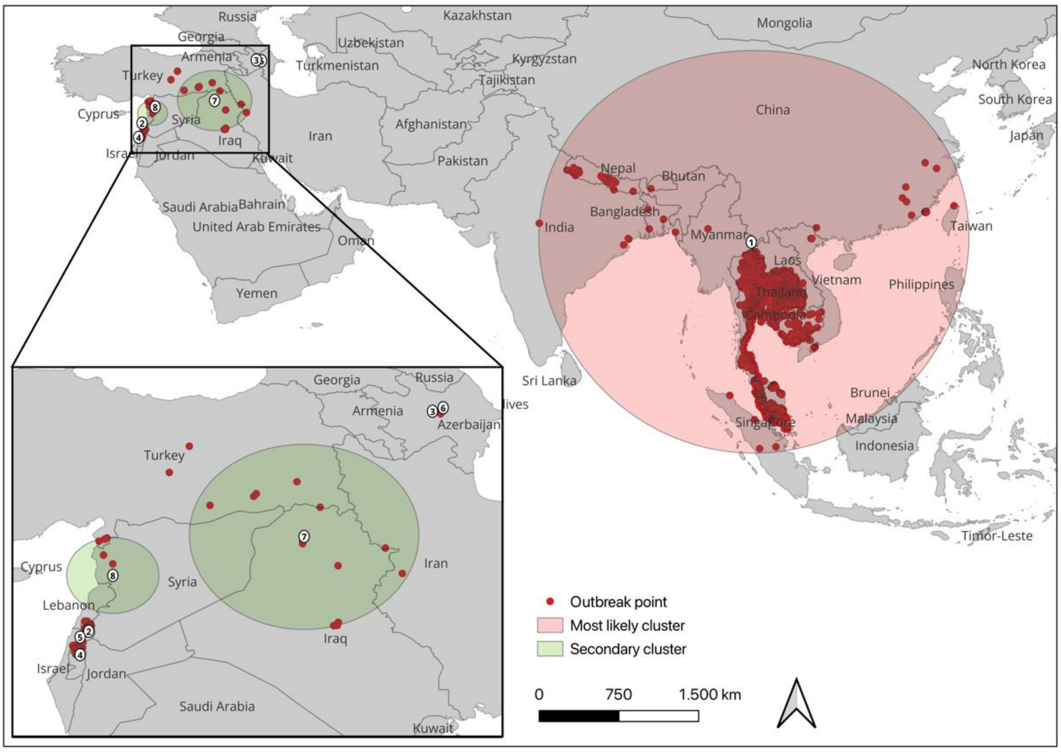

Figure A3.2 presents an analysis of LSD outbreak clusters in Asia, employing the space-time Poisson model. Yearly time aggregation is applied, and the MTCS is set to 1 year. The model identifies one primary cluster and seven secondary clusters.

Model 3

According to Model 3, the table displaying the primary and secondary clusters, along with the corresponding maps for these clusters, is presented below.

Table A3.3 presents an analysis of LSD outbreak clusters in Asia, employing the space-time Poisson model. Monthly time aggregation is applied, and the MTCS is set to 50% of the study period.

Clusters	Cluster time	Coordinates/ radius	Observed cases	Expected cases	Relative risk	LLR	P-value
Cluster 1(C1)	2021/3/1 to 2022/3/31	22.663549 N, 95.299698 E/ 1839.65	570965	84744.86	111.18	1001288.90	<0.001
Cluster 2 (C2)	2012/7/1 to 2012/10/31	33.207053 N, 35.602093 E/ 14.84	2867	1035.63	2.78	1090.76	<0.001

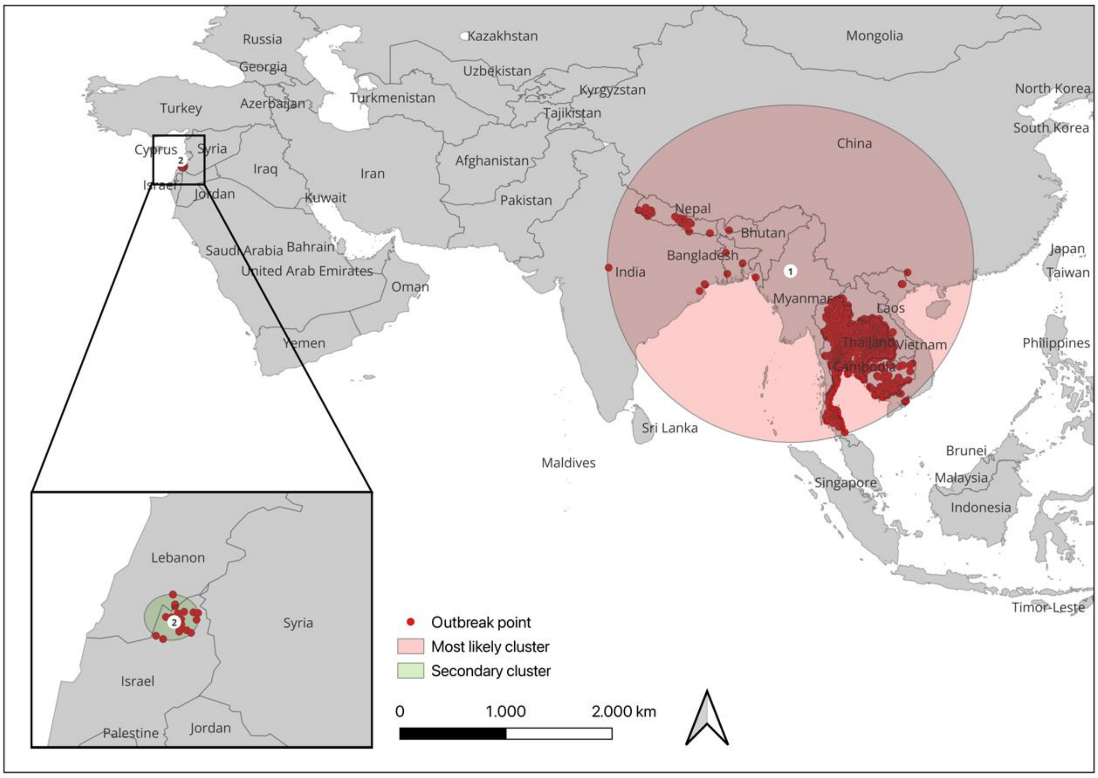

Figure A3.3 presents an analysis of LSD outbreak clusters in Asia, employing the space-time Poisson model. Monthly time aggregation is applied, and the MTCS is set to 50% of the study period. The model identifies one primary cluster and one secondary clusters.

Model 4

According to Model 4, the table displaying the primary and secondary clusters, along with the corresponding maps for these clusters, is presented below.

Table A3.4 presents an analysis of LSD outbreak clusters in Asia, employing the space-time Poisson model. Monthly time aggregation is applied, and the MTCS is set to 1 month

Clusters	**Cluster time**	**Coordinates/ radius**	**Observed cases**	**Expected cases**	**Relative risk**	**LLR**	**P-value**
Cluster 1(C1)	2021/5/1 to 2021/5/31	25.936111 N, 115.901111 E / 2084.62	298975	34754.14	16.10	453369.48	<0.001
Cluster 2 (C2)	2021/8/1 to 2021/8/31	24.759830 N, 67.915350 E / 1690.54	29717	20095.84	1.50	2084.25	<0.001
Cluster 3 (C3)	2012/7/1 to 2012/7/31	33.192979 N, 35.747863 E / 8.49	1683	513.20	3.29	830.18	<0.001
Cluster 4 (C4)	2014/10/1 to 2014/10/31	46.633000 N, 49.520800 E / 702.21	2673	1113.93	2.41	782.65	<0.001

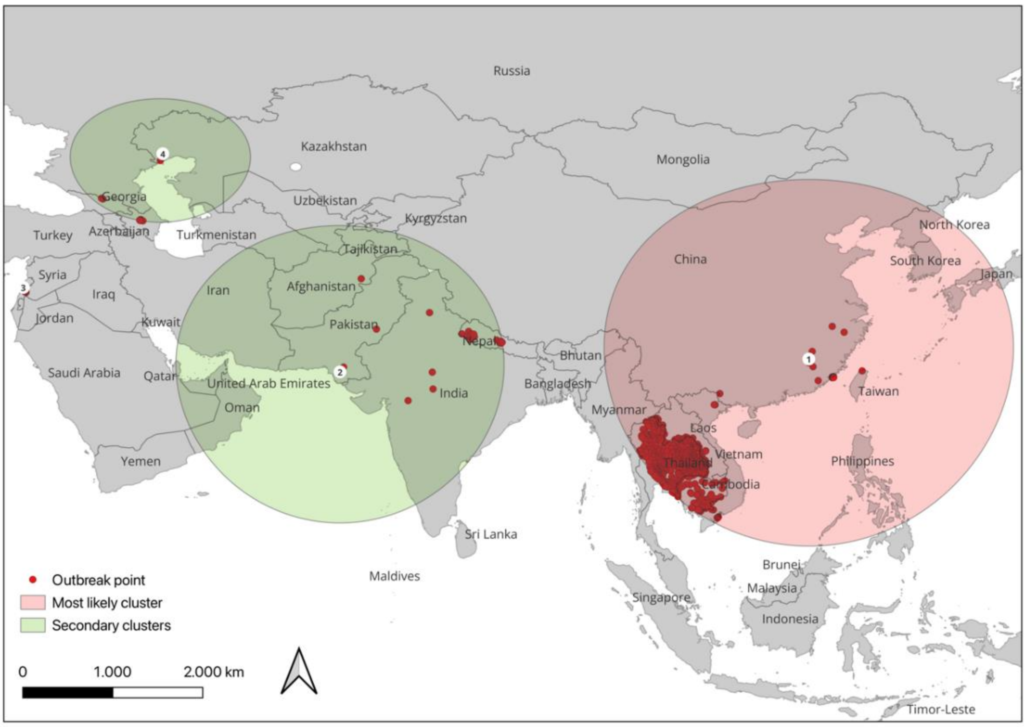

Figure A3.4 presents an analysis of LSD outbreak clusters in Asia, employing the space-time Poisson model. Monthly time aggregation is applied, and the MTCS is set to 1 month. The model identifies one primary cluster and three secondary clusters.

As per the Poisson model (models 1 to 4), when the MTCS was configured to represent 50% of the study period, the primary cluster remained consistent, regardless of whether time aggregations were set as yearly or monthly. The smallest primary cluster was observed when MTCS was set to 1 month, and the time aggregation was configured as monthly.

Model 5

According to Model 5, the table displaying the primary and secondary clusters, along with the corresponding maps for these clusters, is presented below.

Table A3.5 presents an analysis of LSD outbreak clusters in Asia, employing the space-time permutation model. Yearly time aggregation is applied, and the MTCS is set to 50% of the study period.

Clusters	Cluster time	Coordinates/radius	Observed cases	Expected cases	Test statistic	P-value
Cluster 1(C1)	2012/1/1 to 2019/12/31	46.633000 N, 49.520800 E/ 2476.14	18106	574.24	45208.96	<0.001
Cluster 2 (C2)	2022/1/1 to 2023/12/31	4.678979 S, 104.812898 E/ 1342.42	4524	58.93	15189.55	<0.001
Cluster 3 (C3)	2019/1/1 to 2020/12/31	23.685000 N, 90.598000 E/ 834.93	1837	8.54	8040.08	<0.001
Cluster 4 (C4)	2022/1/1 to 2022/12/31	15.638810 N, 100.464310 E/ 46.66	1635	17.43	5809.57	<0.001
Cluster 5 (C5)	2020/1/1 to 2020/12/31	24.441660 N, 118.447590 E/ 1288.20	468	1.73	2153.80	<0.001
Cluster 6 (C6)	2021/1/1 to 2021/12/31	14.918270 N, 104.424700 E/ 203.64	301163	287307.09	638.15	<0.001

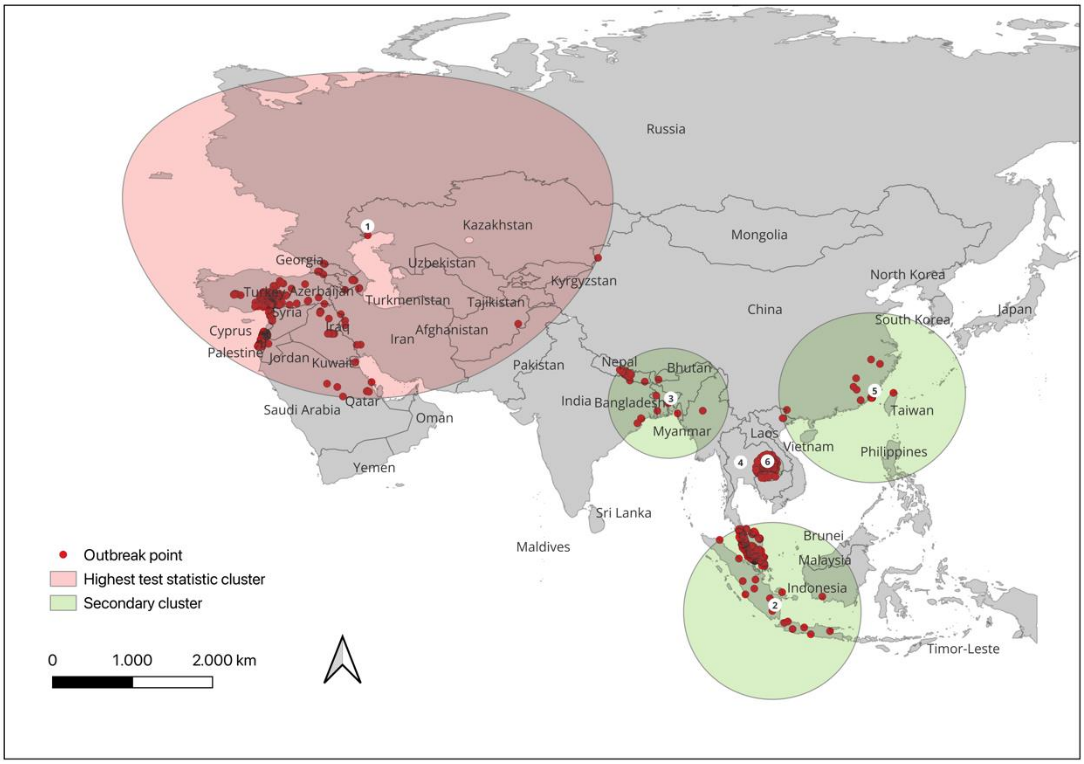

Figure A3.5 presents an analysis of LSD outbreak clusters in Asia, employing the space-time permutation model. Yearly time aggregation is applied, and the MTCS is set to 50% of the study period. The model identifies one primary cluster and five secondary clusters.

Model 6

According to Model 6, the table displaying the primary and secondary clusters, along with the corresponding maps for these clusters, is presented below.

Table A3.6 presents an analysis of LSD outbreak clusters in Asia, employing the space-time permutation model. Yearly time aggregation is applied, and the MTCS is set to 1 year

Clusters	Cluster time	Coordinates/radius	Observed cases	Expected cases	Test statistic	P-value
Cluster 1(C1)	2012/1/1 to 2012/12/31	33.080175 N, 35.552339 E/ 34.27	4058	27.59	16236.73	<0.001
Cluster 2 (C2)	2014/1/1 to 2014/12/31	39.952587 N, 40.962319 E/ 649.08	3610	25.47	14310.61	<0.001
Cluster 3 (C3)	2016/1/1 to 2016/12/31	25.911180 N, 45.363790 E/ 407.89	3515	24.95	13911.55	<0.001
Cluster 4 (C4)	2022/1/1 to 2022/12/31	4.678979 S, 104.812898 E/ 1342.42	4144	55.34	13810.54	<0.001
Cluster 5 (C5)	2020/1/1 to 2020/12/31	49.488000 N, 113.242000 E/ 3438.41	2031	16.95	7710.06	<0.001
Cluster 6 (C6)	2022/1/1 to 2022/12/31	15.638810 N, 100.464310 E/ 46.66	1635	17.43	5809.57	<0.001
Cluster 7 (C7)	2021/1/1 to 2021/12/31	14.918270 N, 104.424700 E/ 203.64	301163	287307.09	638.15	<0.001

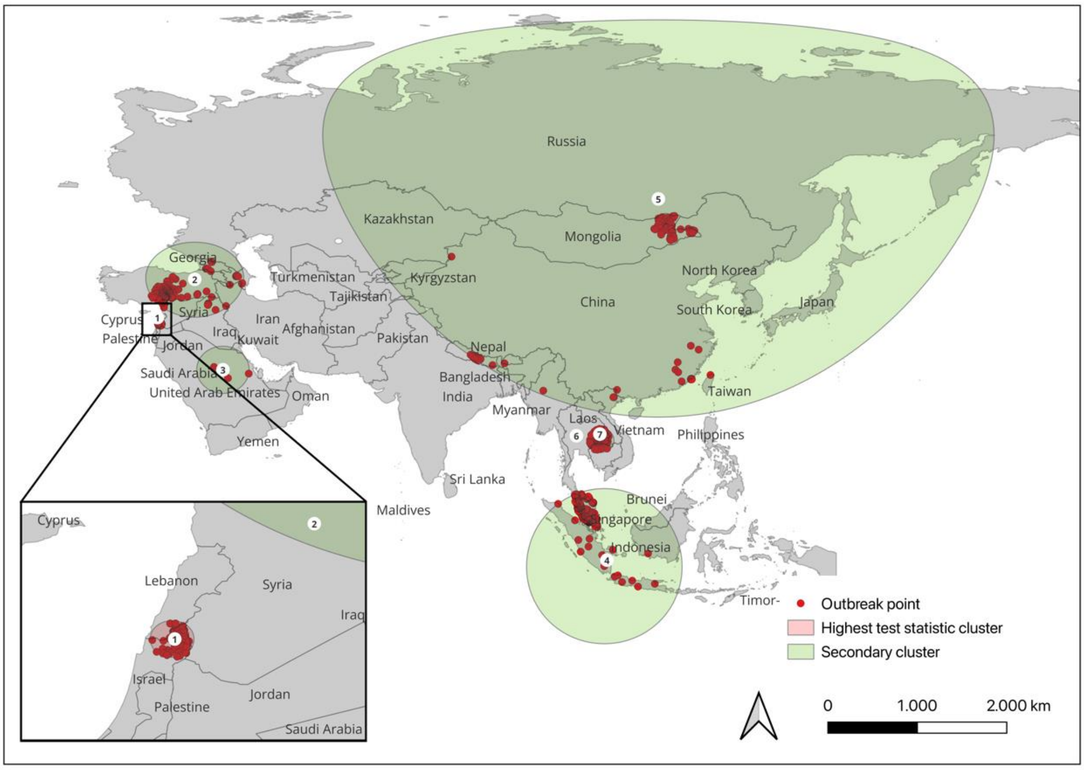

Figure A3.6 presents an analysis of LSD outbreak clusters in Asia, employing the space-time permutation model. Yearly time aggregation is applied, and the MTCS is set to 1 year. The model identifies one primary cluster and six secondary clusters.

Model 7

According to Model 7, the table displaying the primary and secondary clusters, along with the corresponding maps for these clusters, is presented below.

Figure A3.7 presents an analysis of LSD outbreak clusters in Asia, employing the space-time permutation model. Monthly time aggregation is applied, and the MTCS is set to 50% of the study period

Clusters	**Cluster time**	**Coordinates/radius**	**Observed cases**	**Expected cases**	**Test statistic**	**P-value**
Cluster 1(C1)	2021/8/1 to 2021/8/31	24.971000 N, 77.363000 E/ 191.31	29616	1525.62	60415.32	<0.001
Cluster 2 (C2)	2021/4/1 to 2021/4/30	16.166710 N, 103.612595 E/ 69.62	67875	19505.39	38334.03	<0.001
Cluster 3 (C3)	2021/7/1 to 2021/7/31	15.228901 N, 103.615344 E/ 41.23	13417	473.30	32070.25	<0.001
Cluster 4 (C4)	2021/6/1 to 2021/6/30	15.794722 N, 104.140556 E/ 0	21324	2873.98	24573.06	<0.001
Cluster 5 (C5)	2021/5/1 to 2021/5/31	14.830964 N, 99.729599 E/ 357.52	150423	90177.41	20412.85	<0.001
Cluster 6 (C6)	2021/9/1 to 2023/3/31	2.705993 S, 111.635122 E/ 1970.19	7661	205.00	20329.91	<0.001
Cluster 7 (C7)	2021/4/1 to 2021/4/30	14.943823 N, 103.060775 E/ 0	19072	3779.44	15775.27	<0.001
Cluster 8 (C8)	2021/6/1 to 2021/6/30	15.556740 N, 102.985880 E/ 0	9284	1251.27	10627.58	<0.001
Cluster 9 (C9)	2019/7/1 to 2020/11/30	49.693306 N, 113.809472 E/ 3523.04	2192	22.88	7835.53	<0.001

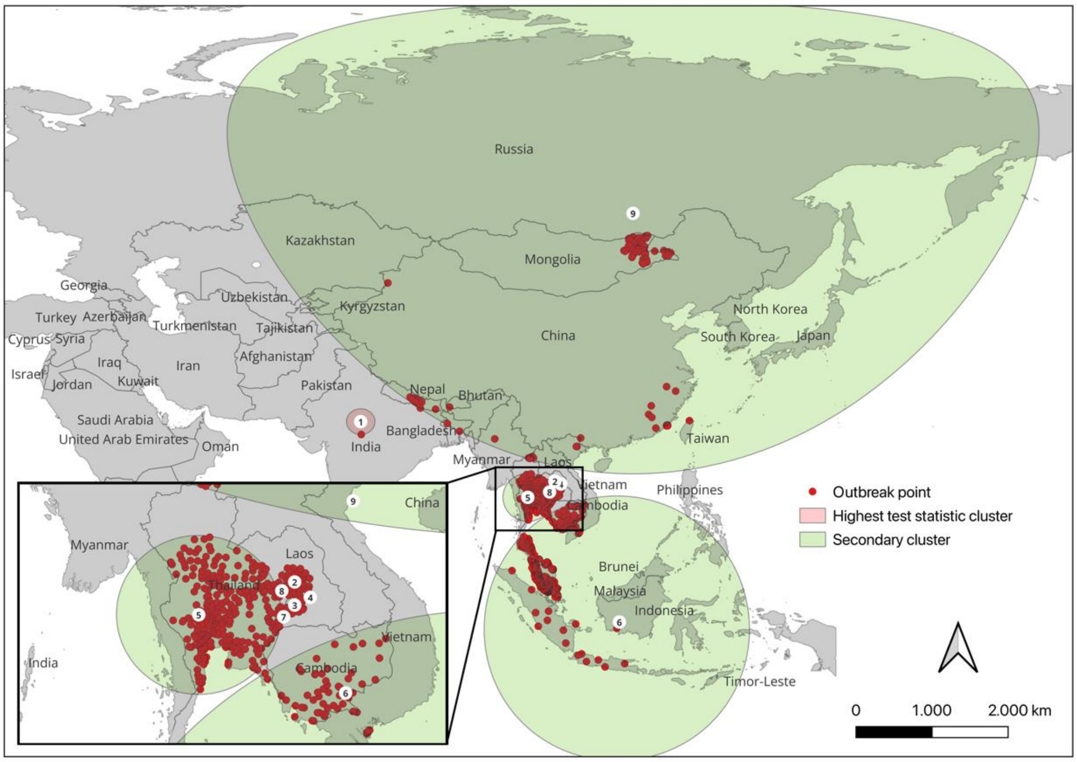

Figure A3.7 presents an analysis of LSD outbreak clusters in Asia, employing the space-time permutation model. Monthly time aggregation is applied, and the MTCS is set to 50% of the study period. The model identifies one primary cluster and eight secondary clusters.

Model 8

According to Model 8, the table displaying the primary and secondary clusters, along with the corresponding maps for these clusters, is presented below.

Table A3.8 presents an analysis of LSD outbreak clusters in Asia, employing the space-time permutation model. Monthly time aggregation is applied, and the MTCS is set to 1 month.

Clusters	Cluster time	Coordinates/radius	Observed cases	Expected cases	Test statistic	P-value
Cluster 1(C1)	2021/8/1 to 2021/8/31	24.971000 N, 77.363000 E/ 191.31	29616	1525.62	60415.32	<0.001
Cluster 2 (C2)	2021/4/1 to 2021/4/30	16.166710 N, 103.612595 E/ 69.62	67875	19505.39	38334.03	<0.001
Cluster 3 (C3)	2021/7/1 to 2021/7/31	15.228901 N, 103.615344 E/ 41.23	13417	473.30	32070.25	<0.001
Cluster 4 (C4)	2021/6/1 to 2021/6/30	15.794722 N, 104.140556 E/ 0	21324	2873.98	24573.06	<0.001
Cluster 5 (C5)	2021/5/1 to 2021/5/31	14.830964 N, 99.729599 E/ 357.52	150423	90177.41	20412.85	<0.001
Cluster 6 (C6)	2021/4/1 to 2021/4/30	14.943823 N, 103.060775 E/ 0	19072	3779.44	15775.27	<0.001
Cluster 7 (C7)	2022/12/1 to 2022/12/31	6.941591 S, 109.160327 E/ 1021.54	2712	14.95	11412.86	<0.001
Cluster 8 (C8)	2021/6/1 to 2021/6/30	15.556740 N, 102.985880 E/ 0	9284	1251.27	10627.58	<0.001
Cluster 9 (C9)	2021/9/1 to 2021/9/30	46.090000 N, 115.166000 E/ 416.16	1418	11.33	5443.77	<0.001

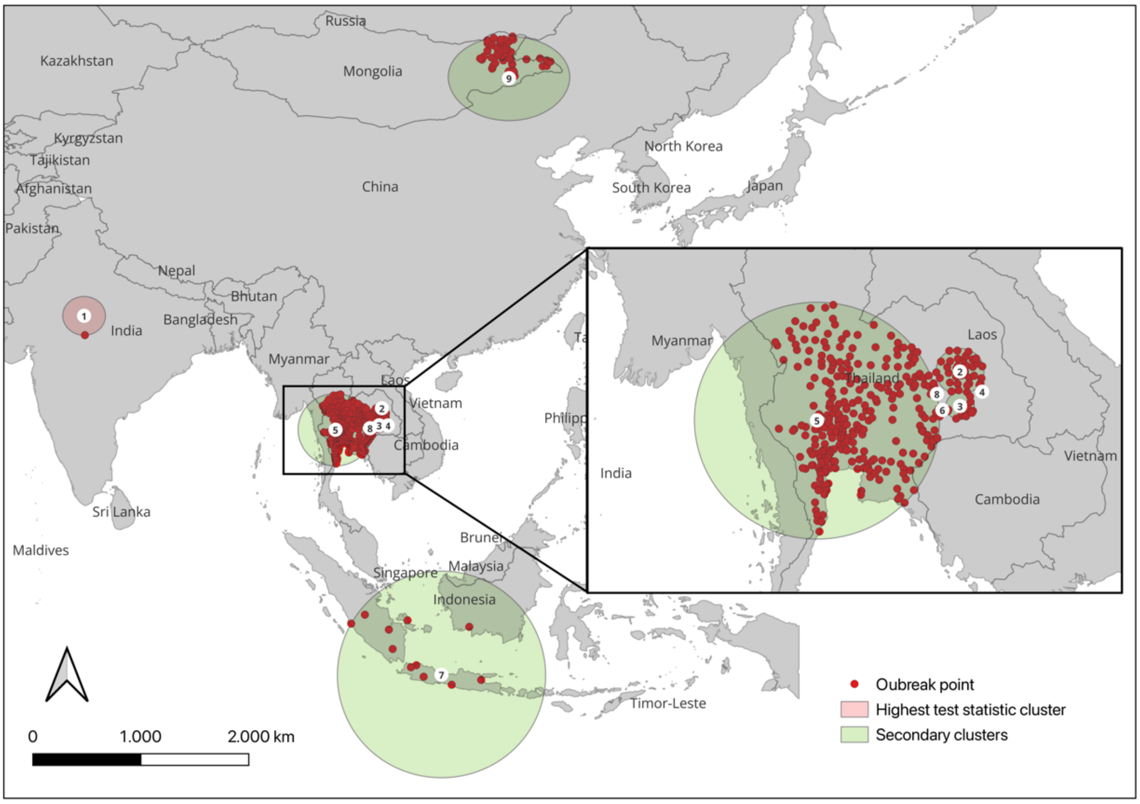

Figure A3.8 presents an analysis of LSD outbreak clusters in Asia, employing the space-time permutation model. Monthly time aggregation is applied, and the MTCS is set to 1 month. The model identifies one primary cluster and eight secondary clusters.

In accordance with the findings from the space-time Poisson models, the results from the STP model (models 4, 5, and 6) also indicate that the largest primary cluster was detected when the MTCS was set to 50% of the study period, and the time aggregation was specified as yearly. This primary cluster covered countries in South and Southeast Asia and had a duration from January 2012 to December 2019. When the time aggregation was set as monthly, the primary clusters from both MTCS settings (models 7 and 8) offered the same clusters which represents to the LSD outbreaks in August, 2021.

Based on the results from all the models, there is significant variability in the total number of clusters produced by each model. Here's an overview of the key findings:

- All clusters generated by the Poisson model, regardless of the time aggregation and MTCS settings, exhibited a relative risk value greater than one. This suggests that all clusters fall within the high-risk category.
- The STP model with year time aggregation and a 50% MTCS setting produced clusters with longer durations than any other model.
- The window of the primary clusters varied across the different models, indicating that the location of the highest-risk clusters differed depending on the model and settings used. This suggests that the choice of model and parameters can influence the spatial and temporal characteristics of the identified clusters.

Both STP and Poisson models identified two clusters, and all of these clusters were classified as primary clusters.

The space-time Poisson model identified two clusters in both settings of MTCS. The STP model in both configurations showed that the main cluster was identified in the same place with the same radius. Moreover, the model resulted in identical values in the observed case, expected case, and test statistic. The main cluster happened in a month during the month of April 2021.

Spatio-temporal clusters using data from countries in SEA

The Poisson and STP models were specifically employed to analyze LSD outbreak data within the countries of Southeast Asia (SEA). This analysis aimed to identify spatiotemporal clusters of LSD outbreaks in this region due to the high number of reported LSD outbreaks in these countries.

The number of spatio-temporal clusters for each model is presented in the following table (Table A4), along with the corresponding figure and table numbers.

Table A4. Model descriptions for spatio-temporal analysis applied to lumpy skin disease outbreak in Southeast Asia.

Model	**Description**	**Number of clusters**	**Table number**	**Figure number**
9	Space time - Poisson model	1	3.9	3.9
10	Space time - Poisson model	1	3.10	3.10
11	Space time - Poisson model	2	3.11	3.11
12	Space time - Poisson model	2	3.12	3.12
13	Space time – STP model	6	3.13	3.13
14	Space time – STP model	6	3.14	3.14
15	Space time – STP model	7	3.15	3.15
16	Space time – STP model	8	3.16	3.16

Space time Poisson models

The following are the results from models 9 to 12. Tables and maps corresponding to the table are also displayed.

Model 9

According to Model 9, the table displaying the primary and secondary clusters, along with the corresponding maps for these clusters, is presented below.

Table A3.9 presents an analysis of LSD outbreak clusters in South East Asia, employing the space-time Poisson model. Yearly time aggregation is applied, and the MTCS is set to 50% of the study period

Clusters	Cluster time	Coordinates/ radius	Observed cases	Expected cases	Relative risk	LLR	P-value
Cluster 1(C1)	2021/1/1 to 2021/12/31	16.510610 N, 101.626988 E/ 280.44	403921	12980.91	116.48	1200466.73	<0.001

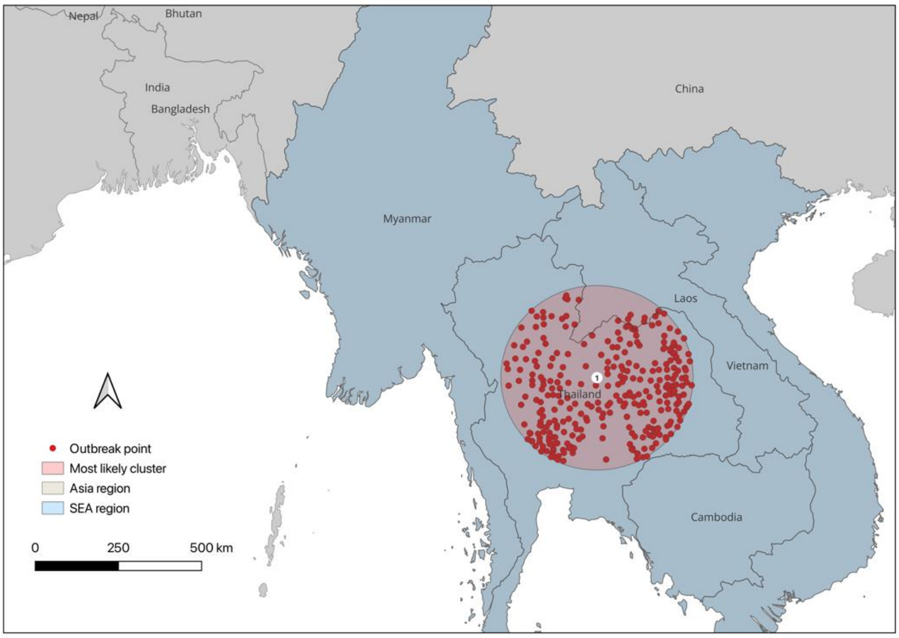

Figure A3.9 presents an analysis of LSD outbreak clusters in South East Asia, employing the space-time Poisson model. Yearly time aggregation is applied, and the MTCS is set to 50% of the study period. The model identifies one primary cluster.

Model 10

According to Model 10, the table displaying the primary and secondary clusters, along with the corresponding maps for these clusters, is presented below.

Table A3.10 presents an analysis of LSD outbreak clusters in South East Asia, employing the space-time Poisson model. Yearly time aggregation is applied, and the MTCS is set to 1 year

Clusters	Cluster time	Coordinates/ radius	Observed cases	Expected cases	Relative risk	LLR	P-value
Cluster 1(C1)	2021/1/1 to 2021/12/31	16.510610 N, 101.626988 E/ 280.44	403921	15145.06	99.43	1138763.81	<0.001

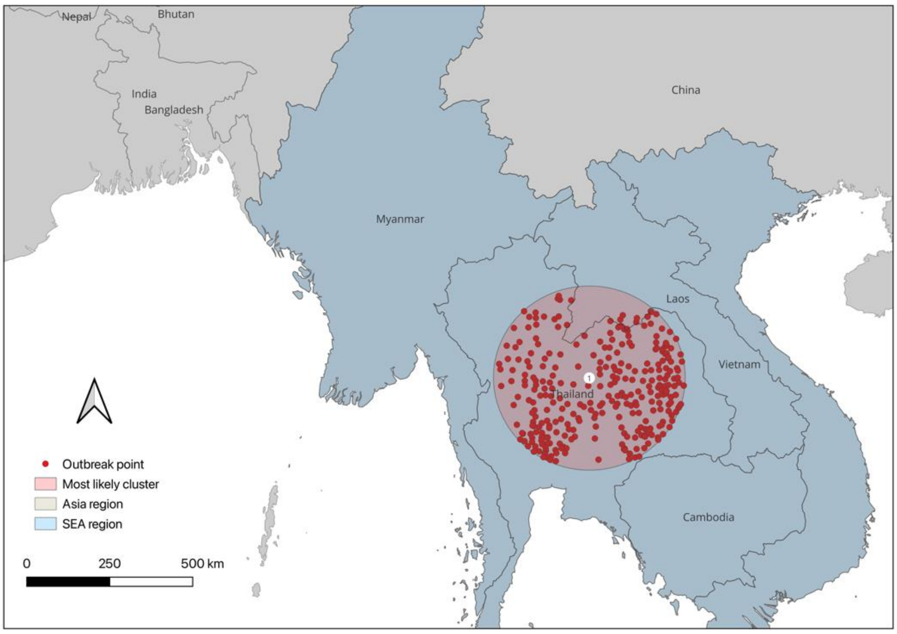

Figure A3.10 presents an analysis of LSD outbreak clusters in South East Asia, employing the space-time Poisson model. Yearly time aggregation is applied, and the MTCS is set to 1 year. The model identifies one primary cluster.

Model 11

According to Model 11, the table displaying the primary and secondary clusters, along with the corresponding maps for these clusters, is presented below.

Table A3.11 presents an analysis of LSD outbreak clusters in South East Asia, employing the space-time Poisson model. Monthly time aggregation is applied, and the MTCS is set to 50% of the study period

Clusters	**Cluster time**	**Coordinates/ radius**	**Observed cases**	**Expected cases**	**Relative risk**	**LLR**	**P-value**
Cluster 1(C1)	2021/4/1 to 2022/3/31	18.227076 N, 104.031501 E/ 613.83	515317	107395.16	67.70	725793.17	<0.001
Cluster 2(C2)	2021/6/1 to 2021/10/31	1.440110 N, 103.709290 E/ 1245.49	6027	1787.08	3.40	3103.43	<0.001

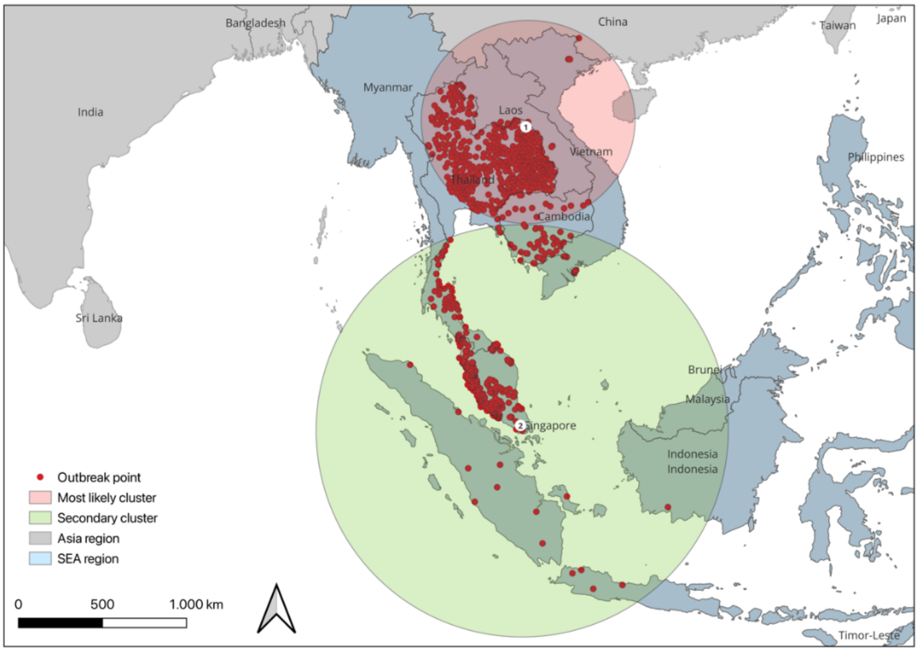

Figure A3.11 presents an analysis of LSD outbreak clusters in South East Asia, employing the space-time Poisson model. Monthly time aggregation is applied, and the MTCS is set to 50% of the study period. The model identifies one primary cluster and one secondary clusters.

Model 12

According to Model 12, the table displaying the primary and secondary clusters, along with the corresponding maps for these clusters, is presented below.

Table A3.12 presents an analysis of LSD outbreak clusters in South East Asia, employing the space-time Poisson model. Monthly time aggregation is applied, and the MTCS is set to 1 month

Clusters	Cluster time	Coordinates/ radius	Observed cases	Expected cases	Relative risk	LLR	P-value
Cluster 1(C1)	2021/5/1 to 2021/5/31	17.865747 N, 103.621266 E/ 543.99	298962	59102.10	9.96	316933.44	<0.001
Cluster 2(C2)	2021/6/1 to 2021/6/30	1.800310 N, 103.700998 E/ 1213.05	3343	872.10	3.85	2026.74	<0.001

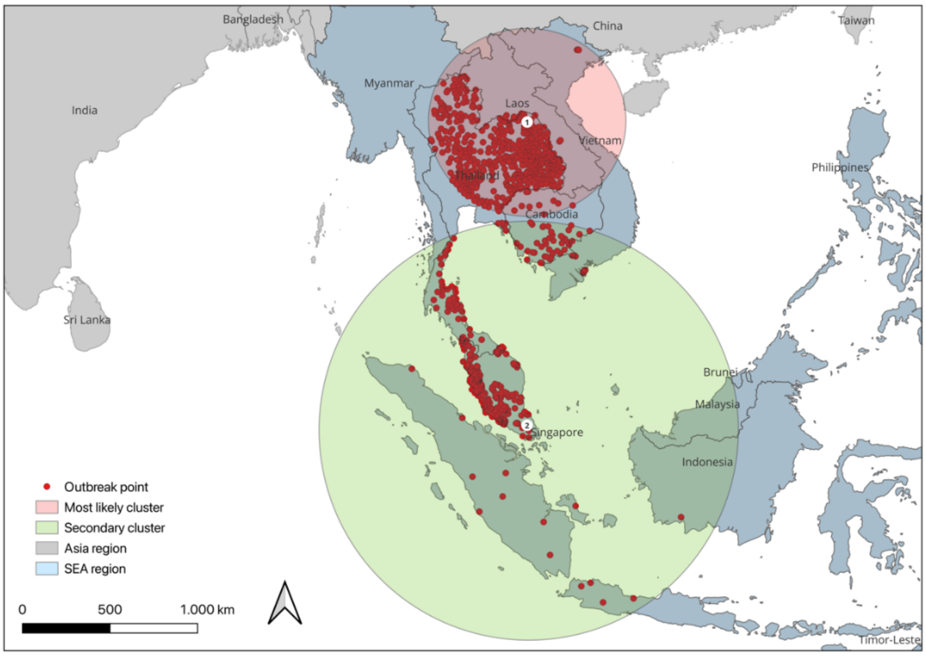

Figure A3.12 presents an analysis of LSD outbreak clusters in South East Asia, employing the space-time Poisson model. Monthly time aggregation is applied, and the MTCS is set to 1 month. The model identifies one primary cluster and one secondary clusters.

According to models 9 to 12, the primary clusters derived from both MTCS settings with yearly time aggregation were similar in terms of their coordinates and cluster time. However, they differed in the number of observed cases, expected cases, relative risk, and Log-Likelihood Ratio (LLR).

Space-time permutation models

The results for models 13 to 16 are presented below, along with the corresponding tables and maps.

Model 13

In accordance with Model 13, the table displaying primary and secondary clusters, along with corresponding maps, is provided below.

Table A3.13 presents an analysis of LSD outbreak clusters in South East Asia, employing the space-time permutation model. Yearly time aggregation is applied, and the MTCS is set to 50% of the study period.

Clusters	Cluster time	Coordinates/radius	Observed cases	Expected cases	Test statistic	P-value
Cluster 1(C1)	2022/1/1 to 2023/12/31	4.678979 S, 104.812898 E/ 1342.42	4524	64.14	14813.22	<0.001
Cluster 2 (C2)	2022/1/1 to 2022/12/31	15.638810 N, 100.464310 E/ 46.66	1635	19.00	5669.90	<0.001
Cluster 3 (C3)	2020/1/1 to 2020/12/31	21.640200 N, 106.218200 E/ 140.27	259	0.13	1717.72	<0.001
Cluster 4 (C4)	2022/1/1 to 2022/12/31	11.616000 N, 105.759450 E/ 142.86	165	8.73	328.65	<0.001
Cluster 5 (C5)	2021/1/1 to 2021/12/31	14.775970 N, 104.476950 E/ 195.56	273211	269868.07	40.90	<0.001
Cluster 6 (C6)	2022/1/1 to 2022/12/31	14.854333 N, 101.779329 E/ 70.61	10	0.81	15.97	<0.001

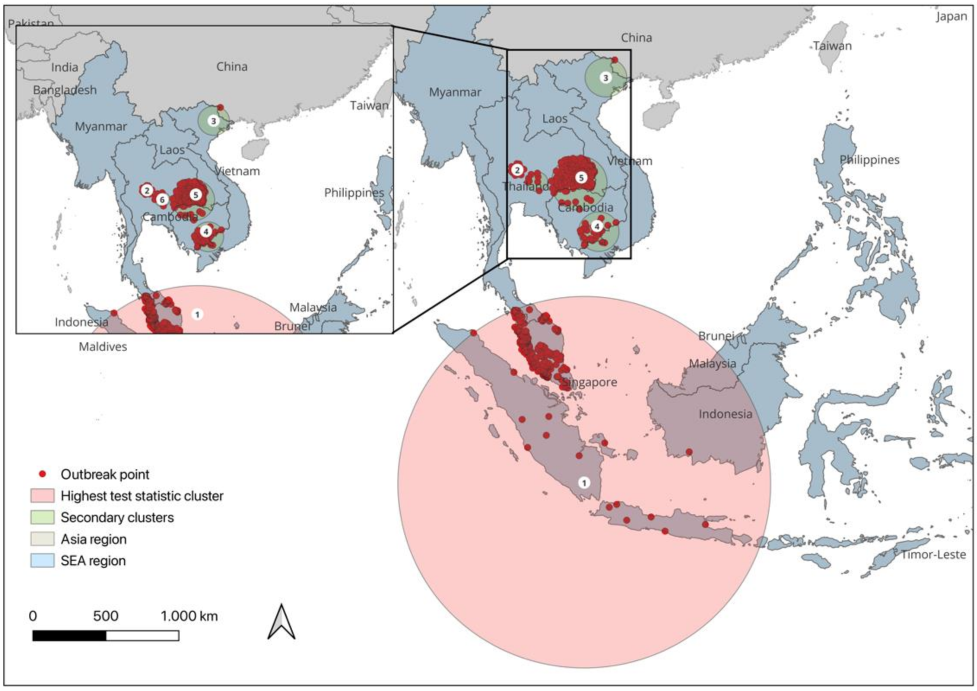

Figure A3.13 presents an analysis of LSD outbreak clusters in South East Asia, employing the space-time permutation model. Yearly time aggregation is applied, and the MTCS is set to 50% of the study period. The model identifies one primary cluster and five secondary clusters

Model 14

In accordance with Model 14, the table displaying primary and secondary clusters, along with corresponding maps, is provided below.

Table A3.14 presents an analysis of LSD outbreak clusters in South East Asia, employing the space-time permutation model. Yearly time aggregation is applied, and the MTCS is set to 1 year

Clusters	Cluster time	Coordinates/radius	Observed cases	Expected cases	Test statistic	P-value
Cluster 1(C1)	2022/1/1 to 2022/12/31	4.678979 S, 104.812898 E/ 1342.42	4144	60.34	13458.36	<0.001
Cluster 2 (C2)	2022/1/1 to 2022/12/31	15.638810 N, 100.464310 E/ 46.66	1635	19.00	5669.90	<0.001
Cluster 3 (C3)	2020/1/1 to 2020/12/31	21.640200 N, 106.218200 E/ 140.27	259	0.13	1717.72	<0.001
Cluster 4 (C4)	2022/1/1 to 2022/12/31	11.616000 N, 105.759450 E/ 142.86	165	8.73	328.65	<0.001
Cluster 5 (C5)	2021/1/1 to 2021/12/31	14.775970 N, 104.476950 E/ 195.56	273211	269868.07	40.90	<0.001
Cluster 6 (C6)	2022/1/1 to 2022/12/31	14.854333 N, 101.779329 E/ 70.61	10	0.81	15.97	<0.001

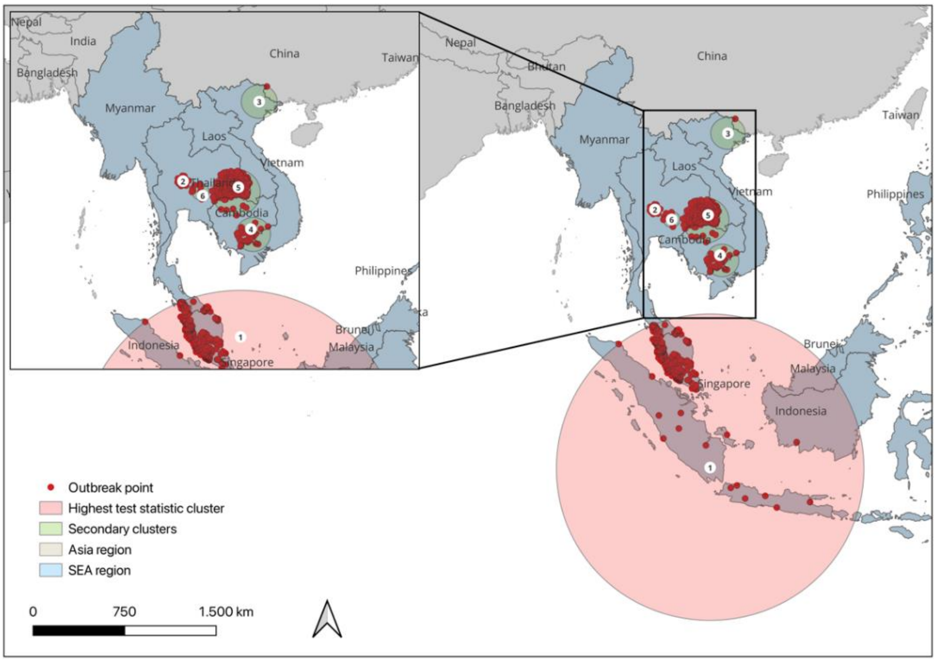

Figure A3.14 presents an analysis of LSD outbreak clusters in South East Asia, employing the space-time permutation model. Yearly time aggregation is applied, and the MTCS is set to 1 year. The model identifies one primary cluster and five secondary clusters

Model 15

In accordance with Model 15, the table displaying primary and secondary clusters, along with corresponding maps, is provided below.

Table A3.15 presents an analysis of LSD outbreak clusters in South East Asia, employing the space-time permutation model. Monthly time aggregation is applied, and the MTCS is set to 50% of the study period

Clusters	**Cluster time**	**Coordinates/radius**	**Observed cases**	**Expected cases**	**Test statistic**	**P-value**
Cluster 1(C1)	2021/4/1 to 2021/4/30	16.166710 N, 103.612595 E/ 69.62	67875	21497.40	33772.57	<0.001
Cluster 2 (C2)	2021/7/1 to 2021/7/31	15.228901 N, 103.615344 E/ 41.23	13417	479.13	31926.29	<0.001
Cluster 3 (C3)	2021/6/1 to 2021/6/30	15.794722 N, 104.140556 E/ 0	21324	3167.96	22810.21	<0.001
Cluster 4 (C4)	2021/8/1 to 2023/3/31	2.705993 S, 111.635122 E/ 2020.32	7958	201.20	21565.17	<0.001
Cluster 5 (C5)	2021/4/1 to 2021/4/30	14.943823 N, 103.060775 E/ 0	19072	4165.42	14316.41	<0.001
Cluster 6 (C6)	2021/5/1 to 2021/5/31	14.884260 N, 100.482920 E/ 276.58	134888	86810.97	13976.72	<0.001
Cluster 7 (C7)	2021/11/1 to 2021/11/30	17.074690 N, 99.045670 E/ 0	2517	13.34	10692.23	<0.001
Cluster 8 (C8)	2021/5/1 to 2021/5/31	17.947168 N, 103.135520 E/ 135.70	40777	27598.28	2907.99	<0.001

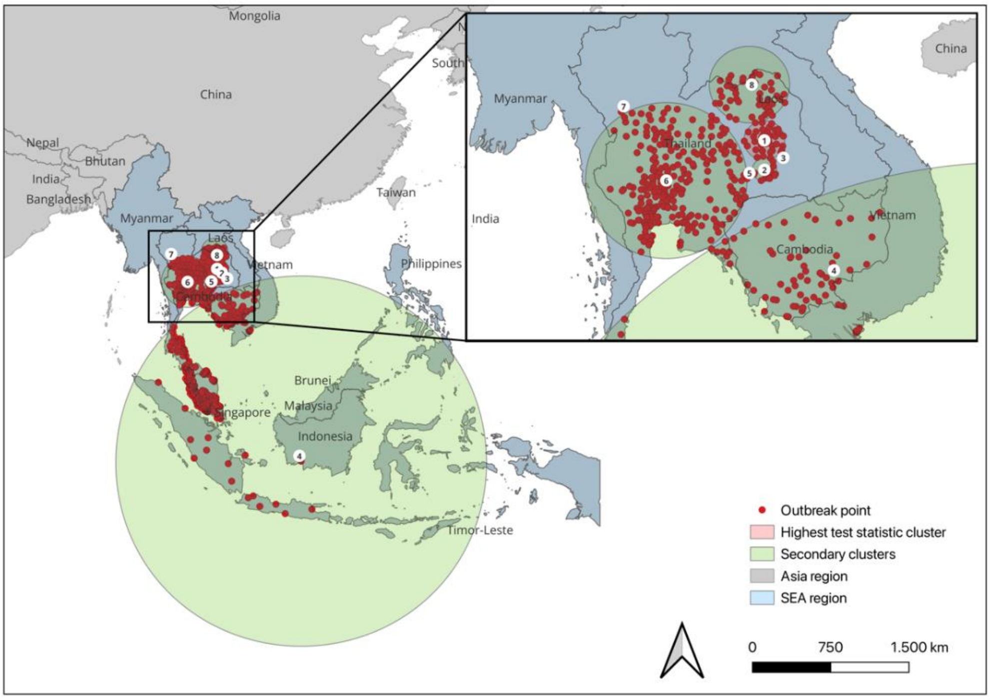

Figure A3.15 presents an analysis of LSD outbreak clusters in South East Asia, employing the space-time permutation model. Monthly time aggregation is applied, and the MTCS is set to 50% of the study period. The model identifies one primary cluster and seven secondary clusters.

Model 16

In accordance with Model 16, the table displaying primary and secondary clusters, along with corresponding maps, is provided below.

Table A3.16 presents an analysis of LSD outbreak clusters in South East Asia, employing the space-time permutation model. Monthly time aggregation is applied, and the MTCS is set to 1 month

Clusters	**Cluster time**	**Coordinates/radius**	**Observed cases**	**Expected cases**	**Test statistic**	**P-value**
Cluster 1(C1)	2021/4/1 to 2021/4/30	16.166710 N, 103.612595 E/ 69.62	67875	21497.40	33772.57	<0.001
Cluster 2 (C2)	2021/7/1 to 2021/7/31	15.228901 N, 103.615344 E/ 41.23	13417	479.13	31926.29	<0.001
Cluster 3 (C3)	2021/6/1 to 2021/6/30	15.794722 N, 104.140556 E/ 0	21324	3167.96	22810.21	<0.001
Cluster 4 (C4)	2021/5/1 to 2021/5/31	14.830964 N, 99.729599 E/ 357.52	150423	99401.86	14325.33	<0.001
Cluster 5 (C5)	2021/4/1 to 2021/4/30	14.943823 N, 103.060775 E/ 0	19072	4165.42	14316.41	<0.001
Cluster 6 (C6)	2022/12/1 to 2022/12/31	6.941591 S, 109.160327 E/ 1021.54	2712	16.48	11150.87	<0.001
Cluster 7 (C7)	2021/5/1 to 2021/5/31	17.947168 N, 103.135520 E/ 135.70	40777	27598.28	2907.99	<0.001

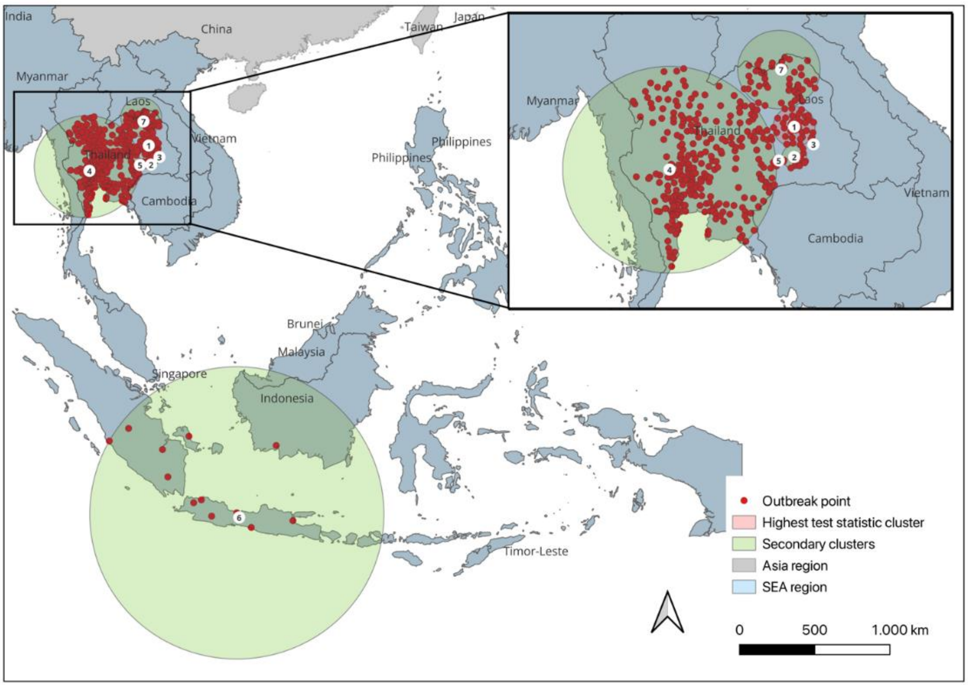

Figure A3.16 presents an analysis of LSD outbreak clusters in South East Asia, employing the space-time permutation model. Monthly time aggregation is applied, and the MTCS is set to 1 month. The model identifies one primary cluster and six secondary clusters.

With a yearly time-aggregation, setting the MTCS to 1 year resulted in a smaller primary cluster compared to the 50% of the study period MTCS setting, despite having the same cluster time. In contrast, when using monthly time aggregation, both STP models (models 14 and 15) identified two clusters in both MTCS settings. Notably, these models produced identical values for observed cases, expected cases, and the test statistic. The primary clusters in both models occurred in April 2021.

When all the spatio-temporal models were applied to the SEA data, they consistently revealed a primary disease cluster centered in Thailand. This primary cluster extended its reach to neighboring countries such as Cambodia, Laos, and Vietnam, indicating a regional pattern of the disease's spread.

Furthermore, the analysis identified secondary clusters in the SEA region, with variations depending on the specific model used. According to the Poisson model, the largest secondary cluster was centered in Malaysia. On the other hand, the STP model indicated that the largest secondary cluster was centered in Indonesia.

Indeed, the results across all models revealed that the number of clusters varied based on the chosen model, time aggregation, and MTCS settings. In the Poisson model for Asia, each setting produced distinct primary and secondary clusters, except for the MTCS 50% settings, which yielded identical cluster locations and periods. However, the observed cases, expected cases, relative risk (RR), and likelihood ratio (LLR) values differed among these identical clusters. In the STP model, the monthly time aggregation setting produced consistent results in terms of the highest test statistic and the total number of clusters, but each cluster exhibited different values. Conversely, the yearly time aggregation setting in the STP model yielded varied results. Similar patterns were observed in SEA compared to Asia, with the Poisson model displaying varying values and the STP model producing consistent values for the highest test statistic cluster in the monthly time aggregation setting.

Discussion

In this study, the aim was to analyze the pattern of LSD outbreaks and identify space-time clusters. To achieve this, multiple tests using different models and settings were conducted. The Poisson and STP models were chosen for analysis based on data availability. Spatial-temporal scan statistics necessitate the selection of a maximum cluster size, with 50% being the most commonly used value for this parameter (Ribeiro and Costa, 2012). However, given the diverse temporal and spatial characteristics of the outbreaks over the study years, various parameter settings were explored to ensure a comprehensive analysis (Chen et al., 2008; Shi and Pun-Cheng, 2019; Lee et al., 2021).

Several aspects need to be considered when interpreting the results from the spatio-temporal analyses applied to LSD outbreak data in this study.

- It should be emphasized the fact that Thailand reported the highest number of LSD outbreaks in Asia. Consequently, the majority of the outbreak location data used in the analysis originates from Thailand. The very high number of LSD cases in Thailand has a notable impact on the identification of outbreak clusters, as a substantial portion of these cases is concentrated in this country.
- Outbreak locations were reported from various countries in Asia. Consequently, the cluster sizes from the spatio-temporal analyses are inherently large when they encompass all these countries and the MTCS was set to 50% of the study period.

LSD outbreak clusters in Asia

The primary clusters from the Poisson models (models 1, 2, 3, and 4) encompass outbreaks in multiple countries in South Asia and Southeast Asia. In contrast, the STP models (models 5, 6, 7, and 8) include several countries in the Middle East and Afghanistan within the primary clusters. However, the STP models also reveal three secondary clusters located in various regions of Asia. These differences in the results are primarily due to the distinct analytical formulas used by the two models. Also, the Poisson model incorporates population-at-risk data, while the STP model does not (Kulldorff, 2021).

The results based on Asian data generally yield larger clusters compared to those from Southeast Asia, encompassing LSD outbreaks across the entire continent. When outbreaks occur in different countries, these clusters tend to be quite extensive and may even cover all outbreaks in certain countries. For example, models 1 to 3 identified primary clusters that included nearly all outbreaks in Thailand. A similar pattern was observed in model 5 using the STP method, where the primary cluster was exceptionally large.

Conversely, the utilization of Asian data can also generate smaller clusters in comparison to the vast expanse of the continent. For instance, the STP models (models 7 and 8) identified India as the primary cluster, which is relatively compact in size when contrasted with the secondary clusters detected by the STP method. In this context, if the primary cluster is the main focus of attention, there is a risk that other clusters, often referred to as secondary clusters, may be overlooked. For example, there's a possibility that the secondary clusters found in countries like Thailand, Vietnam, Indonesia, China, and Taiwan, which encompass numerous outbreaks, may not receive the attention they deserve since they are not identified as the primary cluster.

It is worth noting that when the MTCS is set to 1 month and monthly time aggregation is employed, the identified clusters are more likely to be smaller. Consequently, this allows for more focused investigations within these smaller clusters.

LSD outbreak clusters in Southeast Asia

Given the substantial number of LSD outbreaks reported in Southeast Asia, it is particularly valuable to conduct a detailed investigation in this region. Thailand, in particular, stands out for reporting the highest number of LSD outbreaks, with a significant portion of these incidents taking place in 2021.

According to the Poisson models, the primary clusters identified in models 9 and 10 were situated in Thailand. In contrast, models 11 and 12 revealed primary clusters spanning across Thailand, Laos, Vietnam, and Cambodia. Furthermore, secondary clusters were observed in Thailand, Malaysia, Indonesia, and Singapore. These results highlight the significance of Thailand, where a high number of LSD outbreaks occurred, in contributing to the identification of these clusters. Furthermore, when the MTCS is set at 50% of the study period or 1 year, the STP models yield identical results. However, when the time aggregation is set to a monthly basis, smaller clusters become more apparent. This is a direct result of the smaller unit of time aggregation, as monthly intervals allow for the detection of more finely-grained, smaller clusters.

The discovery of LSD outbreaks across Thailand is significant, and it is noteworthy that multiple secondary clusters have been identified in various regions within Thailand. The presence of clusters spanning more than one country, as seen in the case of model 14, which includes LSD outbreaks in both Thailand and Cambodia, presents a valuable avenue for further exploration and research.

Additionally, the existence of various LSD outbreak clusters within Thailand itself can provide insights into the spatial and temporal patterns of LSD outbreaks in the region. These findings offer valuable information for understanding the dynamics and potential spread of

LSD outbreaks across different areas and over time. Further investigation into these clusters could help enhance our understanding of the factors influencing LSD outbreak occurrences and their impact.

Potential factor for LSD outbreaks

This study identified clusters in the Western, Southern, and Southeastern regions of Asia, suggesting a potential connection between the outbreaks in these areas. Several factors may contribute to the findings.

The movement of infected animals undoubtedly serves as a significant contributor to the long-distance spread of Lumpy Skin Disease Virus (LSDV). However, the disease is more likely to spread rapidly and aggressively over shorter distances through arthropods (Sprygin et al., 2019).

The movement of animals indeed plays a pivotal role in the spread of LSD in Asia (Roche et al., 2020). The lumpy skin disease virus (LSDV) can be transmitted through the transport and movement of infected animals, as these carriers can introduce the virus to new locations and subsequently transmit it to other animals in those areas.

The intricate nature of cattle and buffalo trade in Asia has been extensively studied and documented. It is widely recognized that animal trade in this region significantly contributes to the introduction and propagation of LSD (Roche et al., 2020). Notably, the informal exchange of cattle and buffalo across the lengthy and permeable borders between countries like India, Nepal, and Bangladesh has played a pivotal role in promoting the spread of LSD. A prominent instance of this occurred in July and August 2019, when the virus moved between Bangladesh and India, largely due to such cross-border movements. Similarly, the introduction of LSD to Nepal in June 2020 can be primarily attributed to the continuous flow of informal cattle movements across the border from India into various districts in Eastern Nepal. This informal trade facilitated the transmission of the disease to previously unaffected regions. The outbreak of LSD in Vietnam is another example of this pattern (Roche et al., 2020). The LSDV responsible for these outbreaks in Vietnam closely resembled the strain endemic in Russia and China. It is highly likely that the virus was introduced at the China-Vietnam border, subsequently disseminating throughout all 27 provinces in Vietnam. These cases underscore the critical role of animal trade and cross-border movements in the transmission and diffusion of LSD across the region (Byadovskaya et al., 2022).

This findings from this study are consistent with a predictive model developed previously (An et al., 2023), which integrated LSD outbreak data with bioclimatic factors, land types, and population density to identify high-risk areas in the Asian continent. According to this model, North-eastern China and certain countries in West Asia were identified as having a certain level of risk for LSD outbreaks. Furthermore, it is noted that Southern Asia and South-eastern Asia were environmentally suitable for disease vectors like *Aedes Aegypti*, making these regions high-risk areas for LSD outbreaks (Gubbins, 2019; An et al., 2023). For instance, during the rainy season, which typically spans from June to August in various regions of Nepal, there have been documented instances of LSD outbreaks. These outbreaks might be linked to the increased population of arthropods in the area (Gautam et al., 2022). This observation suggests a possible ecological relationship between LSD outbreaks and arthropod abundance, especially during the monsoon months. Furthermore, several LSD outbreaks in Thailand appear to be connected with the prevalence of LSD insect vectors found throughout the country's regions. The widespread presence of these vectors in Thailand implies a potential correlation between their population and the occurrence of LSD outbreaks in the region (Suwankitwat et al., 2022).

Thailand has consistently recorded the highest number of reported LSD cases when compared to other countries in the region. This notable difference in case reporting may be attributed to the effectiveness of Thailand's surveillance system, which results in more rapid and comprehensive outbreak reporting (Moonchai et al., 2023; Punyapornwithaya et al., 2023). Ultimately, this proactive surveillance system in Thailand has been acknowledged as a pivotal activity in the timely detection and response to disease outbreak (Wilhelm and Ward, 2023).

The geographical distance between these countries is considerable, making it likely that the spread occurred through the movement of animals and/or insect vectors across borders from Russia and Kazakhstan to China. Additionally, migratory wild birds, often infested with LSDV-infected ticks, are known to traverse the northern part of Bangladesh, potentially contributing to the disease's spread. Furthermore, the regular movement of cattle and buffaloes between India, Bangladesh, and Nepal played a significant role in the widespread outbreak in this area (Roche et al., 2020).

Comparison of Spatio-Temporal Models in Analyzing LSD Outbreaks

Research on the spatio-temporal analysis of LSD outbreaks in Asia remains notably limited. To our knowledge, only a single research paper has been published on this topic. In this study, LSD outbreak data from 2012 to 2022, sourced from WOAH, were analyzed using STP models with a 50% MTCS parameter and the maximum radius for the spatial window was set to 1000 km (Wilhelm and Ward, 2023). The findings of such study revealed the presence of nine spatio-temporal clusters across the Asian continent. The results from model 1 in this study indeed identified nine spatio-temporal clusters. However, the sizes and locations of these clusters differ from those in the previous study. This disparity can be attributed to variations in both the dataset used and the parameter settings employed in each of the studies.

The exploration of spatio-temporal analysis at the country level is indeed a promising avenue for future research. Such studies can provide a more comprehensive and detailed understanding of LSD outbreaks within specific regions and countries. By zooming in on the local context, researchers can uncover valuable insights that may not be evident when looking at broader geographic scales. Previous studies, such as those focused on specific areas in Thailand, have already demonstrated the effectiveness of this approach (Arjkumpa et al., 2022; Punyapornwithaya et al., 2022; Modethed et al., 2023). By investigating LSD outbreak clusters at a finer spatial and temporal resolution, researchers can pinpoint high-risk areas, identify potential contributing factors, and devise targeted control and prevention measures.

These localized studies not only aid in managing the disease more effectively but also serve as a template for similar investigations in other countries or regions facing LSD outbreaks.

Implications

The Asian continent comprises numerous countries with diverse geography, environmental policies, budgets, and resources. Given these variations, it is crucial for each country to select the most suitable results from the array of models and settings available. This tailored approach allows countries to align their disease control strategies with the specific clusters that best match their capacity and capability. These strategies may encompass controlling animal movement, implementing vector control measures, or vaccination programs. As a result, it is recommended to utilize spatiotemporal analysis using various models with or without parameter settings to achieve more precise and effective outcomes (Lee et al., 2021; Modethed et al., 2023).

Spatiotemporal analysis serves as a valuable tool to assess the risk of disease spread, especially in countries bordering those with a history of no LSD cases. In particular, countries like the Philippines and Timor Leste, which appear on the risk map despite having no prior LSD cases, should be vigilant. These nations need to proactively evaluate the potential for disease transmission across their borders and take immediate action to mitigate the risk. Implementing stringent biosecurity requirements for cattle imports is a critical step to consider. Additionally, efforts should be made to curb animal trafficking, especially the illegal importation of cattle (Roche et al., 2020). Furthermore, expanding vector control measures and monitoring LSDV in wild animals are also vital strategies. For example, Australia has taken proactive measures to prevent LSD by developing an action plan and conducting numerous studies. Their sizable cattle market and active cattle transport with outbreak-prone countries like Indonesia have allowed them to remain free from LSD to date. It is advisable for other countries to follow this example, as once introduced, LSD can be exceedingly challenging to control and eradicate.

There are several key points to consider when conducting and interpreting spatio-temporal analysis:

- Ensure that the data used in the analysis is of high quality, complete, and accurate. Inaccurate or incomplete data can lead to erroneous results.
- Choose an appropriate spatial and temporal scale for your analysis. The scale should be relevant to the research question and data availability.
- Spatio-temporal analysis provides the flexibility to adjust parameters to align with the specific objectives of the analysis. Relying solely on default settings may not be suitable as a one-size-fits-all approach. Default settings could lead to the identification of clusters that are either too large or too small, potentially rendering the results less relevant to the study's objectives. Therefore, it is crucial to tailor the parameter settings to the specific goals and context of the analysis to obtain meaningful and accurate results.
- Carefully interpret the identified clusters. Clusters can vary in size and significance, and it is important to understand their practical implications.

- Integrate domain-specific knowledge into the analysis. Understanding the subject matter can help in interpreting results more accurately.
- Collaborate with experts from relevant fields, such as epidemiologists, geographers, or statisticians, to ensure a comprehensive analysis. By carefully considering these points, one can conduct a meaningful and insightful spatio-temporal analysis.

Directional distribution analysis

The objective of the analysis is to determine directional distribution of lumpy skin disease outbreaks in Asia using directional distribution analysis.

Introduction

Directional distribution analysis in the context of a disease outbreak is a valuable tool for understanding the spread and transmission patterns of the disease within a geographic area. This technique is used to study data that is inherently directional in nature. In the context of disease outbreak investigations, it can provide valuable insights into the spatial patterns and the direction in which outbreaks are spreading or clustering.

With the mapped data, directional distribution analysis can be utilized to identify any patterns or trends in the movement of the disease. It can reveal the primary direction in which the disease is spreading.

Notably, the directional distribution is also known as standard deviation ellipse (SDE) (Zhao et al., 2022). This analysis can be performed using some GIS software such as ArcGis and QGIS.

Materials and Methods

For two-dimensional data, the directional distribution tool creates a new feature class containing an elliptical polygon centered on the mean center for all outbreaks. The attribute values for these output ellipse polygons include two standard distances (long and short axes) and the orientation of the ellipse. The orientation represents the rotation of the long axis measured clockwise from noon (Murad and Khashoggi, 2020).

In this study, two models were investigated including the model with a weighted standard deviational ellipse based on the number of LSD cases at each outbreak location and the model without weight.

Software

The direction distribution analysis can be performed using QGIS with the "Deviational Ellipse Plugin". The plugin can be downloaded via QGIS software as illustrated in Figure B1 and B2. After installation of the plugin, the standard deviation ellipse can be found under the vector menu (Figure B3).

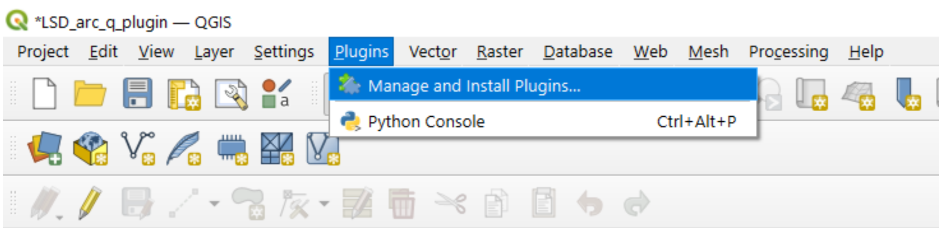

Figure B1. The method to install plugin for QGIS.

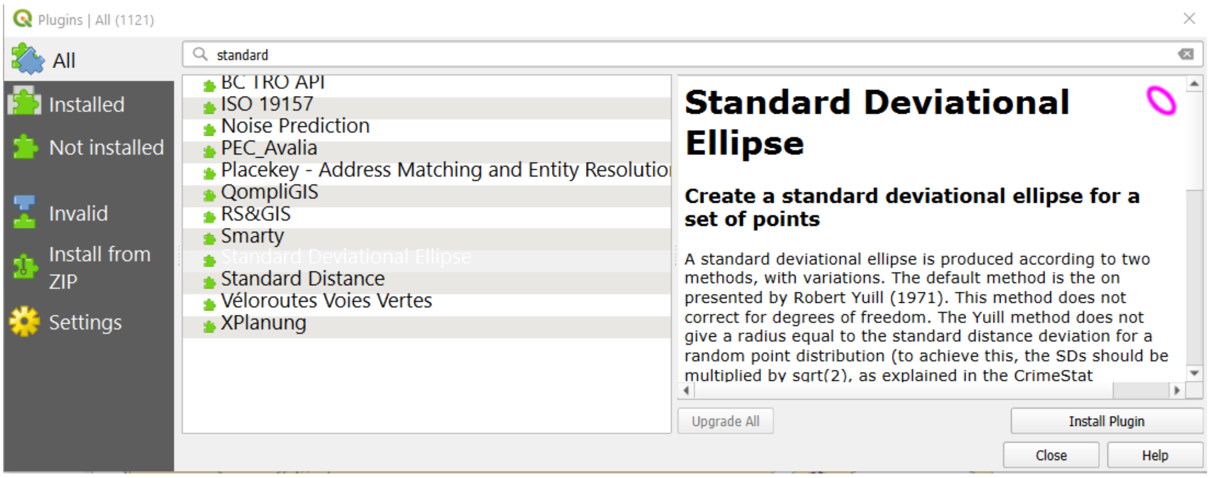

Figure B2. The standard deviational ellipse is available for download via QGIS.

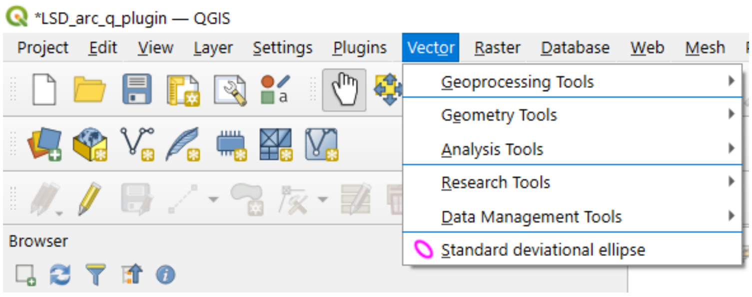

Figure B3. The standard deviation ellipse is located under Vector menu.

Two methods are employed to generate a standard deviational ellipse, each with its own variations.

- The default approach is based on Robert Yuill's method from 1971, which does not account for degrees of freedom. Thus, the Yuill method does not yield a radius equivalent to the standard distance deviation for a random point distribution. To achieve this equivalence, the standard deviations should be multiplied by the square root of 2, as detailed in the CrimeStat documentation. Notably, it is possible to set a DOF (degrees of freedom) correction and a square root of 2 correction, denoted as sqrt(2) in order to make the standard deviational ellipse equal to the standard distance deviation when the distribution of points is random and even in all directions. With both of these corrections applied, the result will be the same as for the CrimeStat method.

- The alternative approach is the CrimeStat/aspace method, which incorporates corrections for degrees of freedom and the square root of 2.

Within this study, the Yuill method, incorporating a square root of 2 correction factor, and CrimeStat are applied for SDE in the evaluation of LSD outbreaks. The analysis encompasses both weighted and unweighted scenarios related to LSD cases. Consequently, the exploration comprises a total of four distinct scenarios (Table B1).

Table B1. Methods and setting for each scenario for the standard deviation ellipse.

Scenario	Method	Adjustment	Weight field
1	Yuill	sqrt(2)	-
2	Yuill	sqrt(2)	cases
3	CrimeStat	-	-
4	CrimeStat	-	cases

This result from the directional distribution is a polygon vector layer featuring the following attributes: mean-x, mean-y, major-sd, minor-sd, major-angle, direction, and eccentricity, as described in the documentation

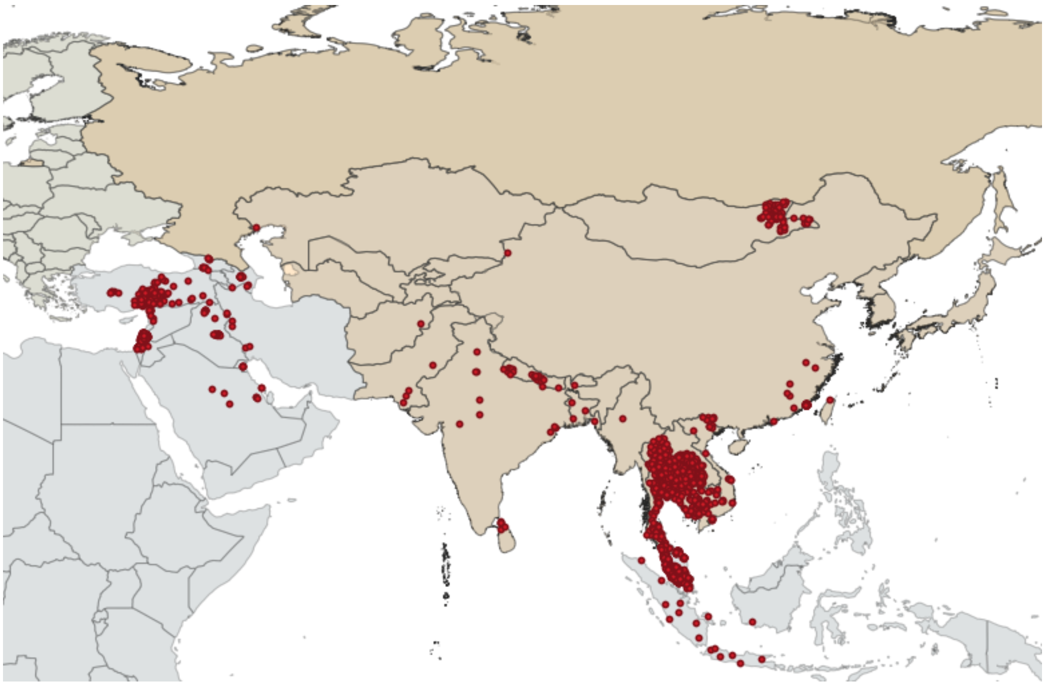

Figure B4. Locations (XY-coordinate: latitude and longitude) of lumpy skin disease outbreaks

Outbreak period

To investigate the progression of LSD outbreaks, the data were classified into 5 phases (Table B2).

Table B2. Description of study periods and their duration.

Period	Duration	Description
1	2006-2023	Overall outbreak in Asia
2	2006-2019	From Middle East to the first outbreak in Bangladesh
3	2019-2023	From Bangladesh to other countries
4	2020-2023	Outbreaks in Southeast Asia
5	2021-2023	Outbreak in Southeast Asia, majorly in Thailand

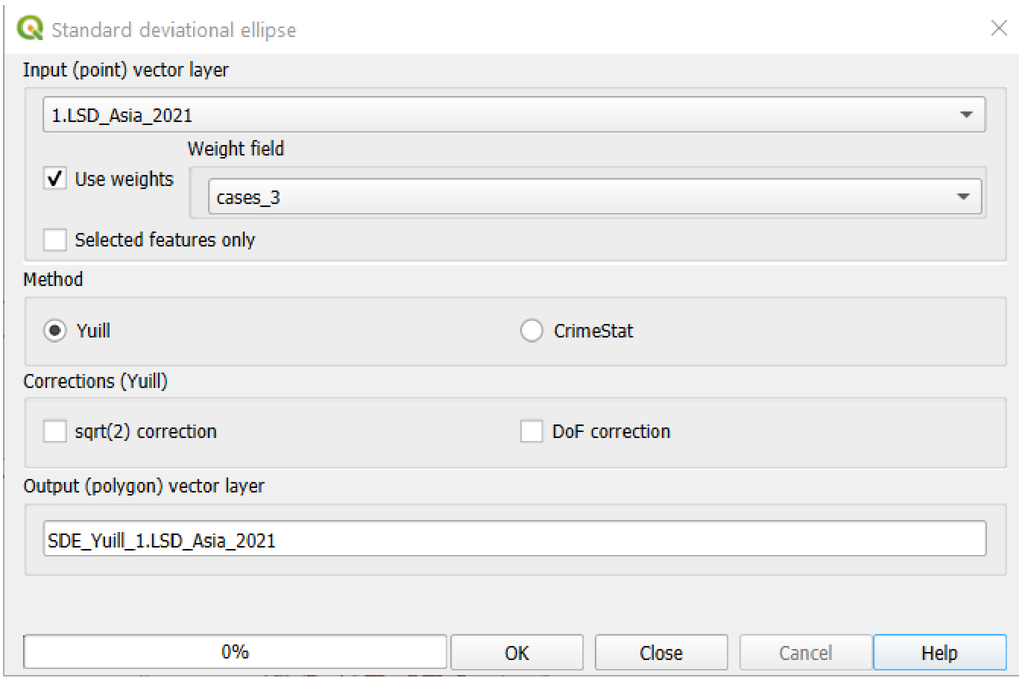

Figure B5. The standard deviational ellipse is set by using Yuill method weighted by number of cases.

Results

According to the SDE, the results from each scenario with different study phrases are depicted below (Figure B6 to Figure B10).

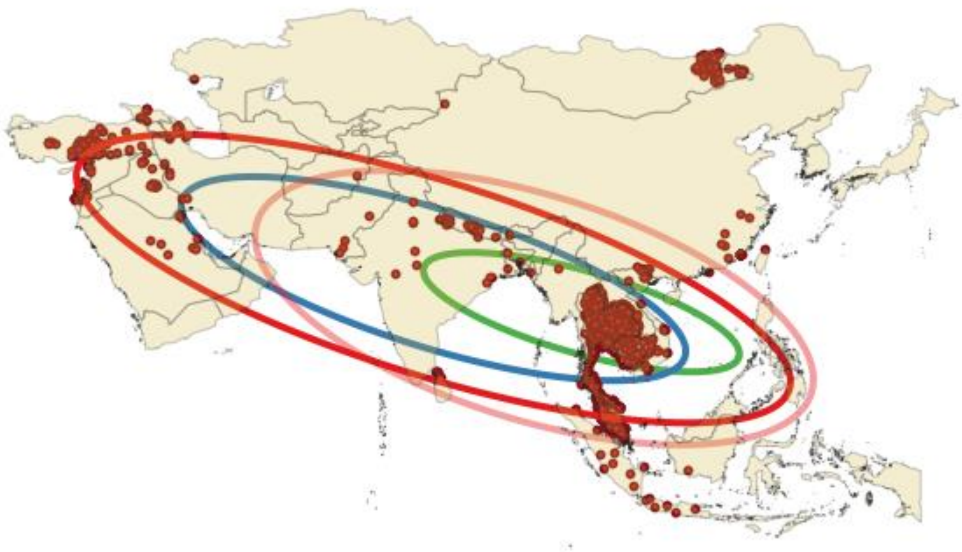

Figure B6. Standard deviation ellipses were obtained from the Yuill method, with (green line) and without weighting (blue line) and CrimeStat with (pink line) and without weighting (red line) based on lumpy skin disease outbreak data from 2006 to 2023.

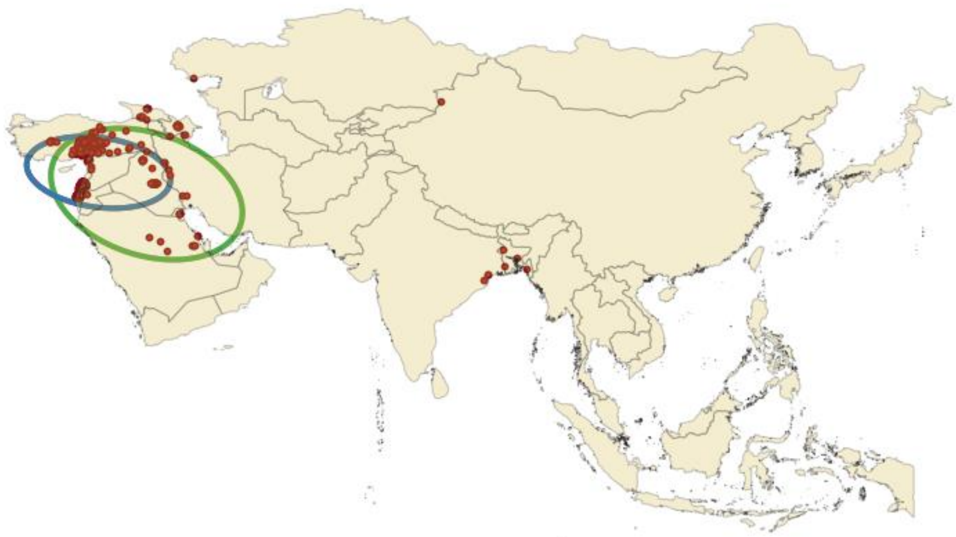

Figure B7. Standard deviation ellipses were obtained from the Yuill method, with (green line) and without weighting (blue line) and CrimeStat, with (green line) and without weighting (blue line) based on lumpy skin disease outbreak data from 2006 to 2019.

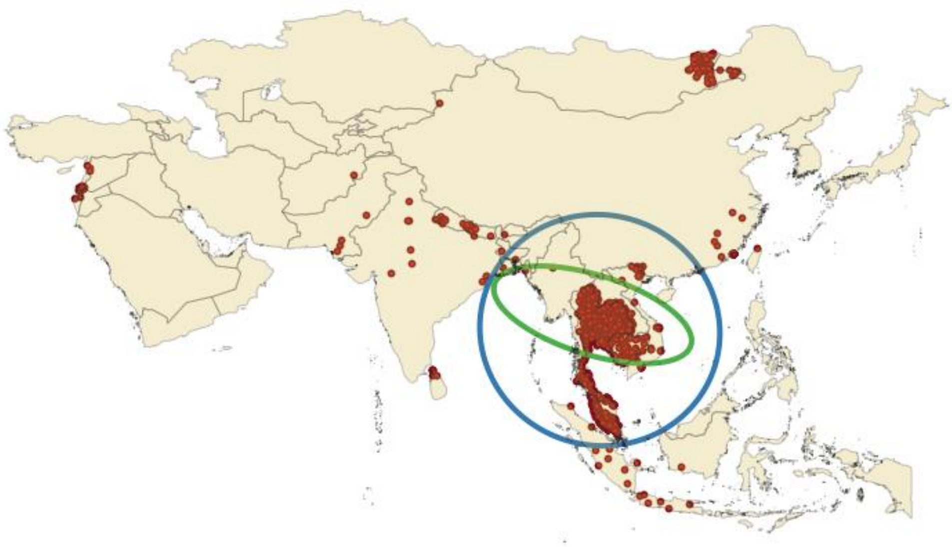

Figure B8. Standard deviation ellipses were obtained from the Yuill method, with (green line) and without weighting (blue line) and CrimeStat, with (green line) and without weighting (blue line) based on lumpy skin disease outbreak data from 2019 to 2023,

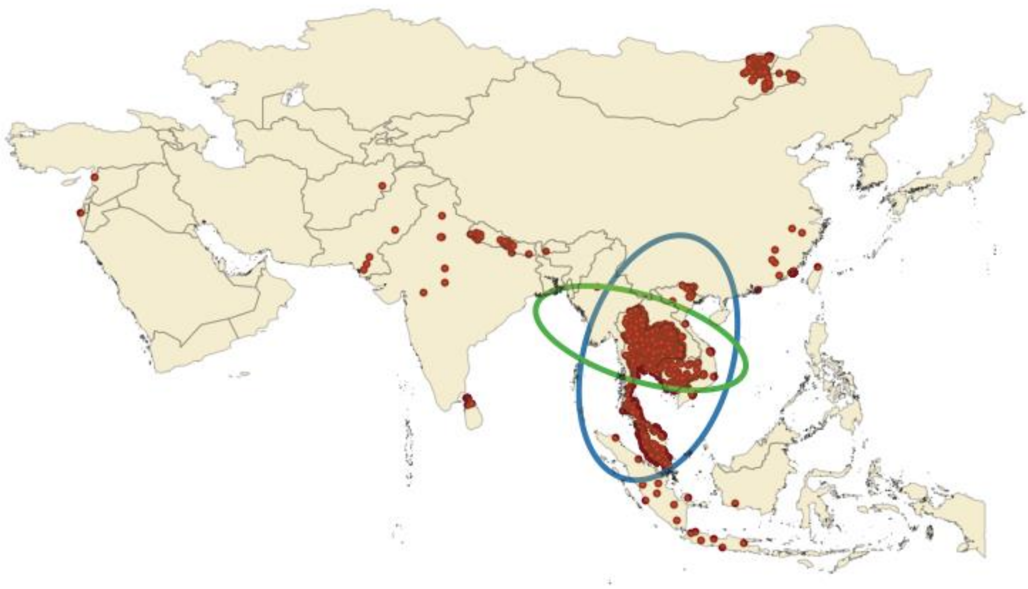

Figure B9. Standard deviation ellipses were obtained from the Yuill method, with (green line) and without weighting (blue line) and CrimeStat, with (green line) and without weighting (blue line) based on lumpy skin disease outbreak data from 2020 to 2023.

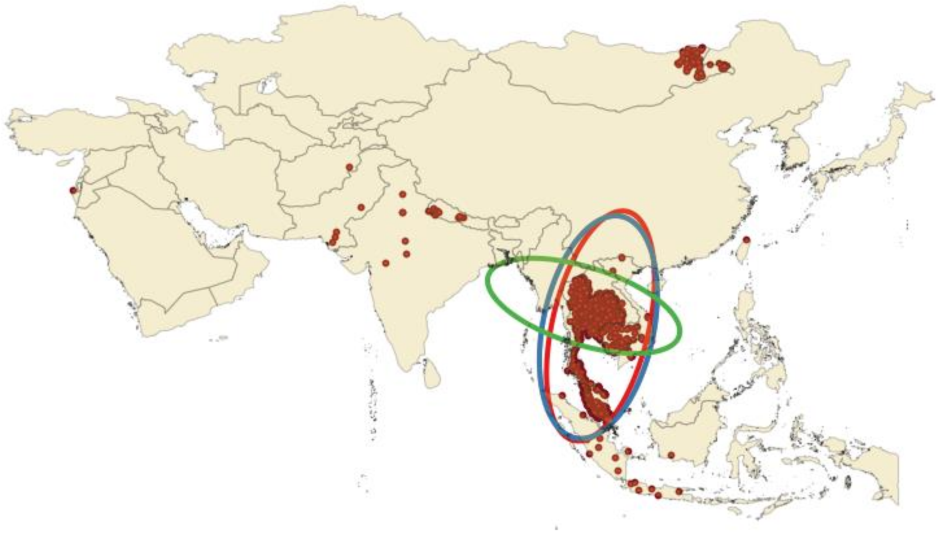

Figure B10. Standard deviation ellipses were obtained from the Yuill method, with (green line) and without weighting (blue line) and CrimeStat, with (pink line) and without weighting (red line) based on lumpy skin disease outbreak data from 2021 to 2023.

Based on 2006 to 2023 data, it is evident that the general trajectory of LSD outbreaks followed a path originating from the Middle East, proceeding towards South Asia, and eventually reaching Southeast Asia. The results from all SDE analyses consistently confirm this directional pattern, although there may be variations in the sizes of the ellipses (Figure B6).

When examining data within the 2006 to 2019 timeframe, it is worth mentioning that the SDE does not encompass any Asian countries. Nevertheless, the outbreak direction still consistently suggests a movement toward South Asia (Figure B7). Additionally, when scrutinizing data spanning from 2019 to 2023, the SDE illustrates a direction from South Asia to Southeast Asia (Figure B8).

It is worth highlighting that when examining data from both the 2019 to 2023 period and the 2020 to 2023 period, both the Yuill and CrimeStat methods consistently yield the SDE results, regardless of whether weight is taken into consideration or not.

Moreover, when examining data from 2020 to 2023, both the Yuill and CrimeStat methods yield varying directions for the SDE depending on whether weight is taken into account. In one scenario, the SDE shows a trend from the upper north to the lower southeast, while in the absence of weight considerations, the orientation shifts to a north-to-south direction within Thailand (Figure 9).

Furthermore, when analyzing data from 2021 to 2023, the Yuill method with weighting, and CrimeStat both with and without weighting, generate standard deviation ellipses that originate from the northeast and extend towards the south (Figure B10).

Discussion

The SDE was applied to LSD outbreaks in Asia in order to determine whether the outbreaks are farther from a special point in one direction than in another direction.

The results from the analysis of LSD outbreak data covering the period from 2006 to 2023 provide overall insights into the geographical patterns and directional trends of these occurrences. The LSD outbreaks expand from the Middle East, progresses through South Asia, and eventually extends into Southeast Asia.

The analysis covering the years 2006 to 2019 uncovers an interesting pattern in the SDE results. During this time frame, the SDE does not encompass any Asian countries, yet the directional trend remains unwavering. It persistently suggests a movement toward South Asia. As we shift our focus to the period spanning 2019 to 2023, a notable change in the SDE's direction becomes apparent. During this particular time period, which includes the first report of an LSD outbreak in Bangladesh, a South Asian nation, a noteworthy observation emerges. While Bangladesh is not encompassed within the SDE, this exclusion can be attributed to the substantial number of LSD outbreaks in Thailand, which effectively influences the SDE's position, shifting it towards Southeast Asia. Nonetheless, it is reasonable to make the assumption that the predominant trend during this period is directed from South Asia to Southeast Asia, with the SDE predominantly covering the landscape of Thailand. This pattern aligns with the progression of LSD outbreaks in the region as described in previous publications (Das et al., 2021; Anwar et al., 2022; Liang et al., 2022; Ratyotha et al., 2022).

It is worth emphasizing that the dataset spanning from 2020 to 2023 reveals a divergence in the directional trends observed through the Yuill and CrimeStat methods, contingent on whether weight is incorporated into the analysis. When weight is considered, the SDE indicates a notable east-to-southeast trend, moving from the upper north to the lower southeast. However, in the absence of weight considerations, the direction shifts, aligning more with a north-to-south orientation within Thailand. This discrepancy underscores the profound impact of data weighting on the perception of directional trends.

Based on the dataset from 2021 to 2023, the majority of LSD outbreaks were observed in Thailand. The results of the Standard Deviation Ellipse (SDE) analysis based on this dataset align with expectations, indicating that the direction of LSD outbreaks extends from the northeast to the south. This finding is consistent with previous reports describing the direction of LSD outbreaks in Thailand as moving from north to south (Suwankitwat et al., 2022).

The application of SDE for investigating the distribution of LSD outbreaks in Asia has thus far been somewhat constrained. The previous study had a limited scope, concentrating on the occurrences of LSD outbreaks between October 2020 and 2021. Consequently, the primary emphasis was on discerning the distribution of LSD outbreaks primarily within Thailand (Wilhelm and Ward, 2023). In contrast, the present study adopts a more expansive approach, broadening our comprehension of directional distribution across the wider Asian region by taking into account various time periods.

The SDE analyses conducted in this study yield invaluable insights into the directional patterns of LSD outbreaks in the Asian region. These findings align with the chronological progression of the disease, as previously documented in previous studies (Anwar et al., 2022; Liang et al., 2022; Akther et al., 2023), thereby providing substantial corroboration of the real-world situation. The results of this analysis offer essential information within the domain of spatial epidemiology, depicting the geographic distribution of the disease. These findings not only deepen our understanding of the outbreak's trajectory but also establish a robust foundation for future investigations in this field. This analytical approach is adaptable and can be applied to individual countries or specific regions within a country, allowing for the exploration of SDE patterns within areas of particular interest.

The direction of LSD outbreaks can vary based on the dataset and the analytical methods employed. The findings suggest a general west-to-east trend across an extended time frame. However, shifts in direction and patterns emerge when considering shorter time intervals, highlighting the dynamic nature of the outbreaks and the influence of weighting in the analysis. The specific directional trends observed in each dataset provide valuable insights for understanding the spatiotemporal dynamics of LSD outbreaks.

Phylogenetic analysis of Asian LSDV isolates suggests the presence of transboundary spatial pathways. The isolates circulating in South Asian countries bear similarities to LSDV isolates from Kenya, while those in Southeast and Eastern Asia are recombinant viruses with genetic components from the Neethling vaccine strain and local field isolates (Badhy et al., 2021; Koirala et al., 2022; Sudhakar et al., 2022; Sendow et al., 2024). For instance, analysis of LSDV isolates in India indicates close genetic relationships with Kenyan strains and those from neighboring countries like Bangladesh, Nepal, and Myanmar. Additionally, LSDV isolates from outbreaks in Thailand show remarkable similarity to strains found in Russia, China, and Vietnam (Suwankitwat et al., 2022; Suwankitwat et al., 2023). Notably, Indonesian LSDV isolates are nearly identical to recently discovered LSDV recombinants from East and Southeast Asia, including China, Thailand, Taiwan, Vietnam, and Hong Kong (Sendow et al., 2024).

Indeed, the molecular epidemiology findings are consistent with those of the spatiotemporal models and directional analysis. Both the spatiotemporal models and directional analysis also demonstrate a pattern of LSD outbreaks spreading from South to Southeast Asia, as well as from the northern to the southern regions within Southeast Asia. Thus, the transboundary spread across borders is hypothesized as the transmission route for this disease. This hypothesis is supported by the recognized trading market routes, where animal movement traditionally occurs from South Asia to Southeast Asia (Roche et al., 2020), and the common practice of trading cattle among countries in Southeast Asia (Kerr et al., 2012; Kerr et al., 2013).

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World Organisation for Animal Health

Australian Government
Department of Agriculture, Fisheries and Forestry

In country study

Component

Objective #2 & #3

Summary of in country study

- Bangladesh and Thailand were selected as representatives of countries in South and Southeast Asia. A questionnaire survey with dairy farmers and focus group discussions among stakeholders in the value chain were conducted in the study areas.
- In both study areas, the cooperation of governments, livestock officers, veterinarian officers, relevant stakeholders, and farmers is highlighted as a crucial component for LSD outbreak prevention and control.
- In the value chain study conducted in Thailand, there has been a noticeable drop in the market value of beef cattle displaying clinical signs of LSD. Selling cattle to slaughterhouses has become challenging due to animal movement control measures. Furthermore, stakeholders in the dairy value chain are concerned about the decline in milk production on dairy farms. Additionally, cattle collectors for trading, farmers, and live cattle markets are identified as key stakeholders responsible for the dissemination of LSD. Additionally, the focus group highlights that timely identification of outbreaks is imperative.
- In Bangladesh study, both dairy and beef value chains involve multiple stakeholders from production to consumption. The primary actors identified as responsible for the occurrence and spread of LSD are cattle traders, farmers, live cattle markets, veterinarians, and other healthcare providers.
- Vaccination coverage in the study area in Thailand was notably higher compared to that in Bangladesh, demonstrating varied vaccination coverage in the region.
- The study highlights Insect vector control may be necessary to restrict short-distance transmission through insect vectors, particularly in naïve herds.
- Economic losses vary among the study areas in both countries. This difference may be due to variations in herd size, duration and severity of LSD outbreaks, management practices, and other factors.
- Vaccination is emphasized as a cost-effective approach, offering long-term prevention advantages compared to short-term methods like insecticide and disinfectant use.
- The utilization of insecticides and disinfectants comes with associated costs, and the efficacy of these agents is not thoroughly substantiated. Nevertheless, in scenarios where LSD vaccination is not an option, these practices could be beneficial.

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In country study

Objective#2

Objective 2: Strategies and practices for preventing and controlling lumpy skin disease outbreak

Objective#2

- To assess management and control strategies of farmers, traders, and veterinary services during and post LSD outbreaks in selected countries to identify best practices

Introduction

Previous research has identified various risk factors associated with LSD outbreaks, including breed, source of replacement stock, herd size, communal grazing and watering practices, introduction of new animals, semi-intensive management system and housing type, herd size, and utilization of communal grazing and watering resources (Gari et al., 2010; Kiplagat et al., 2020). Factors such as herd size, purchasing and selling animals during an LSD outbreak, have also been linked to LSD outbreaks in various regions (Ochwo et al., 2019; Issimov et al., 2022).

Identifying risk factors associated with LSD outbreak is important as it enables authorities and stakeholders to develop an effective control strategy, essential for anticipating and managing disease outbreaks effectively.

To assess the management and control strategies of farmers, traders, and veterinary services during and after lumpy skin disease outbreaks in Thailand, fieldwork was conducted to collect primary data.

The objective of this study was to evaluate the management and control strategies employed by farmers, traders, and veterinary services in response to lumpy skin disease outbreaks within selected outbreak areas in Thailand and Bangladesh.

A study in Thailand

Summary

- Dairy cattle in the study areas lacked immunity to LSD, resulting in widespread infection.
- In the study area, LSD primarily spreads through insect vectors over short distances, given the stringent restriction on animal movement.
- Ineffective control measures, such as smoke, may not fully manage insect vectors, especially during the daytime. Large housing areas and residual manure can contribute to vector presence.
- Government-led control measures, including restrictions on animal movement, market closures, insecticide use, and mass vaccination campaigns, have proven effective in managing LSD outbreaks.
- According to a research publication, the nationwide mass vaccination campaign resulted in a reduction of up to 119% in new cases of LSD.

Materials and Methods

A study in Thailand comprises two approaches: a field study to gather primary data from a dairy farming area experiencing LSD outbreaks, and a review of existing data, reports, and research publications on lumpy skin disease control conducted in Thailand.

Approach 1: A field study

Study area

A research investigation was conducted at the Khokkho dairy cooperative in the province of Mahasarakham, situated in northeastern Thailand, as depicted in Figure A1. The cooperative consists of around 100 dairy farmers who faced the issue of an LSD outbreak on their farms during the initial instance of the disease in Thailand in 2021.

Figure A1. The geographical representation highlights Mahasarakham province in red, while the location of Khokkho dairy cooperative is marked by a red star shape.

Figure A2. A questionnaire survey conducted on dairy farms in the studied area

Survey using Questionnaires

For this particular study, the questionnaire was created as an electronic form using the Google application. The questions were tailored specifically to the objective of the study, aiming to elicit direct and clear responses from the participants. A questionnaire survey was conducted at each farm (Figure A2).

Focus group discussion (FGD)

Focus Group Discussions (FGD) and the user-friendly mobile application Mentimeter (https://www.mentimeter.com) were utilized to promote an open exchange of opinions and information among participants. The participants included four members and officers from the KhokKo dairy cooperative, two dairy farmers, a middleman involved in cattle collection for trading, a paraprofessional veterinarian, three provincial DLD officers, and three regional DLD officers who enrolled in the FGD.

FGD sessions, lasting 2 to 2.5 hours, were designed for efficiency, ensuring participant focus on key topics. Post-sessions, results underwent a thorough review and discussion to address concerns like biases, data reliability, and limitations. In this section, a stakeholder analysis for LSD outbreak, spread, prevention, and control was conducted to achieve the objective of this study.

In a particular section, the roles of stakeholder analysis in the context of LSD outbreak, spread, prevention, and control were determined to achieve the objective of this study.

Results

Questionnaire survey

In total, 90 farmers provided their responses. On average, the farmers were 42±10.39 years old. Most farmers in these cooperatives possessed approximately 10±7.19 years of experience in dairy farming. Dairy cattle farms had an average of 46±22.29 dairy cattle. Approximately 2±3.64 calves under the age of one year old displayed symptoms of LSD, whereas the occurrence of LSD symptoms in cattle older than one year old was approximately 4±5.26 cattle.

In Figure A3, the depicted data represents the collective number of dairy cattle on each farm. The red bar denotes cattle displaying clinical signs of LSD, while the light-brown bar indicates cattle that show no observable clinical signs of LSD. This figure demonstrates that the number of cattle showing LSD clinical signs varies by farms.

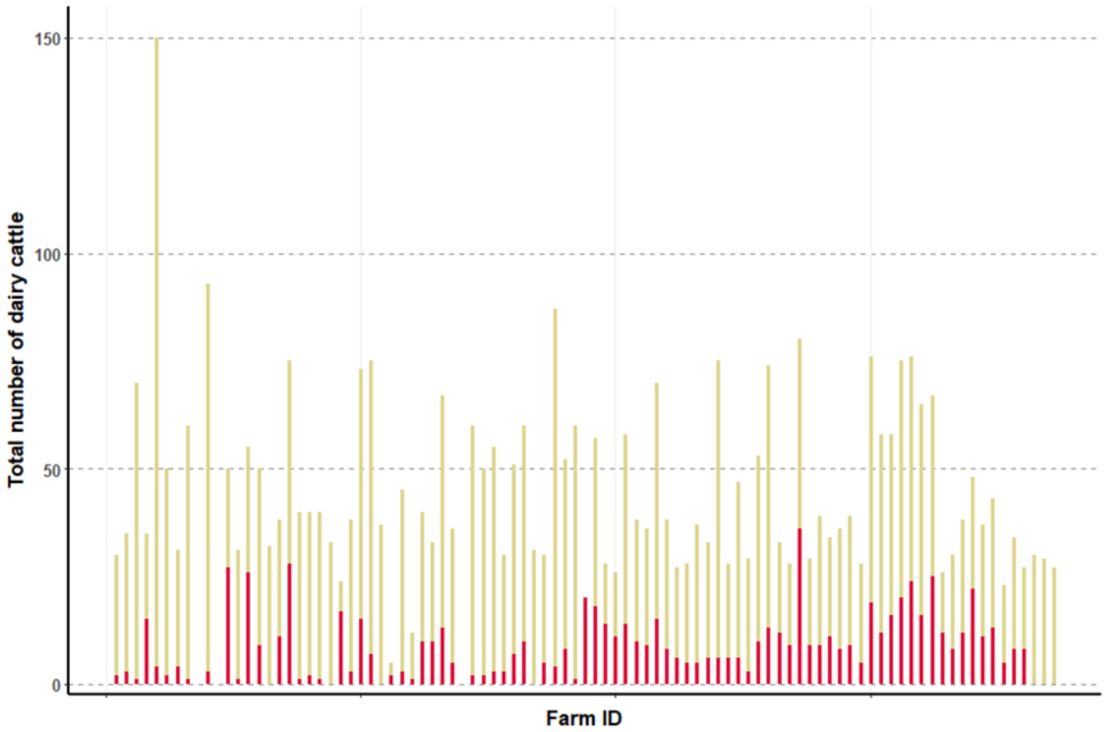

Figure A3. Total number of dairy cattle in each farm, with the red bar representing cattle with LSD clinical signs and the light-brown bar representing cattle without LSD clinical signs.

Table A1 displays the management practices employed in dairy farms. All farms had a fence whereas none of farms shared water source with other farms. Additionally, 82 % of farms had other animals, such as chickens, on their premises. About 8.6% of the cattle farms introduced cattle within two months prior to the LSD outbreak. A minimal 3.3% of farms did not have disinfectant on their floors, while only 4.4% lacked records of vehicle movement. Only two farms had the possibility that the cattle in the farm have a chance to contact cattle from other farms. There was a deworming program for dairy cattle (98.9%) under animal health management. No farm was permitted to raise cattle with other farms, and every farm had its own enclosure. Furthermore, insects including stable flies and mosquitoes were found in all farm.

Table A1. The frequency of farms categorized by each management practice.

Managements	**Yes**	**No**
Farm has a fence	90	0
Farm shares a water source with other farms	0	90
Having other animals (e.g., poultry) on the farm	74	16
Using disinfectant	87	3
Cattle on the farm have a chance to come into contact with cattle from other farms	2	88
Keeping a log-book record for visitors	86	4
Farm has a deworming program for cattle	89	1
Insects are present on the farm	90	0
History of purchasing cattle before the LSD outbreak	8	82

Concerning manure management, 41.9% of cattle farms sold their manure, and 28.7% utilized it as fertilizer on their rice or grass fields. Notably, 16.3% of manure remained in the surrounding farmland.

Before the LSD outbreak, a significant proportion of cattle farms (45.5%) did not have vector control management. Additionally, 31.7% of these farms had a smoking area close to their housing. Some farmers (17.9%) used insecticide spray.

During the LSD outbreak, a majority of cattle farms had administered vaccinations to their cattle both before (54.8%) and during (40.9%) the outbreak. All farmers had administered the LSD vaccine approximately two weeks before the outbreak. Only 4.3% had never received an LSD vaccine. After a year of LSD outbreak, the majority of farms (92%), used insect control such as light bulbs (90%), and regularly observed LSD clinical signs in cattle (90%). Also, all of farms implemented LSD vaccination program.

Stakeholder analysis for LSD outbreak, spread, prevention and control

After identifying the key stakeholders in both beef cattle and dairy cattle value chains, the participants were asked to rank these stakeholders in terms of their significance in the outbreak, spread, prevention, and control of LSD, as depicted in Figure A4.

The ranking process primarily considered the stakeholders' level of interest and influence concerning LSD-related issues. The results indicated the highest-ranked stakeholders for both LSD outbreak and its spread, which displayed significant overlap. These critical stakeholders included collectors, farmers, live cattle markets, and private health caretakers, with each holding respective positions based on their involvement. Furthermore, transporters and animal feed providers were incorporated into the LSD spread category due to the inherent risk associated with their activities.

Regarding LSD prevention and control, the key stakeholders remained largely consistent, with farmers emerging as the most pivotal contributors to these aspects. Cooperative organizations and livestock officers from the DLD at both district and provincial levels were also deemed crucial, and participants anticipated collaborative efforts between these agencies.

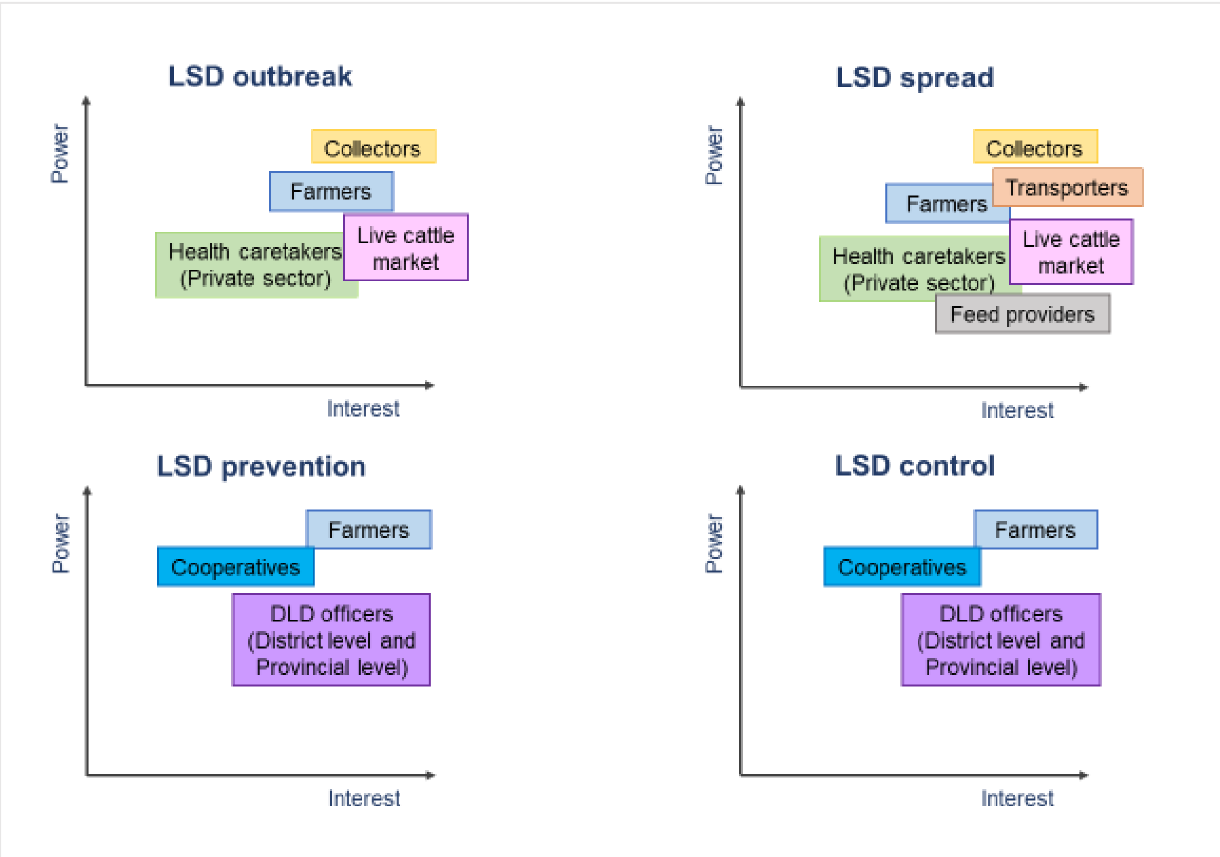

Figure A4. Stakeholder analysis for LSD epidemiological issues.

Results from FGD indicated that regular meetings occurred among provincial and district veterinary authorities, the dairy cooperative committee, artificial insemination providers, animal traders, and other pertinent stakeholders. The animal traders adhered to the regulations implemented by the veterinary authority; consequently, animal movements in the outbreak area were restricted. In the event of cattle mortality, farmers were mandated to bury deceased cattle in areas designated by the veterinary authorities. This practice is essential for securing compensation for the deceased cattle, as provided by the government. The veterinary authorities conducted an active case-finding approach in accordance with the policy established by the DLD. Additionally, farmers must notify the authorities if they suspect an LSD outbreak on their farms, following a directive enforced by the dairy committee.

Discussion

Due to the lack of immunity in the dairy cattle within the study areas, these herds were considered naïve to the disease, resulting in nearly all herds being affected by LSDV. This scenario is common in numerous cattle farming areas in Thailand, where the disease affects the majority of herds in specific regions (Arjkumpa et al., 2022; WOAH, 2022). In such a scenario, conducting a case-control study is not feasible, and the identification of risk factors through this type of study is unattainable. Nonetheless, regarding the first outbreaks, it is worthwhile to explore various aspects related to potential risk factors. In the study area, vector control measures and the administration of LSD vaccines are crucial considerations.

In vector control and management, research indicates that bloodsucking insects play a role in short-distance transmission, while longer distances are mainly associated with animal movement (Sprygin et al., 2019). The findings from this study indicate that the disease is likely spread through insect vectors, given the stringent restrictions on animal movement. The absence of control measures for insect vectors creates an opportunity for the disease to reach the farm. Furthermore, the use of ineffective insect control measures may not effectively manage the insect vectors. The result from this study showed that significant proportion of cattle farms did not have vector control management. However, even though some farmers employed smoke during the night time, there remained the possibility of vectors spreading the virus during the daytime. Additionally, in cases where the farm had a large housing area, the use of smoke might not be effective. Moreover, certain farms had residual manure in the adjacent farmland, which could serve as a potential habitat for insects.

The potential presence of insect vectors on the farm is substantiated by previous investigations in both beef and dairy cattle herds in Thailand, with odds of being an LSD outbreak farm calculated at 4.6 for dairy herds and 2.8 for beef herds, respectively (Promsathit et al., 2022). Furthermore, an epidemiological study conducted in several regions of Thailand reveals that absent of insect vector control is a risk for LSD outbreaks. Herds that did not implement insect vector control measures were found to have 2.05 times greater odds of being affected by LSDV compared to those implementing these control measures (Arjkumpa et al., 2024).

Numerous studies conducted in Thailand have provided evidence supporting the transmission of LSD among cattle herds within cattle farming areas. This transmission is believed to occur primarily through insect vectors, which is considered a form of short-distance transmission (Arjkumpa et al., 2022; Punyapornwithaya et al., 2022; Modethed et al., 2023; Punyapornwithaya et al., 2023). The model-based study, employing a kernel transmission model, further suggests that the LSD outbreak in two study areas in Thailand is likely attributable to transmission via insect vectors (Punyapornwithaya et al., 2023). However, it is essential to note that LSD outbreaks have been reported on a nationwide scale suggesting that the transmission of LSD may not be limited solely to short distances; it likely involves long-distance transmission routes. The long-distance transmission of LSD can be attributed to various factors. Firstly, it may occur as a result of infected animals moving between different regions. Additionally, another plausible route for long-distance transmission could involve the transportation of insect vectors via vehicles. Consequently, these vectors can then spread the disease over extended distances.

Most farmers in the area had administered the LSD vaccine to their cattle before and during the outbreak. However, despite these preventative measures, some of the cattle still became infected. In the early phase of the LSD outbreak, farmers obtained vaccines from unregistered sources, leading to a consideration of the effectiveness of the vaccine. Additionally, administering the LSD vaccine approximately two weeks before and during the outbreaks may not provide full protection against the disease, as immunity may not have fully developed in that timeframe.

The FGD findings underscore the pivotal role of cooperation among stakeholders, including veterinary authorities, the dairy cooperative committee, and animal traders, in supporting LSD prevention and control efforts. Biosecurity practices, such as compliance with veterinary regulations by animal traders to restrict animal movements in outbreak areas and farmers burying deceased cattle, help limit the spread of LSDV. Moreover, active case-finding initiatives led by veterinary authorities and the cooperation of farmers in reporting suspected LSD outbreaks serve as early warning mechanisms crucial for LSD prevention and control.

The findings of this study offer insights into LSD outbreaks. Nevertheless, incorporating data from other sources, such as country reports and prior publications, will significantly enhance our understanding of the management of nationwide LSD outbreaks in the region.

It is crucial to emphasize that government-led nationwide control measures can effectively manage LSD outbreaks (WOAH, 2022). Swift implementation of control measures, following the initial outbreak, includes restrictions on animal movement, temporary closure of live cattle markets, the use of insecticides and disinfectants, rapid response by veterinary authorities, active detection of LSD outbreak herds, and the creation of a webpage for disseminating knowledge on disease control and prevention, as well as updates on LSD outbreak situations (WOAH, 2021a; Suwankitwat et al., 2022; WOAH, 2022).

Following the 2021 outbreaks, the dairy cooperative committee, livestock officers, and veterinary authorities from the Department of Livestock Development (DLD) continued their efforts to prevent LSD. As a result, all farms implemented an LSD vaccination program. Furthermore, the majority of farms have continued to maintain insect control measures.

This report has certain limitations. A potential recall bias may have arisen in the study since it is retrospective and the outbreaks occurred over a year ago. Additionally, due to the very small number of herds unaffected by LSD, the data analysis primarily focuses on descriptive statistics rather than conducting in-depth risk factor analysis. Despite these limitations, the study offers valuable insights into the epidemiology of LSD and potential risk factors.

In conclusion, this report highlights the challenges and factors related to LSD outbreaks in Thailand, stressing the significance of nationwide control measures. It is recommended to continue prevention efforts by implementing crucial measures such as annual vaccination and enhancing the biosecurity of cattle farms.

Approach#2: Reviews of existing data, reports and research publication based on lumpy skin disease control conducted in Thailand

Recognizing that a study conducted in a specific location may not precisely mirror nationwide activities or control measures, this approach involves reviewing existing data and reports as secondary sources. This method broadens the perspective on management and control strategies, providing insights into the comprehensive aspects of LSD control and prevention in Thailand. Hence, insights from prior reports and publications were examined to enhance understanding regarding control measures for LSD outbreaks in Thailand.

To develop a comprehensive understanding of the economic impact of LSD outbreaks in Thailand, existing research materials, such as academic publications, Thai language reports, and WOAH country reports, were reviewed.

The Thai government supported research on the impact of LSD outbreaks. Two studies have been conducted in dairy and beef cattle farming areas. The survey in the dairy farming area involved the assessment of 144 dairy herds located in Lopburi province, situated in the central region of Thailand. The results of this study are available in the Thai language but have not been formally published (Promsathit et al., 2022). In the beef cattle farming area, a total of 351 beef cattle herds situated in Roi Et province in the northeast of Thailand were investigated, with a questionnaire survey serving as the primary data collection method (Promsathit et al., 2022).

Several research publications, containing pertinent insights into the control measures of LSD outbreaks in Thailand, were explored. These studies utilize spatio-temporal analysis to identify outbreak clusters (Punyapornwithaya et al., 2022) and transmission models (Punyapornwithaya et al., 2023), providing a deeper understanding of the spread of LSDV based on farm proximity. Additionally, reports detailing the LSD outbreak situation and control measures at WOAH are incorporated into this study (WOAH, 2021a, b, 2022).

Results

Management factors

The findings from the questionnaire survey conducted in dairy herds in Lopburi province unveiled several risk factors for LSD outbreaks (Promsathit et al., 2022). These factors include having other animals, primarily poultry (Odd Ratio [OR] = 4.04), and the presence of mosquitoes in the farm (OR=4.16). Additionally, farms with a history of LSD vaccination had lower odds compared to those without a vaccination history (OR=0.45).

In a survey of beef cattle herds, several risk factors contributing to LSD outbreaks were identified (Promsathit et al., 2022). These factors encompass having more than 10 cattle (OR=2.42), a higher density of forest (OR=2.69), cattle movement by traders (OR=1.96), and the absence of insect control (OR=2.8).

A study in three provinces of Thailand including Nakhon Phanom, Buriram and Prachuap Khiri Khan indicated that beef cattle farms without insect vector control measures had 2 times (OR = 2.05) greater odds for experiencing an LSD outbreak compared to those implementing such measures (Arjkumpa et al., 2024).

Control measures at national scale

Following a WOAH meeting presentation (WOAH, 2021a, b), the control measures implemented immediately after the first outbreak in 2021 included:

- Controlling vectors.
- Utilizing disinfectants.
- Establishing a containment zone with a 50 km radius around outbreak farms.
- Conducting active surveillance in areas adjacent to the containment zone to monitor new cases.
- Employing active LSD cases finding approaches for active surveillance within the containment zone.
- Implementing quarantine measures for all confirmed and suspected herds.
- Enforcing a ban on animal movement both into and out of the contaminant zones.

The follow-up WOAH meeting, which focused on LSD prevention and control (WOAH, 2022), provided the following updates on LSD vaccination:

- Live attenuated vaccines, including LUMPYVAX and MEVAC, with a total of 5,923,000 doses imported, and an additional 6,300,000 doses are expected in 2023.
- Data revealed that 5,923,000 doses were administered.
- Spot-on insecticide was applied in 38,348 farms, while spray insecticide was used in 227,121 farms. Additionally, insecticide was distributed to 134,863 farms.
- Disinfectant was utilized in 174,353 farms.
- Public relations and education initiatives were conducted involving 434,994 farmers.

Insights from research publications

The control measures for LSD outbreaks conducted during the LSD outbreaks are described in previous publication including vaccination campaigns and vector control measures. Data shown that initial 360,000 ring vaccine doses were administrated to disease-free areas and at risk-animals within a 5-50 km radius of epidemic areas in the north and northeast regions in June 2021 (WOAH, 2021b; Suwankitwat et al., 2022). An active approach in finding the LSD outbreak farms is also mentioned (Suwankitwat et al., 2022).

Various studies have detailed the insect vector control practices commonly employed by farmers (Arjkumpa et al., 2022; Punyapornwithaya et al., 2022; Arjkumpa et al., 2024).

Additionally, the mass vaccination campaign has significantly reduced the number of new LSD cases, as indicated by the time series interrupted model (Punyapornwithaya et al., 2024).

Discussion

The implementation of a national vaccination campaign is believed to play a crucial role in controlling LSD outbreaks, especially for naïve cattle. The previous study observed a peak in new LSD cases, with nearly 30,000 reported cases per day in June 2021, followed by a significant decline in July 2021. This reduction is thought to be associated with the initiation of the vaccination campaign in June 2021 (Suwankitwat et al., 2022). Reports to WOAH also support this observation, confirming a decrease in LSD cases after the implementation of national vaccination campaigns in high-risk areas (WOAH, 2021a, 2022). The effectiveness of mass vaccination in reducing LSD cases has been supported by a Bayesian structural time series analysis, underscoring the significant impact of the vaccination campaign (Punyapornwithaya et al., 2024).

The prompt identification of outbreaks plays a crucial role in the swift implementation of control measures. In Thailand, the significance of actively seeking LSD cases and quickly confirming affected animals is underscored as a pivotal strategy for controlling LSD outbreaks (Suwankitwat et al., 2022). Additionally, the regular dissemination of updates through a dedicated website is proposed to enhance farmers' awareness, thereby enabling a more effective response to the outbreak (Arjkumpa et al., 2022). Hence, these proactive control measures are recommended for adoption in other settings.

The rapid spread of LSD outbreaks across Thailand within a short timeframe implies a combination of both long and short-distance transmission. However, the understanding of the long-distance spread, particularly over hundreds of kilometers, remains limited. This is attributed to the strict controls on animal movement implemented during the outbreak period (WOAH, 2021b; Suwankitwat et al., 2022), which theoretically should have restricted long-distance transmission.

On the contrary, the transmission of LSDV over short distances through insect vectors seems evident. Spatio-temporal analyses in several studies have indicated that the majority of LSD outbreak clusters had a radius of less than 1 km, pointing towards short-distance transmission (Arjkumpa et al., 2022; Punyapornwithaya et al., 2022). Additionally, the prevalence of ineffective insect controls, often practiced by farmers, contributes to the abundant presence of insects. This creates a significant potential for the spread of LSDV, as evidenced in various outbreak areas (Arjkumpa et al., 2022).

Moreover, according to the kernel transmission model previously employed to assess LSDV transmission in the Middle East, the outbreaks of LSD in two farming areas in Thailand are categorized as short-distance transmission, presumably facilitated by insect vectors. While recommendations exist for establishing a radius for animal movement control zones, there is currently no standardized recommendation for the distance radius of insect controls. The common perception is that controlling insects over large areas is challenging and may not be effective According to results from several studies (Arjkumpa et al., 2022;

Punyapornwithaya et al., 2022; Punyapornwithaya et al., 2023), a suggested approach is to confine insect vector control to a radius of 1 km around LSD outbreak farms. However, it is important to note that this radius may be subject to modification based on the specific context of the outbreak area.

This study provides information on the prevention and control of LSD outbreaks in Thailand at both the farm and national levels, drawing insights from surveys, reports, and research publications. Various key activities have been identified as crucial in controlling LSD outbreaks. The findings from this study are deemed valuable and applicable to other settings.

A study in Bangladesh

Summary

- The absence of insect vector control in cattle-raising areas is a critical risk factor for LSD outbreaks in Bangladesh.
- Raising cattle through public grass grazing is associated with LSD outbreaks due to potential disease transmission through direct contact or blood-sucking insects.
- Herds with a history of LSD outbreaks have higher odds of subsequent outbreaks, despite reported similar farm management practices. Possible reasons could include constraints in improving biosecurity measures.

Materials and Methods

Study areas

A field study was conducted at the Bangladesh Milk Producer's Co-Operative Union Ltd. (known as 'Milk Vita') at Shahjadpur upazila of Sirajganj district, situated in the north-western part of Bangladesh (*Site 1*) and Bhaluka upazila of Mymensingh district (*Site 2*) (Figure B1). Shahjadpur upazila is known as one of the major dairy hubs in Bangladesh. Furthermore, Milk Vita, the largest dairy cooperative, operates here with around 3700 registered members. Bhaluka upazila is considered an emerging dairy area. Since 1st outbreak of LSD in Bangladesh, both the upazilas experienced continued outbreaks.

Figure B1. Study sites in Bangladesh [Red-colour shaded areas].

Questionnaire survey

An unmatched case-control study was conducted on randomly selected 200 dairy farms having 100 from each site. On each site, 50 case farms (LSD affected) and 50 control farms (LSD non-affected) were selected. A pre-tested structured questionnaire was administered to collect data related to farm and cattle demography, management practices, biosecurity, vector control, and LSD history. The smartphone with *KoBoCollect* mobile data collection app (https://kf.kobotoolbox.org) was used for data collection (Figure B2).

Figure B2. Questionnaire surveys

Statistical analysis

The association between outbreak status (0=non-outbreak, 1=outbreak) and farm facilities and management practices were examined through logistic regression analysis. The analysis comprised two steps, involving both univariable and multivariable procedures. In the univariable analysis, the association between outbreak status and each factor was tested. Factors with a p-value ≤ 0.2 from the univariable logistic regression were then chosen for inclusion in the multivariable logistic regression.

Model selection in the multivariable logistic regression employed a stepwise approach, utilizing Akaike's Information Criteria (AIC) as the criterion for determining the most appropriate model. The final analysis included an examination of multicollinearity among factors and the interaction between factors. The assessment of model assumptions was also conducted. The statistical analysis was conducted using R 4.3.2 (https://www.r-project.org/).

Results

The average and median herd sizes were 6.22 and 4, respectively. Figure B3 displays the total number of cattle and the count of LSD-affected cattle for each farm. The mean and median values for the number of cattle affected by LSD were 1 and 0.5, respectively.

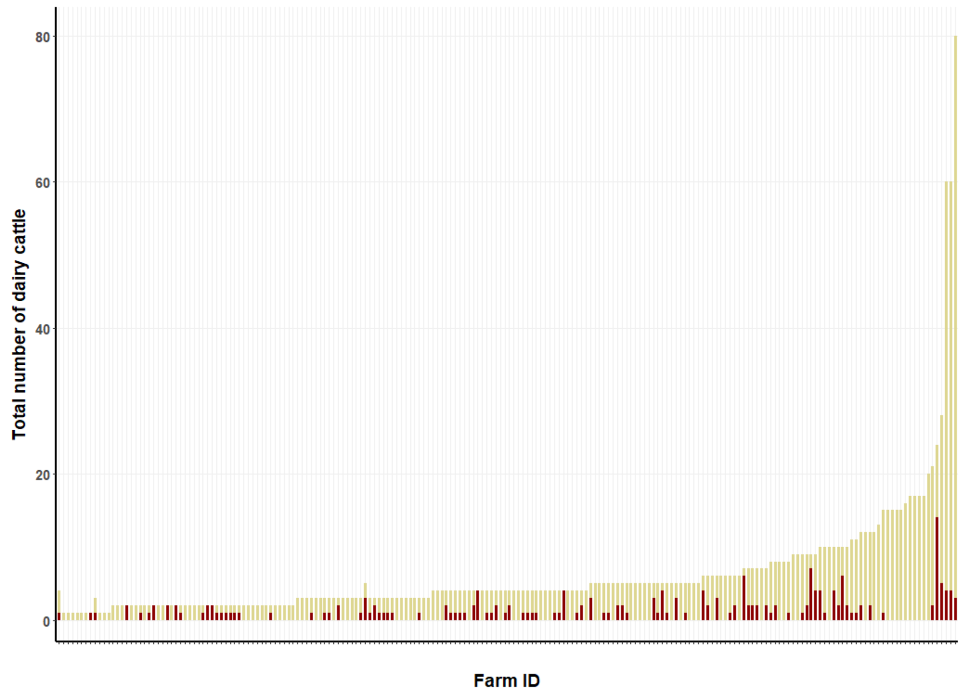

Figure B3. The total number of cattle and the count of LSD-affected cattle for each farm.

Farm management practices and facilities for both LSD outbreak and non-LSD outbreak herds are detailed in Table B1. The results indicate that management practices and farm facilities within each category are similar between herds experiencing LSD outbreaks and those not affected. For instance, there were notable similarities in the number of owners who ensured sufficient space between animals, provided adequate lighting and engaged in daily bathing for cattle. Nevertheless, there is a notable difference in the number of farms with and without a history of LSD outbreaks.

It is important to underline that approximately 25% of cattle owners reported vaccinating their cattle against LSD.

Table B1. Farm management practices and facilities for both LSD outbreak and non-LSD outbreak herds

Variable	**Category**	**Outbreak Herd**	**Non-outbreak herd**
Sufficient spacing between animals (stocking density)	Yes	74	77
	No	26	23
Sufficient ventilation	Yes	83	89
	No	17	11
Sufficient lighting	Yes	82	88
	No	18	12
Using a communal water source	Yes	63	58
	No	37	42
Using common utensils	Yes	69	61
	No	31	39
Using common syringes and needles	Yes	47	51
	No	53	49
Raise cattle by public grass grazing	Yes	84	73
	No	16	27
Absence of biosecurity fencing	Yes	37	43
	No	63	57
Absence of disinfection	Yes	45	46
	No	55	54
Daily bathing	Yes	62	62
	No	38	38
Lacking restriction control for vehicle	Yes	42	34
	No	57	66
Lacking restriction control for human	Yes	99	97
	No	1	3
Contact of cattle with other herds	Yes	41	37
	No	59	63
Daily washing of floor	Yes	97	95
	No	3	5
Lacking manure removal from the farm	Yes	10	14
	No	90	86
Purchase new cattle 2 months before LSD outbreak	Yes	7	7
	No	93	93
Presence of external parasite (tick, lice)	Yes	56	50
	No	44	50
Lacking deworming	Yes	14	17
	No	86	83
Presence of bush around farm	Yes	51	40
	No	49	60
Lacking vector management practice	Yes	46	31
	No	54	69

Variable	Category	Outbreak Herd	Non-outbreak herd
Lacking vaccination against	Yes	67	84
LSD	No	33	16
Previous history of LSD	Yes	72	6
outbreak	No	28	94

The univariable logistic regression identified risk factors associated with LSD outbreaks, including the absence of vector management practices (OR= 1.9) and a history of previous LSD outbreaks (OR= 40.29). Notably, the results indicated that farms without vaccinating their cattle against LSD had lower odds (OR = 0.39) compared to those with vaccination (Table B2). However, this factor was not included in the final logistic regression model.

Table B2. Risk factors of lumpy skin disease in cattle identified through univariable logistic regression analysis

Variable	Category	Odds Ratios	95% Confidence Interval (95%CI)	p-value
Sufficient spacing between	Yes	0.85	0.44-1.62	0.622
animal (stocking density)	No			
Sufficient ventilation	Yes	0.6	0.26 – 1.35	0.225
	No			
Sufficient lighting	Yes	0.62	0.28 – 1.36	0.238
	No			
Using a communal water	Yes	1.23	0.70 – 2.18	0.47
source	No			
Using common utensils	Yes	1.42	0.80 – 2.56	0.236
	No			
Using common syringe and	Yes	0.85	0.49 – 1.48	0.572
needles	No			
Raise cattle by public grass	Yes	1.94	0.98 – 3.95	0.061
grazing	No			
Absence of biosecurity	Yes	0.78	0.44 – 1.37	0.387
fencing	No			
Absence of disinfection	Yes	0.96	0.55 – 1.68	0.887
	No			
Daily bathing	Yes	1	0.56 – 1.77	1
	No			
Lacking restriction control for	Yes	1.43	0.81 – 2.55	0.222
vehicle	No			

Variable	Category	Odds Ratios	95% Confidence Interval (95%CI)	p-value
Lacking restriction control for human	Yes No	3.06	0.38 – 62.48	0.336
Contact of cattle with other herds	Yes No	1.18	0.67 – 2.09	0.562
Daily washing of floor	Yes No	1.7	0.41 – 8.48	0.475
Lacking manure removal from the farm	Yes No	0.68	0.28 – 1.61	0.386
Purchase new cattle 2 months before LSD outbreak	Yes No	1	0.33 – 3.03	1
Presence of external parasite (tick, lice)	Yes No	1.27	0.73 – 2.23	0.396
Lacking deworming	Yes No	0.79	0.36 – 1.71	0.558
Presence of bush around farm	Yes No	1.56	0.89 – 2.74	0.119
Presence of insects	Yes No	0.66	0.09 – 4.07	0.653
Lacking vector management practice	**Yes** **No**	**1.9**	**1.07 – 3.40**	**0.03**
Lacking vaccination against LSD	**Yes** **No**	**0.39**	**0.19 – 0.75**	**0.006**
Previous history of LSD outbreak	**Yes** **No**	**40.29**	**16.98 – 112.83**	**<0.001**

In the final logistic regression model, three potential risk factors associated with the occurrence of LSD outbreaks were identified (Table B3). The risk factors were i) cattle raised by public grass grazing exhibited an odds ratio of 2.95 when compared to farms where cattle did not graze on public grass, ii) farms lacking external parasite control showed a higher odd of experiencing LSD outbreaks compared to those implementing effective management control practices, and iii) Farms with a previous history of LSD outbreaks had a significantly higher odds ratio compared to those with no prior history of the disease.

Table B3. Potential risk factors of lumpy skin disease identified through multivariable logistic regression analysis

Risk factors	Odds ratios	95% Confidence Interval	P-value
Raise cattle by public grass grazing	2.95	1.03 – 9.51	0.053
Lacking vector management practice	3.15	1.39 – 7.47	**0.007**
Previous history of LSD outbreak	52.49	20.20 – 165.82	**<0.001**

Discussion

The absence of insect vector control has been identified as a critical risk factor contributing to LSD outbreaks in Bangladesh, aligning with findings observed in several studies (Susanti et al., 2023; Arjkumpa et al., 2024). This is particularly relevant given the prevalence of insects in cattle-raising areas, where the environment typically includes dirt and cattle dung. The presence of insects creates a conducive environment for disease transmission among cattle. Moreover, when households with cattle are in close proximity, the likelihood of LSD transmission among cattle significantly increases (Sprygin et al., 2019; Modethed et al., 2023).

In the present study, raising cattle through public grass grazing was found to be linked to the occurrence of LSD outbreaks. The mingling of cattle in such settings presents a potential avenue for disease transmission, either through direct contact or via blood-sucking insects.

Significantly, the results of the univariable logistic regression analysis indicated a potential association between the absence of LSD vaccination and LSD outbreaks. However, upon further examination through multivariable logistic regression, this factor did not emerge as statistically significant for LSD outbreaks. The lack of significance for this factor is explained by the observation that LSD outbreaks, as reported in the survey, were present in both LSD and non-LSD outbreak herds without any clear differences. It is important to note that the interpretation of vaccination effects should be approached with caution. From a biological standpoint, vaccination is anticipated to confer protection to cattle against the disease. The absence of statistical significance in this context may be influenced by some other factors that were not considered in the study. Constraints such as the timing of vaccination, the method of administration, the type of vaccine utilized, and the extent of vaccination coverage could play a role in shaping this outcome. Nevertheless, the study did not delve into the specific details of these contributing factors.

Additionally, it is interesting to mention that herds with a history of LSD outbreaks had greater odds of experiencing a subsequent outbreak compared to those without such a history. Explaining this finding poses a challenge, as the surveyed cattle owners reported similar farm management practices. It may be due owners of herds with history of LSD outbreak may have some constraints to improve their biosecurity in order to prevent the disease outbreak.

Supplementary Information

The Milk Vita authority in Shahjadpur area of Sirajganj district advised their member farmers to vaccinate cattle, typically with Goat pox vaccine (produced by the Livestock Research Institute under the Department of Livestock Services (DLS) – a government institution). If the Goat pox vaccine is unavailable, the commercial vaccine Lumpyvac (Vetal Animal Health, South Africa, imported by Rafique Medicine, Pabna) was suggested. The member farmers were also advised to isolate their sick animals from the healthy ones, to wash the floor with PPM solution, and to implement vector control techniques such as mosquito nets, and mosquito coils. Most farmers did not administer vaccines to their cattle. Besides, the free vaccination campaign by DLS was conducted in some areas of Shahjadpur.

Some individuals vaccinated their animals with a government-provided Goat pox vaccine with self-initiative while few used commercial vaccines. However, farmers were hesitant to vaccinate their animals with commercial vaccines due to their expensive costs. It is to be noted that biosecurity was also poorly maintained in this area.

In Bhaluka upazila of Mymensingh district, the DLS implemented various control strategies including vaccination, training, and distributing leaflets to raise public awareness. The government organized a free vaccination campaign using the Goat pox vaccine, which covered 50 farms with approximately 3500 cattle. In addition, several farmers inoculated their cattle with commercial vaccines such as Lumpyvax (MSD Animal Health, imported by Bengal Overseas Ltd), and LSD-NDoll (Dollvet, Turkey). However, government personnel, pharmaceutical companies, and pharmacists contributed to promoting cattle vaccination.

To be noted that DLS approved import of five commercial vaccines such as Bovivax LSD-N (MCI Sante Animal, Morocco – imported by ACI Animal Health), Lumpyvax (MSD Animal Health, SA – imported by Bengal Overseas Ltd), Lumpy Shield (Jordan Bio Industries Centre, Jovac – imported by NASCO Agro Products), Lumpyvac (Vetal Animal Health, South Africa, imported by Rafique Medicine, Pabna), Servac Lumpy Skin (Veterinary Serum and Vaccine Research Institute, Africa – imported by Pharma and Firm, Dhaka).

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Supplementary Figures

Thailand

Figures related to the prevention and control of the lumpy skin disease outbreak in 2021 in Thailand were obtained through collaborative efforts among stakeholders, including dairy farmers, the dairy cooperative committee, veterinary authorities, livestock officers, and veterinarians.

Figure S1. Treatment of LSD-affected cattle

Figure S2. Sample collection to confirm lumpy skin disease

Figure S3. S mobile car designed for spraying insecticide on a farm.

Figure S4. the provision of public relations and knowledge to farmers regarding lumpy skin disease outbreaks

Figure S5. he lumpy skin disease vaccine and the associated vaccine management processes.

Bangladesh

Figures related to the field study conducted in two different regions.

Figure S6. Smallholder dairy farms having indigenous cattle

Figure S7. Medium-scale dairy farmers having crossbred cows

Figure S8. Short briefing on value chain analysis with different stakeholders

Figure S9. Focus group discussion on value chain analysis

Figure S10. Female farmers’ participation in focus group discussion

Figure S11. Door-to-door data collection

World Organisation for Animal Health

Australian Government
Department of Agriculture, Fisheries and Forestry

In country study

Objective#3

Objective 3: Value chain analysis and socio-economic impact of lumpy skin disease outbreaks on key stakeholders within the value chain

Objective#3:

To assess the socio-economic impact of LSD outbreaks on key stakeholders along the value chain

Specific Aim#1: To identify the stakeholders along the value chain of beef cattle and dairy cattle

Introduction

The outbreak of lumpy skin disease (LSD) significantly impactss cattle production and poses a substantial threat to the economic sustainability of this vital sector (Molla et al., 2017; Limon et al., 2020). Effectively addressing the intricate challenges and multifaceted complexities associated with LSD outbreaks demands a profound understanding of the value chain and the diverse array of stakeholders involved.

Controlling and preventing LSD outbreaks is a complex challenge that relies on the collective efforts of a diverse range of stakeholders, including farmers, veterinarians, government agencies, cattle cooperative committees, research institutions, and advocacy groups. Understanding their roles, responsibilities, and interactions is crucial for the effective design and implementation of LSD control strategies (Roche et al., 2020).

Value chain analysis (VCA) is a tool that holds great potential in supporting epidemiological frameworks. This technique is capable of gathering data that is not only instrumental in epidemiological risk analysis but also forms the foundation for a spectrum of risk-based approaches to disease outbreak investigations. One of the remarkable facets of VCA is its ability to generate risk pathways by integrating value chain diagrams with disease-related information. This multifaceted approach extends its utility to assessing biosecurity measures and management practices, enabling the identification of risk levels and critical control points. These findings, in turn, serve as a pivotal baseline for the formulation of risk-based strategies, which act as guiding principles for conducting outbreak investigations and implementing risk mitigation efforts (FAO, 2011). Certainly, the effectiveness of VCA is evident through practical applications. For example, it has been successfully employed to meticulously trace the origins and consequences of food-borne disease outbreaks (Weiser et al., 2016). Furthermore, VCA has provided valuable insights into the adverse effects of Marek's disease throughout the value chain of layer production (Dejyong et al., 2023).

Conducting a comprehensive analysis of the value chain and stakeholders offers a robust framework for exploring the entire range of activities pertinent to cattle production. When applied to LSD prevention and control, this analytical approach not only facilitates comprehension of the resource and knowledge flow within the value chain but also helps in identifying the key participants who wield influence and hold pivotal roles in shaping strategies, policies, and practices for disease prevention and management.

The aim of this study is to ascertain the cattle production value chain and assess the participation of stakeholders within the context of LSD outbreaks in the selected cattle farming area.

Specific Aim#2: To assess the economic impact of LSD outbreaks in selected dairy farming area

Introduction

The incidence and geographical expansion of Lumpy Skin Disease (LSD) have witnessed a concerning increase, notably in the Asian region (WOAH, 2023). This upsurge in LSD cases presents a significant challenge to the overall well-being and economic stability of the affected nation (Tuppurainen and Oura, 2012).

The impact of LSD reverberates across multiple economic dimensions. It extends beyond immediate costs associated with disease containment and management. Instead, it unfolds as a complex tapestry of challenges that encompass not only the fiscal aspects but also the welfare of livestock, milk production, international trade relationships, and the financial resilience of farmers and agribusinesses (Gari et al., 2011; Roche et al., 2020). Furthermore, the occurrence of LSD outbreaks can disrupt international trade, leading to far-reaching consequences. Importing countries may impose trade restrictions and bans on the movement of livestock and livestock products to prevent disease transmission (Tuppurainen and Oura, 2012; Roche et al., 2020). These measures can potentially disrupt established trade partnerships, resulting in economic losses for exporting nations.

The economic burden of LSD is most evident in the direct costs incurred to manage and prevent the disease (Casal et al., 2018; Kiplagat et al., 2020). These costs comprise the financial resources allocated to treat infected animals, undertake extensive vaccination campaigns, and implement vector control measures (WOAH, 2022). Such investments can place significant financial pressure on both governments and individual farmers, emphasizing the necessity for effective disease management strategies.

The study aimed to assess the economic consequences of LSD outbreaks within the dairy farming regions situated in the northeastern part of Thailand. The findings from this study are anticipated to offer critical insights into the financial losses incurred by dairy farms grappling with LSD outbreaks. This information holds significant value as it can inform the formulation of effective mitigation strategies and policies aimed at protecting the livestock industry and bolstering the economic stability of the region against the detrimental impacts of this disease.

A study in Thailand

Study area

A field study was carried out at the Khokkho dairy cooperative, located in the northeastern province of Mahasarakham, Thailand, as illustrated in Figure A1. The cooperative comprises approximately 100 dairy farmers who encountered the challenge of an LSD outbreak on their farms during the first recorded occurrence of the disease in Thailand in 2021.

Figure A1. Khokkho dairy cooperative

Specific Aim#1: To identify the stakeholders along the value chain of beef cattle and dairy cattle

Summary

- Understanding the dynamics of cattle production value chains and the roles of stakeholders is essential for effective management. Given the distinct nature of beef and dairy production, the midstream and downstream stakeholders involved in each sector tend to be different.
- In both production systems, the primary stakeholders involved in the outbreak and spread of LSD include cattle collectors for trading, farmers, live cattle markets, and private animal health personnels (e.g., para-veterinarians).
- The clinical symptoms in LSD-infected cattle have significantly reduced their market value, including a drop in milk production for dairy cattle and a decline in meat quality for beef cattle.
- The active participation of various government agencies, such as the DLD and the University is the key for the control of LSD outbreaks.

Materials and Methods

Participants: Cattle production stakeholders

The identification of stakeholders followed a protocol previously employed in a prior study (Promsathit et al., 2022), and as part of this process, fourteen participants were invited to participate in a focus group discussion.

These participants included:

- Four members and officers from the KhokKo dairy cooperative
- Two dairy farmers
- A middleman who collects cattle from farms for trading purposes (cattle collector for trading)
- One paraprofessional veterinarian
- Three provincial DLD officers
- Three regional DLD officers

It is important to note that all of these stakeholders possess extensive experience in cattle production as well as dealing with the challenges of LSD outbreak and control. This diverse group of participants was brought together to contribute their insights and expertise to the discussion.

Focus group discussion (FGD)

Focus Group Discussions and the user-friendly mobile application, Mentimeter (https://www.mentimeter.com), were employed to encourage open sharing of opinions and information among the participants (Figure A2). Mentimeter served as an icebreaker, facilitating the introduction of participants and later assisting in the ranking process in the stakeholder analysis matrix.

Figure A2. Focus group discussion using mobile application

During the sessions, visual aids, such as drafted value chain diagrams for both beef and dairy cattle, were displayed on screens. Participants were encouraged to verify and suggest any additional stakeholders that might be specific to their respective areas. The criteria for stakeholder analysis, focusing on their interest and influence in LSD outbreak prevention and control, were clearly explained.

To make the discussions more interactive and visible to all, value chain diagrams and simple rankings of stakeholders in terms of their impact on LSD were drawn on flip chart paper using sticky notes and permanent markers. The results were promptly shared with the participants to ensure clarity and facilitate detailed discussions regarding the reasoning behind their responses and any additional insights.

It is worth highlighting that each FGD session was thoughtfully designed for efficiency, with a duration of 2 to 2.5 hours, ensuring that participants could maintain their focus on the key topics at hand. Following the sessions, the results underwent a comprehensive review and in-depth discussion to address specific concerns, including the potential for biases, the reliability of data, and any limitations associated with the information gathered during the FGD. This critical evaluation aimed to enhance the quality and trustworthiness of the insights and findings generated through this participatory process.

Figure A3. Data collection for value chain analysis

Results

Stakeholder identification for beef and dairy cattle value chain

Stakeholder identification and the evaluation of the value chain in dairy and beef cattle production within Mahasarakham province were carried out by a diverse group of participants with expertise spanning various fields. This group included professionals from DLD at both the provincial and district levels, dedicated livestock volunteers, administrators, and agricultural officers from the Khokkho dairy cooperative.

Additionally, local veterinarians, beef cattle collectors, and representatives from dairy and beef cattle farming communities were actively involved in the process (Figure A3). The analysis yielded the following results:

Stakeholder identification in beef cattle value chain

The findings pertaining to the value chain and stakeholders in beef cattle production have been summarized in Figure A4. The stakeholders can be categorized into three distinct groups, as outlined below:

Upstream stakeholders

This sector encompasses a collective of individuals involved in the rearing of beef cattle. This group includes:

1) **Farmers or farm owners**, each with distinct objectives for raising these animals. These objectives encompass:
   - **Bloodstock production**, which involves sourcing beef cattle from various entities such as the Department of Livestock Development's (DLD) Cattle Bank Project, the KhokkhoDairy Cooperative, live cattle trade and markets, as well as local cattle traders within the area. The study revealed that the predominant form of bloodstock trading in the area was the introduction of cows with their newborn calves, while approximately 10 percent of bulls were traded in this region.

   - **Fattening cattle production** for commercial purposes, which involves animals sourced from cattle markets, fattened dairy cows from dairy farms, and cattle from various projects within the area. This sector includes a collection of high-grade beef cattle, particularly of the Charolais, Angus, and Wagyu breeds, although they are present in limited quantities.

   - **Calves production**, primarily relying on calves born on local farms, constituting approximately 90 percent of the total calf production. The remaining 10 percent is sourced through the purchase and sale of calves from the market, in conjunction with beef cows.

2) The stakeholders in the upstream sector, which encompasses the production of beef cattle, can be further categorized as follows:

   - **Semen and artificial insemination service providers**: This group includes the Department of Livestock Development (DLD), private service providers, and the Khokkho dairy cooperative. Private suppliers account for the majority, making up 90% of the total semen supply. Among farmers, the Red Brahman breed is the most preferred for artificial insemination. The individuals offering artificial insemination services consist of a variety of professionals, including government livestock officers, artificial insemination volunteers, private sector personnel, and agricultural cooperative officers.

- **Cattle health caretakers**: These individuals come from various sectors, including DLD officers, cooperative officers, and private company sales representatives. In addition to their expertise, these caretakers make use of the "ZyanWoa application," which was co-developed by Mahasarakham University and the Khokkho dairy cooperative. This mobile application serves multiple purposes and offers health management consultation services to various stakeholders in the area.

- **Vaccine providers and distributors**: This category comprises entities such as the District Livestock Office, Provincial Livestock Office, and private clinics that provide vaccination services. The administration of LSD vaccination is limited exclusively to farmers who have completed the registration process.

- **Animal feed producers**: This group includes both cooperative members and farmers engaged in the cultivation of animal feed crops.

- **Middlemen or Collectors**: These intermediaries play a pivotal role in the procurement and acquisition of both cattle. They facilitate the flow of goods and services between the upstream and midstream of the supply chain, which encompasses production and processing. The cattle acquired by middlemen or collectors are sourced from both cattle farms and cattle trade markets, and they are typically held in designated pens before being transported to the slaughterhouse.

The Midstream stakeholders

This stakeholder is a collective of individuals and organizations engaged in the process of slaughtering and commercializing beef cattle. They were responsible for a range of actions, which could be categorized as follows:

- **The slaughterhouse**, located in the city central, Mueang District involved **slaughter operators and animal disease inspectors**. In addition, a portion of beef cattle were sent to Samut Prakan province.
- The cattle trade market served as a prominent hub for local beef cattle farmers to trade their animals. Mahasarakham livestock market located in Mueang District and held significant prominence due to its substantial size.

The downstream Stakeholders

The stakeholders who engaged in the trade activities related to trade of live cattle, together with their associated products were included. These stakeholders were categorized as follows:

- **general markets for commercial quality of beef**
- **high-end markets** which primarily deal with high-quality beef cattle or premium quality beef
- **online market**, which the main focus was on advertising breeding bulls and cows for sale.

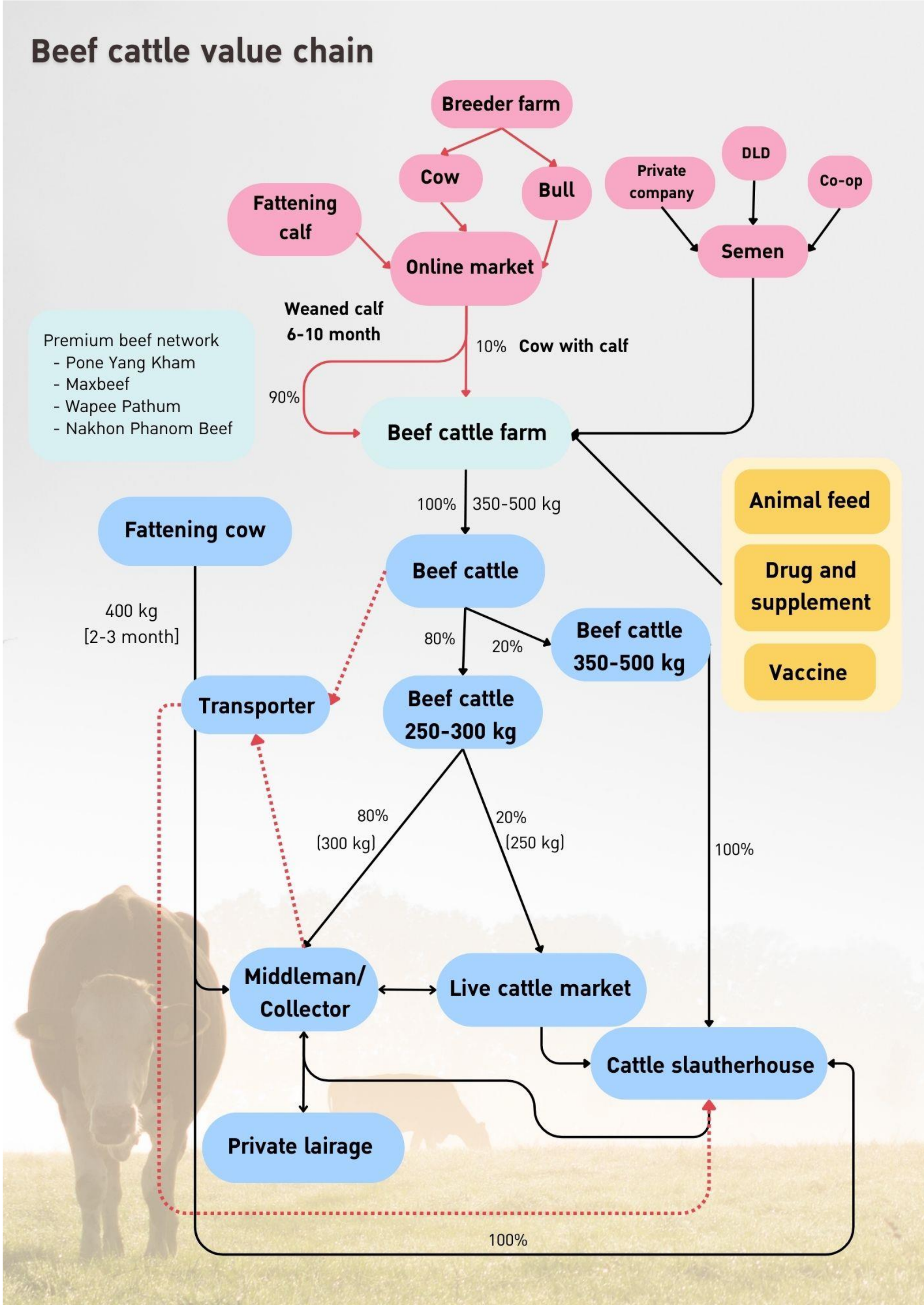

Figure A4. Beef Cattle Value Chain in Maha Sarakham

Stakeholder identification in dairy cattle value chain

The findings of dairy cattle value chain and stakeholders were summarized as shown in Figure A5. The stakeholder could be also categorized into 3 groups as follow:

The Upstream stakeholders

This sector comprised of individuals related to dairy cattle production including:

1) **Farmers or farm owners** which had different purposes of farming compare to general dairy farms. The group of dairy cows raised on these farms was summarized as below:
    - **The production of replacement heifers** involved providing breeder cows from various sources for producing both calves and milk purpose. The study showed that 70% of replacement heifers were raised in their own farms while 20% were bought from other provinces and only 10% were sourced from other local farms.
    - **The production of breeder** bulls played a crucial role in the supply of both frozen semen and bulls. In dairy cattle farming, farmers displayed a clear preference for artificial insemination (AI) over natural mating. The findings in this study highlighted that all dairy farms in the area relied solely on frozen semen for AI. Moreover, approximately 10% of these farms kept breeding bulls on-site to manage reproductive challenges through AI. It is worth noting that frozen semen predominantly originated from three key sources: private companies, the DLD, and dairy cooperatives.

    - **The production of male calves** was primarily associated with beef production. Subsequently, 90% of dairy male calves were sold to intermediaries or collectors within 5-15 days after birth, fetching prices ranging from 800 to 1,500 THB per calf. The remaining 10% of the calves were raised on the farms for approximately 1.5 years for fattening before being sold at a price of 10,000 THB.

2) **Animal feed producer** which included dairy cooperatives that provided animal feed as well as farmers who grow their own animal feed crops.

3) **Artificial insemination service providers** and cattle health caretakers encompass a range of professionals, including government livestock officers, artificial insemination volunteers, private sector personnel, and agricultural cooperative officers.

4) **Drug and vaccine providers** offered vaccination and treatment services by many entities, including the District Livestock Office, Provincial Livestock Office and private clinics. The administration of LSD vaccination will be limited exclusively to farmers who have completed the registration process.

5) **Middlemen or Animal Collector** engaged in the procurement and acquisition of dairy calves and used dairy cows. Their primary function was to serve as intermediaries, facilitating the flow of goods and services between the upstream and midstream of supply chain, and encompassing production and processing. The acquired dairy cattle took place at farms and trade market.

6) **Manure trader** served for buying manure from the dairy farms and then selling to agricultural farms in the area such as sugar cane and jicama planting. These agricultural farmers used manure to reduce the amount of chemical fertilizer usage. The price was 30-35 THB/sack which contained 15-20 kg of dried manure.

The midstream stakeholders

The midstream stakeholders comprise of individuals and organizations engaged in the raw milk processing or slaughtering of cattle or calves. They played for a range of roles, which could be categorized as follows:

1) Khokkho **dairy cooperative** was responsible for buying raw milk directly from its member farmers.
2) **Slaughterhouses** that purchase culled dairy cattle or calves from collectors. The cattle slaughterhouse could be used alternatively between dairy and beef cattle.
3) **Online animal market** was the important trade pattern of culled dairy cow and calves in this area due to the preference of traders. Online trading was operated through "ZyanWoa applications", so direct trading would be more convenience because there were producer, middlemen, customers and others registered in this application.

The downstream stakeholders

The stakeholders who engaged in the trade activities related to trading of raw milk with their associated products. These stakeholders were categorized as follows:

1) **Khokkho dairy cooperative** which produced pasteurized milk (gallon milk) and processed milk products such as milkshake, nougat and ice cream.
2) **Raw milk customers** played a role in buying bulk milk varied from 500 kg/day to 9.5 tons/day. Raw milk was processed to be pasteurized milk, school milk, and commercial milk. The customers were comprised of private companies, other dairy cooperatives and local food and beverages businesses.

Other related government agencies

Multiple agencies, including the DLD and the University, play an active role in the dairy production sector, covering its upstream, midstream, and downstream stages. Collaboration has been fostered between the Khokkho dairy cooperative and Mahasarakham University to create a dairy production database system. This system serves as a valuable tool for managing the health of dairy animals, enhancing the quality of dairy production, and facilitating effective oversight throughout the entire dairy production process.

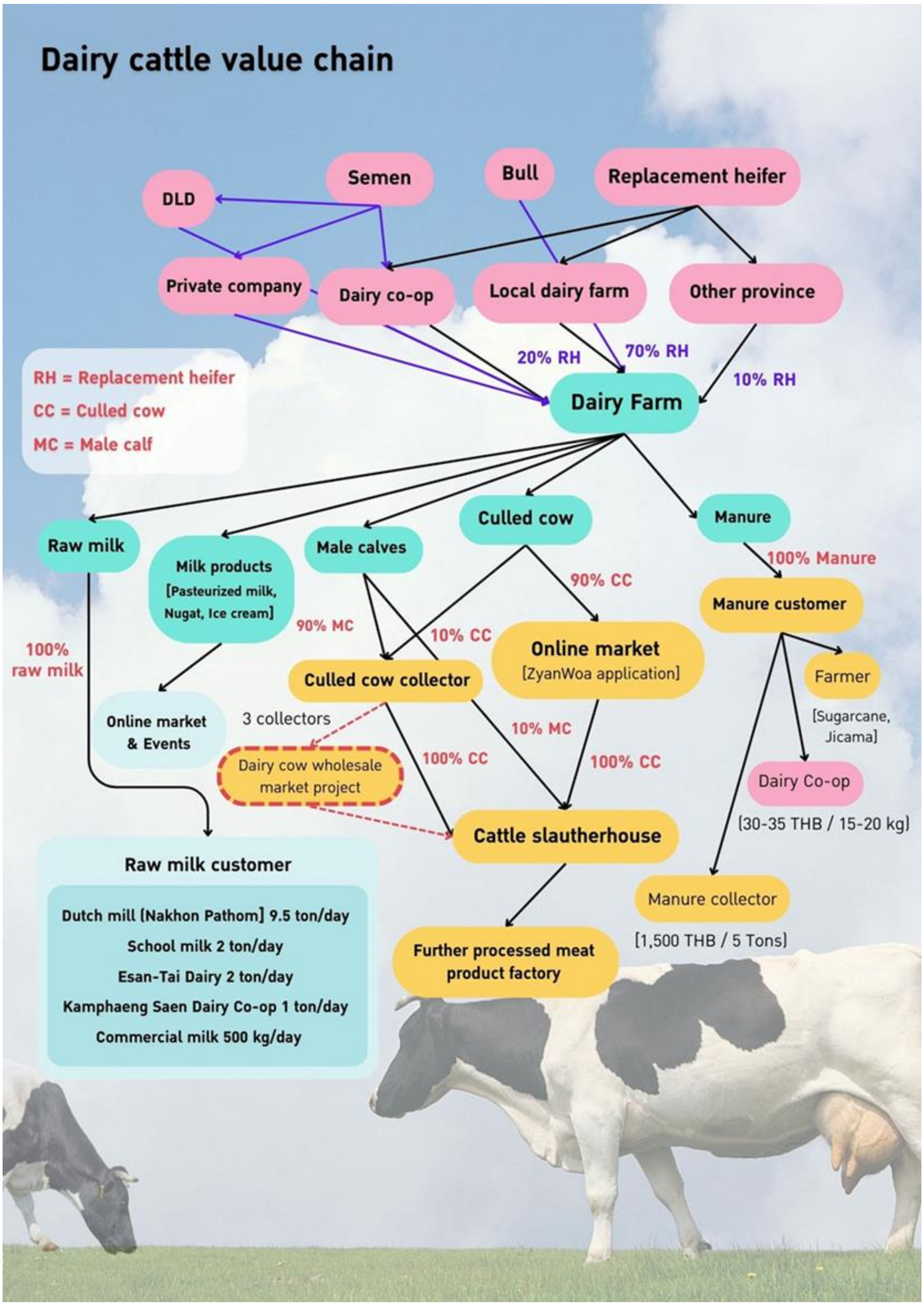

Figure A5. Dairy cattle value chain in Maha Sarakham

Impact of LSD outbreaks through the value chain

Cattle infected with LSD exhibited clear clinical symptoms and, consequently, their market value significantly diminished. In many instances, traders refrained from purchasing these animals due to the associated drop in carcass quality. Moreover, constraints on cattle mobility and the closure of live cattle markets further constrained the trading of live cattle.

The decline in milk production on dairy farms experiencing LSD outbreaks has raised concerns both at the farm and cooperative levels. To address this issue, there has been an increased demand for antibiotics, antipyretic drugs, NSAID medications, vitamins, and various other supportive agents required to treat cattle displaying clinical signs of LSD.

Additional information from FGD

According to the proactive work and collaboration between farmers, cooperative and DLD officers for providing LSD vaccine. The outbreak situation of LSD in Mahasarakham was not excessive and only a few numbers of LSD cases were found during the outbreak period. The Khokkho dairy cooperative had its own regulation to encourage the dairy farm owners to register their farms in DLD database before submitting their co-op member application form. This will be useful for number of animal estimation which is very important for free vaccination campaign or compensation supported by DLD or government agencies.

Discussion

In this study a thorough examination of the cattle production value chains and the associated stakeholders within Mahasarakham province was undertaken. The analysis involved a diverse group of participants. A comparison between the beef cattle and dairy production value chain analysis and the stakeholder identification for the dairy cattle value chain reveals both similarities and differences in the stakeholders involved.

In the present study, the value chain analysis reveals differences in characteristics and stakeholder roles between beef and dairy cattle value chains. Similarities are found in the presence of shared upstream stakeholders, including farmers and artificial insemination service providers, in both beef and dairy cattle production. Additionally, the involvement of cattle health caretakers and drug and vaccine providers is crucial in both value chains. However, distinctions arise when examining midstream and downstream stakeholders. In the beef cattle production value chain, midstream stakeholders comprise slaughterhouses and cattle trade markets, which do not have a direct counterpart in the dairy cattle value chain analysis. Instead, the dairy cattle value chain features midstream stakeholders like the Khokkho dairy cooperative and online animal markets. Regarding downstream stakeholders, the beef cattle value chain includes general markets, high-end markets, and online markets specializing in different types of beef. In contrast, the dairy cattle value chain's downstream stakeholders involve the Khokkho dairy cooperative and raw milk customers who primarily purchase bulk milk for various purposes.

The results additionally highlighted the active participation of various government agencies, such as the DLD and the University, in the dairy production sector, spanning all stages from upstream to midstream and downstream. Notably, collaboration between the dairy cooperative and nearby University led to the creation of a dairy production database system. This system proved to be a valuable tool for managing dairy cattle' health, improving dairy production quality, and ensuring effective oversight throughout the entire production process.

In terms of LSD outbreak, spread, prevention, and control, this study entailed identifying and ranking vital stakeholders in both beef and dairy cattle value chains. The ranking process factored in the stakeholders' level of interest and influence in LSD-related matters. The findings highlight the key stakeholders responsible for the outbreak and dissemination of LSD, including cattle collectors for trading, farmers, live cattle markets, and private health caretakers. Additionally, transporters and animal feed providers fall into the category of contributors to LSD transmission due to the inherent risks associated with their roles. The findings, which highlight the significant role played by animal collectors in disease outbreaks, align with various studies that have indicated that middlemen or animal collectors involved in animal trading can be potential risk factors for livestock diseases such as foot and mouth disease (Poolkhet et al., 2019) and other diseases (Leslie et al., 2016).

The impact of LSD outbreaks on the value chain is apparent. The manifestation of clinical symptoms in LSD-infected cattle has affected their market value, resulting in a considerable reduction. The decline in market value has led numerous traders to approach their cattle purchases more cautiously, with the main concern being the decline in the quality of the meat. Furthermore, the implementation of limitations on cattle mobility, along with the closure of live cattle markets, has added to the difficulties in the live cattle trade (Arjkumpa et al., 2024). Furthermore, the noticeable decline in milk production within dairy farms impacted by LSD outbreaks has initiated discussions and raised concerns at both the individual farm and cooperative levels. This finding aligns with previous research indicating that LSD outbreaks lead to a decrease in milk collected by dairy cooperative (Vinitchaikul et al., 2023).

In conclusion, the study examined cattle production and stakeholders in Mahasarakham province, comparing the beef and dairy sectors. Commonalities and differences among the stakeholders were identified. Government agencies played an active role in improving dairy production. For outbreak management, key stakeholders like collectors, farmers, and markets were identified. The impact on cattle markets and milk production highlights the need for swift action. Efficient management and mitigation strategies are crucial. Moreover, the identification of key stakeholders such as collectors, farmers, and markets in outbreak management highlights the significance of their contributions to LSD prevention and control. This report not only enhances our comprehension of their contributions but also provides a valuable foundation of information for future endeavors.

Specific Aim#2: To assess the economic impact of LSD outbreaks in selected dairy farming area

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Summary

- The average total economic losses on the study farms were $2461 USD.
- The primary cause of losses during the LSD outbreaks was attributed to the mortality of LSD-affected cattle ($1801 USD), followed by losses due to a reduction in milk sales ($227 USD).
- Nearly half of the dairy farmers experienced economic losses due to milk discard caused by antibiotic residues and a decrease in milk yield among LSD-affected cows.
- Vaccination expenses were lower than treatment costs. However, the vaccination cost varied depending on the number of cattle on the farm.

Materials and Methods

Questionnaire survey

Local veterinary authority conducted a questionnaire survey (Figure B1). The meeting among the veterinarians and research team was held before the survey to ensure the interviewer understood all questions in the questionnaires. The questionnaire used in this study was adapted from the version employed by veterinary authorities. This particular version had been extensively utilized in various LSD outbreak investigations (Arjkumpa et al., 2022).

In this study, the questionnaire was constructed as an electronic form using the Google application. The questions were designed to be highly specific to the study in order to elicit direct and unambiguous responses from the respondents.

Review of existing data and studies

To gain a more comprehensive understanding of the economic impact of LSD outbreaks in Thailand, existing studies, including research publications, WOAH country reports and local language research reports, were explored. The insights gleaned from these studies were subsequently compared and thoroughly discussed alongside the results obtained from the study.

It's important to note that the Thai government supported a study examining the impact of LSD, encompassing various aspects, including its economic ramifications. A study on economic impact of LSD was performed in dairy farming area located in the central part of Thailand. In such a study, a questionnaire survey was conducted on 48 dairy farms. The results from such study are available in Thai language format and have not yet been published as a research publication (Promsathit et al., 2022).

Figure B1. A questionnaire survey conducted on dairy farms in the studied area

Results

Data were collected from a total of 90 dairy farms, which were classified into two groups: 83 farms as outbreak farms and 3 farms as non-outbreak farms. Figure B2 illustrates the economic losses incurred by dairy farms in the study area as a result of the LSD outbreak. The data is presented in ascending order, ranging from the lowest to the highest losses.

There were reports of cattle mortality in numerous farms due to LSD. The majority of affected farms actively administered treatment to their LSD-infected cattle. Furthermore, as an integral component of their disease control strategies, all farms employed insecticides and disinfectants.

Out of the 90 farms, 87 of them implemented LSD vaccines. Among these, 48 farms had implemented the vaccines before the LSD outbreaks, while the remaining 39 farms implemented them during the outbreaks.

One significant economic impact was observed in nearly half of the dairy farms, where losses were incurred through both milk discard, a necessary step when administering antibiotics, and a drop in milk yield among LSD-affected cows.

In terms of other expenses, over 90% of the farmers who responded to this question mentioned that they incurred costs for the burial of deceased cows. A few farmers also indicated that they had expenses related to equipment and gasoline.

Table B1. Economic loss due to lumpy skin disease outbreaks

Items	**Mean±Standard deviation (Thai Bath)**	**USD ***
Loss due to mortality of cattle	64,000±61,366.46	1,801± 1,727
Treatment cost	5,227 ±7,273.22	147± 204
Insecticide cost	2,026 ±1,430.01	57± 40
Disinfectant cost	1,858±1,435.26	52± 40
Loss due to reduction in milk sold	8,084±1,722.71	227± 48
Vaccination cost	3,327±34,66.17	93± 97
Other costs	2,903 ±5,651.59	81± 150
Total economic loss	87,429 ± 74,903.06	2,461 ±2,108

*Approximate 35.5 Thai Bath equal 1 USD

Table B1 presents the averages and standard deviations for costs and losses resulting from LSD outbreaks. The results can be summarized as follows:

- The primary source of losses during the LSD outbreaks was attributed to the mortality of LSD-affected cattle.
- The costs of using disinfectants and insecticides were found to be approximately equivalent.
- The vaccination cost was lower in comparison to the treatment cost. The vaccination cost is varied as it is influenced by the number of cattle in the farm.
- Other associated costs were varied.

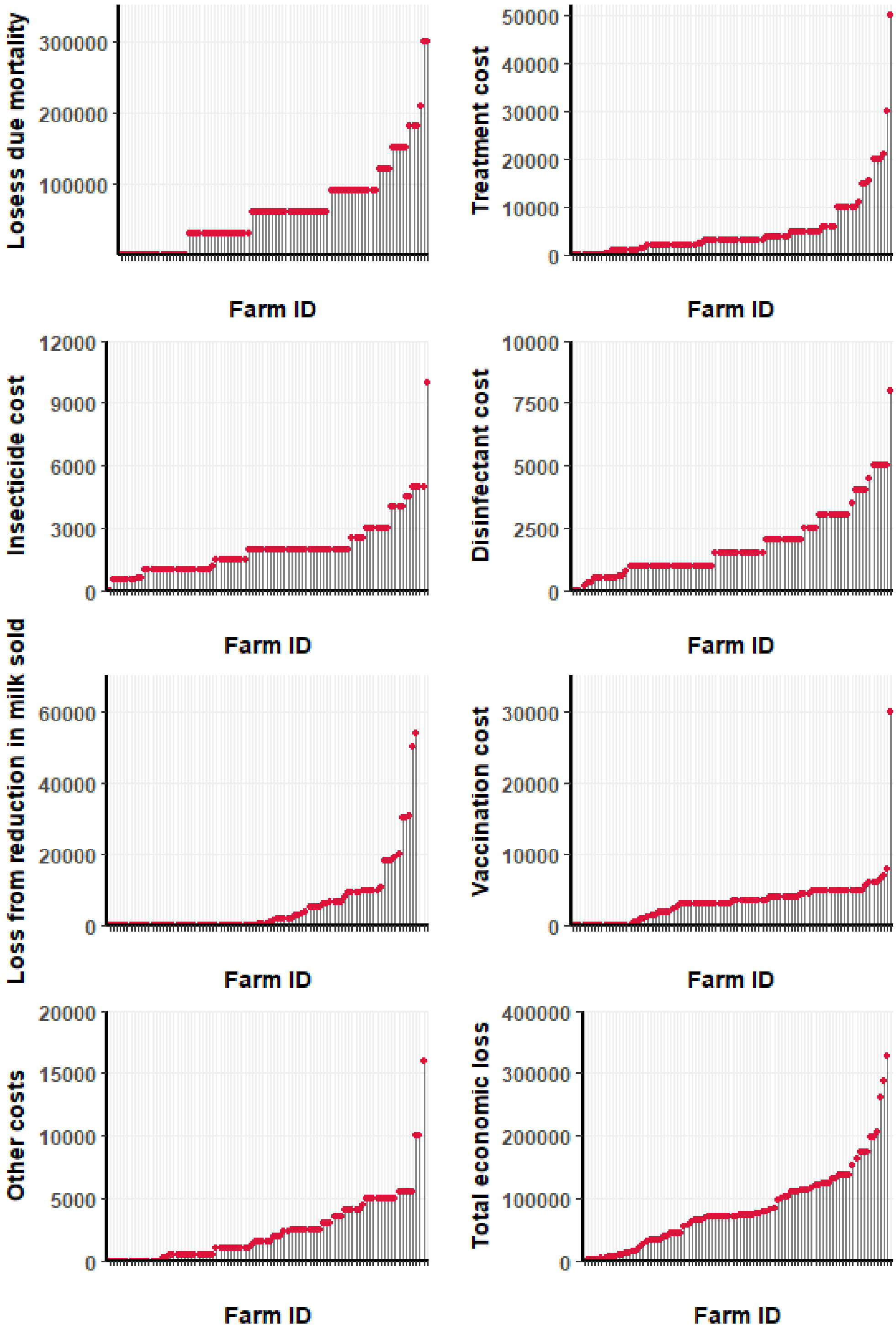

Figure B2. Costs and losses in relation to lumpy skin disease outbreaks in dairy farms

Table 2 provides a comprehensive overview of the economic losses incurred during LSD outbreaks in Lopburi province (Promsathit et al., 2022). A comparison with the findings of this study reveals the following:

- Khokkho's pronounced commitment to disease control measures, as evidenced by the substantial investments of ฿2,079 (Thai Baht) for insect control and ฿1,895 for disinfectant. In contrast, Lopburi's data lacks specific information regarding disinfectant expenses.
- The disparity in vaccination and treatment costs, with Khok Kor reporting higher expenditures compared to Lopburi.
- Khokkho's notably greater reduction in milk sales
- Additionally, Khokkho includes "other expenses" which are not detailed in the Lopburi dataset

These findings underscore substantial economic discrepancies in the strategies employed by the two regions to manage and alleviate the economic repercussions of LSD outbreaks.

Table B2. Economic loss due to LSD outbreaks in Lopburi province (Promsathit et al., 2022).

Items	**Thai Baht**	**USD**
Mortality of cattle	5,000	14.7
Insect control	1,515	42.6
Disinfectant	NA	-
Vaccination	2,520	70.9
Treatment cost	3,835	107.9
Reduction in milk sold	5,385	151.5
Other expenses	NA	
Total economic losses	14,221	400.23

NA = data is not available

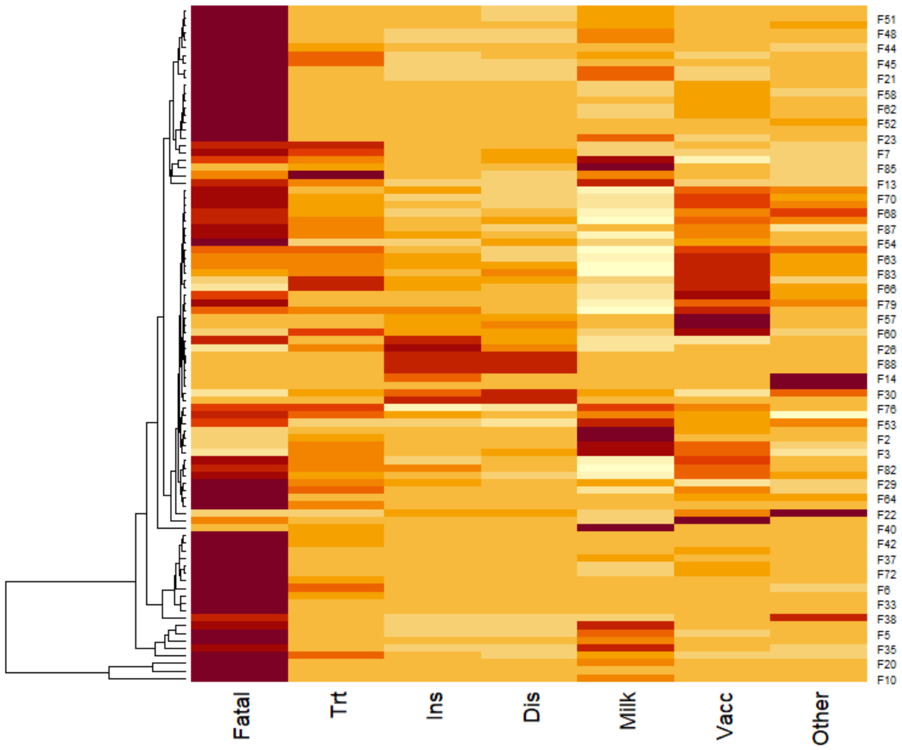

Figure B3. Heatmap of economic losses due to LSD outbreak for each dairy farm

A heatmap provides a clear and visual representation of the economic impact caused by LSD outbreaks on individual farms, where darker shades emphasize greater financial losses (Figure B3). The predominant factor leading to these financial setbacks is the mortality of cows affected by LSD. Many farmers incur significant expenses in treating cows affected by LSD. Additionally, a decline in milk sales results in economic losses for numerous farms. Moreover, various farms experience a considerable financial burden as they invest in vaccines. Also, several farms incurred substantial expenses for insecticides.

Discussion

In this study, the economic impact of LSD outbreaks was evaluated through a questionnaire survey conducted in the selected area that was initially affected by the disease. Various losses and costs associated with the prevention and control of LSD outbreaks were determined.

This study underscores that the primary source of loss stems from the mortality of dairy cattle exhibiting LSD symptoms. Considering the substantial value that dairy cattle hold within the context of Thailand, their mortality has a notable and adverse economic impact on farmers. It is important to note that the losses resulting from dairy cattle mortality in this study are higher than those reported previously. The differences in losses between this study and the previous one conducted in Thailand (Promsathit et al., 2022) can be attributed to the fact that, in this study, most of the cattle affected by the disease were dairy cows, whereas the previous study mostly found young calves.

From a socio-economic perspective, cattle fatalities not only have a direct economic impact on farms but also deeply affect the emotional well-being of certain farmers. For many, these animals are regarded as integral members of their families, with their well-being intertwined with the emotional fabric of rural life. The emotional toll of losing these animals cannot be underestimated, and it highlights the complex interplay between economic and social aspects of livestock farming.

Treating cows that exhibit clinical signs of LSD is of utmost importance. Farmers incur costs for antibiotics, NSAIDs, antipyretic medications, and supportive agents, including vitamins, for the treatment of their cows. This expenditure does indeed contribute to the overall economic losses on the affected farms. Furthermore, the use of antibiotics also leads to discarded milk, adding to the financial impact of the outbreak.

LSD outbreaks can lead to a significant reduction in milk production. Cows affected by the disease may produce less milk, and in severe cases, they may stop producing milk altogether. This reduction in milk output directly affects dairy farms' revenues, leading to financial losses (Gupta et al., 2020). A prior study conducted in the northeastern region of Thailand investigated the losses in monthly bulk milk production from dairy herds experiencing LSD outbreaks. The study revealed that these outbreaks led to losses ranging from ฿4180 ($119; USD) to ฿14440 ($412), as determined by farm milk sales records (Vinitchaikul et al., 2023). The losses attributed to a reduction in milk sales observed in the present study fall within this range, and they closely align with the findings from the study in Lopburi province (Promsathit et al., 2022).

In this survey, all farms followed the recommendation of the veterinary authority and the dairy cooperative committee by using insecticides (Suwankitwat et al., 2022). The farmers have turned to insecticides as a quick response to manage LSD outbreaks (WOAH, 2021). While this approach can potentially help control the insect vectors responsible for spreading the disease, its effectiveness remains difficult to ascertain (Arjkumpa et al., 2022). Additionally, applying insecticides across a large area may not guarantee comprehensive protection against flying blood-sucking insects for cattle. Insects might depart during the spraying process and linger in adjacent areas. Subsequently, they could return to the farm to bite the cattle. The use of insecticides incurs costs for farmers. Therefore, it is essential to provide appropriate guidance on their usage to ensure their effectiveness.

It is worth noting that many of the farms included in this study had previously administered LSD vaccinations, albeit in the form of emergency vaccination (WOAH, 2021). These vaccinations were typically administered shortly before or during disease outbreaks. This practice implies that the cattle did not have sufficient time to develop full immunity to the disease. Consequently, it was observed that LSD outbreaks occurred in farms with a history of these emergency vaccinations. This finding underscores the importance of well-timed and comprehensive vaccination strategies for effective disease prevention.

Examining the heatmap, which provides a visual representation of costs and losses for each farm, it becomes evident that the primary driver behind these financial setbacks is the mortality of cows afflicted by LSD. This imposes a significant financial burden on many farmers. Furthermore, substantial expenses are frequently incurred for treating LSD-affected cows, exacerbating the economic challenges. Additionally, a decrease in milk sales stands as another significant contributor to financial losses experienced by multiple farms. Notably, several farms face a substantial financial strain as they invest in vaccines to effectively counter the challenges posed by LSD. It is also important to highlight that some farms encounter considerable expenses associated with the use of insecticides in their efforts to address LSD outbreaks.

Research conducted in Ethiopia revealed that economic losses resulting from LSD amount to $1,176 per farm (Molla et al., 2017), whereas a study in Kenya estimated the economic losses due to this disease to be around $755 per farm (Kiplagat et al., 2020). This study estimates the total economic loss at approximately $2,461, surpassing the figures found in previous research. These variations in economic losses can be attributed to differing circumstances, including variations in herd size, the severity of outbreaks, the specific factors considered when determining losses, and the valuations of cattle and milk. Therefore, when comparing studies, it is essential to take into account these factors, as well as other considerations such as the calculation methods and the duration of the outbreak period. This will help ensure a more accurate and comprehensive evaluation of the findings.

This study has certain limitations. Since 2021, the number of LSD outbreak reports in Thailand has been minimal, with only a few farms affected by LSD. Therefore, this study had to adopt a retrospective approach, gathering historical information from farms that had experienced LSD outbreaks in 2021. Considering the design of this study, the potential for recall bias is a noteworthy concern in this scenario. Additionally, the economic loss estimated in this study is acknowledged as a partial approach, as found in several previous studies (Molla et al., 2017; Kiplagat et al., 2020; Limon et al., 2020; Promsathit et al., 2022). To achieve a more comprehensive comprehension of the overall economic impact, it is essential to explore advanced economic models in future research.

It is important to emphasize that although the results indicate a higher average vaccination cost compared to that of insecticide and disinfectant, this does not imply that using insecticide and disinfectant is a more economical approach than vaccination. The cost of vaccination involves a one-time payment per year approximately to obtain the herd immunity. Also, the cost of vaccination varies depending on the number of cattle in the herd to be vaccinated, with smaller herds paying less for vaccines in this regard. On the other hands, the effectiveness of insecticide and disinfectant is short-lived, and prolonged use leads to continuous increases in expenses and the cumulative cost may higher than the vaccination cost.

Importantly, the objectives of vaccination and the use of insecticide and disinfectant practices are fundamentally different. Comparing the economics of using vaccines versus using insecticide and disinfectant may lead to misconceptions. Vaccination provides long-term immunity to protect cattle from the disease, while insecticide and disinfectant usage primarily targets vector control and LSDV elimination, respectively. Therefore, vaccination is recommended for the prevention of LSD in the herd. The using of insecticide and disinfectant is an option for naïve herd (herd without vaccination) with the aim targeting vectors or LSDV elimination.

The economic implications of LSD outbreaks are multifaceted and extend throughout the dairy supply chain. Farmers, dairy processors, consumers, and governments are all affected by the economic consequences of this disease. Effective control and prevention measures, including vaccination and improved biosecurity practices, are essential to mitigate these economic impacts and safeguard the dairy industry.

A study in Bangladesh

Study area

A field study was conducted at the Bangladesh Milk Producer's Co-Operative Union Ltd. (known as 'Milk Vita') at Shahjadpur upazila of Sirajganj district, situated in the north-western part of Bangladesh (*Site 1*) and Bhaluka upazila of Mymensingh district (*Site 2*). These study sites were the same locations as those included in the study as outlined in objective #2.

Specific Aim#1: To identify the stakeholders along the value chain of beef cattle and dairy cattle

Summary

- The dairy cattle value chain demonstrates various dynamics, including procurement of cattle from other farms or markets, highlighting interconnectivity within the local dairy industry.
- Beef cattle are predominantly sourced from local markets, traders, and neighboring farms, with strategic planning to capitalize on festive demand. Marketing involves multiple stakeholders, including producers, traders, processors, and butchers, focusing on targeted cultivation for specific market opportunities.
- Dairy and beef cattle value chains differ, as dairy value chains feature a diversified distribution network, while beef value chains prioritize seasonal demand patterns.
- Decreased milk yield raises cost per liter and affects milk supply chain, impacting producers and dairy co-operative authorities.
- The efficiency of the beef value chain is compromised by a decline in the population of healthy cattle, resulting in elevated meat prices and impacting numerous stakeholders.

Materials and Methods

Identification of stakeholders

The identification of the stakeholders or participants was done based on preliminary discussion with the Milk Vita personnel and Veterinary Surgeon and/or Upazila Livestock Officer of the respective areas. A total of 62 participants, having 36 from Shahjadpur upazila and 26 from Bhaluka upazila were invited to participate in the focus group-discussions (FGDs) (Table C1).

This heterogeneous assembly of the participants was convened to provide their perspectives and field knowledge to the discourse. All the stakeholders were directly or indirectly linked to the cattle value chain and LSD outbreak and management.

Table C1. A list of the stakeholders who participated in the focus group discussions in Shahjadpur and Bhaluka upazilas

Stakeholders	Shahjadpur upazila	Bhaluka upazila
Milk Vita officers (Cattle Development and Training Division)	2	-
Dairy farmers	5	4
Beef cattle farmers	1	3
Representatives of dairy farmers' society	4	-
DLS officers (Veterinary Surgeons/Upazila Livestock Officer/Livestock Extension Officer)	1	2
Cattle traders	2	2
AI technician	5	3
Milkmen	4	2
Cattle feed dealer	1	1
Household processors	2	1
Local representatives of pharmaceutical companies	2	2
Pharmacists	4	2
Butcher	1	2
Sweetmeat shop owners	2	2

DLS = Department of Livestock Services, AI = Artificial insemination.

Figure C1. Short briefing on value chain analysis with different stakeholders

Operations of FGD

Data related to the dairy and beef cattle value chain analysis were gathered through the implementation of FGD at each site (Figure C1). During the FGD session, draft dairy and beef value chain diagrams, prepared in Bangla, were displayed before the participants and thoroughly explained to them collectively. Then the participants were requested to verify and propose any other stakeholders to be included. The stakeholder identification criteria, which were focused on evaluating their level of interest and impact in preventing and controlling LSD outbreaks, were effectively described.

To enhance the interactivity and visibility of the conversations, value chain maps, and stakeholder rankings, indicating their influence on LSD, were depicted on poster paper using permanent markers. The findings were immediately communicated to the participants to ensure lucidity and facilitate comprehensive discussions concerning the rationale behind their responses and any supplementary observations.

Each FGD session was carefully planned to be efficient, lasting two to three hours, to ensure that participants could concentrate on the primary themes (Figure C2).

Figure C2. Focus group discussion on value chain analysis

Results

Dairy cattle value chain

The dairy farmers acquired their dairy cattle (80%) from other dairy farms, local or regional markets, and heifers from their own farms while 20% of the cattle were sourced from cattle traders. Crossbred dairy cattle constituted 50% of the farms while 28% raised indigenous cattle and 22% maintained both crossbred and indigenous cows. In most dairy farms (87%), artificial insemination (AI) was practiced whereas 5% of the farmers relied on natural service and 8% utilized both methods (Figure C3).

The main output of the dairy farms was milk. The other outputs were culled cows, male calves, and manure.

Raw milk

Raw milk is associated with a variety of stakeholders. The majority of milk in the Shahjadpur area is directed towards the Milk Vita Dairy Co-operative. A portion is distributed to individual milkmen, a small amount is sold in the local market, and some is used by household processors and sweetmeat shops. The milk produced in the Baluka upazila is primarily distributed to consumers either directly or through milkmen. A small portion is also sold in the local market, sweetmeat shops, and tea stalls.

Milk Vita, a reputable formal milk processor, provides a range of milk products such as pasteurized and UHT milk, as well as yogurt, ghee, chocolate, ice cream, and butter. This milk and milk product is distributed to both retail markets and superstores.

The milkman distributes milk to several establishments, including the local market, sweetmeat shops, formal milk processors, household processors, and household consumers.

The local market provides milk to domestic consumers, household processors, sweetmeat shops, and tea stalls. The household processor distributes their product to both the local market, sweetmeat shop, and online markets.

Culled cows and male calves

The culled cows and male calves are typically sold to cattle traders, local markets, butchers, and online markets. The cattle traders vend the cows and calves either in the local market or to the butcher and fellow farmers.

Manure

The manure is mostly utilized by the farmers themselves (99%) as dung cake for home cooking, as fertilizer, biogas, and for usage in fish ponds.

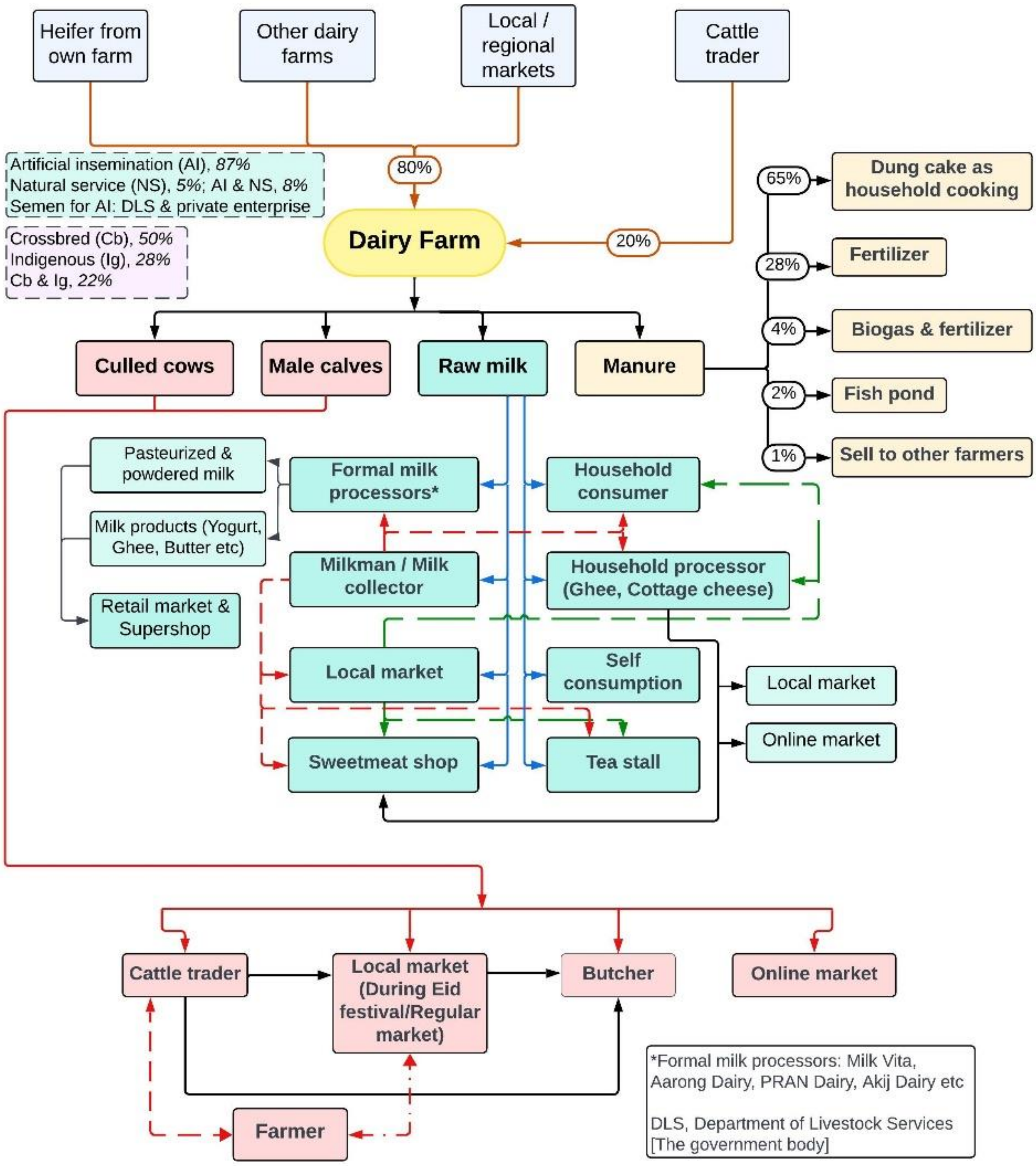

Figure C3. A diagram showing the dairy cattle value chain from the constitution of the farms to the production and marketing of milk and milk products

Beef cattle value chain

The cattle for beef fattening were sourced from local and regional markets, cattle traders, and neighboring and owned farms. It was also observed that the cattle were imported from neighboring countries (Figure C4).

The producers/farmers

The beef cattle are sold to the local market, cattle traders, and meat processors round the year. A significant quantity of beef cattle is exchanged throughout several festivals, particularly during Eid-ul-Adha, a holy festival of Muslims. Several farmers are engaged in the cultivation of beef cattle specifically for sale during the Eid festival. The producers directly sell their products to consumers either in local markets or through cattle traders. Farmers often vend their livestock on online platforms during the Eid festival. Aside from the Eid festival, farmers sell their livestock, such as bulls and culled cows, to butchers and meat processors.

Cattle traders

The cattle trader plays a crucial role in the marketing of beef cattle. They provide beef cattle to the butchers, meat processors, and directly to the consumer. In most of the cases, they work as the bridge between the farmers and consumers.

Meat processors

Meat processors primarily operate inside the urban meat supply chain. Their production includes chilled meat, frozen meat, and various meat products such as sausages, momo, and minced beef (keema), etc. They provide meat and meat products mostly to residential hotels and private hospitals; however, these are also distributed to the super shops and retail markets. In addition, frozen meat and meat products are exported to different countries.

Butchers

Butchers are a group of stakeholders who directly supply meat to consumers. The butchers play a crucial part in the beef value chain by overseeing the transformation of cattle into different meat products that are ultimately consumed by customers. Butchers collaborate with multiple stakeholders in the beef value chain, including cattle farmers, distributors, retailers, and chefs or restaurant owners.

Hides, skin and bone collectors, and processors

Hides and skins that are collected by seasonal collectors and dealers are sold to tanneries where these are processed for export. Having been collected by different collectors, inedible bones (e.g., skull, scapula, jaws) are processed in the bone-crushing mills, which are then sold to gelatin manufacturing companies, and exported as well.

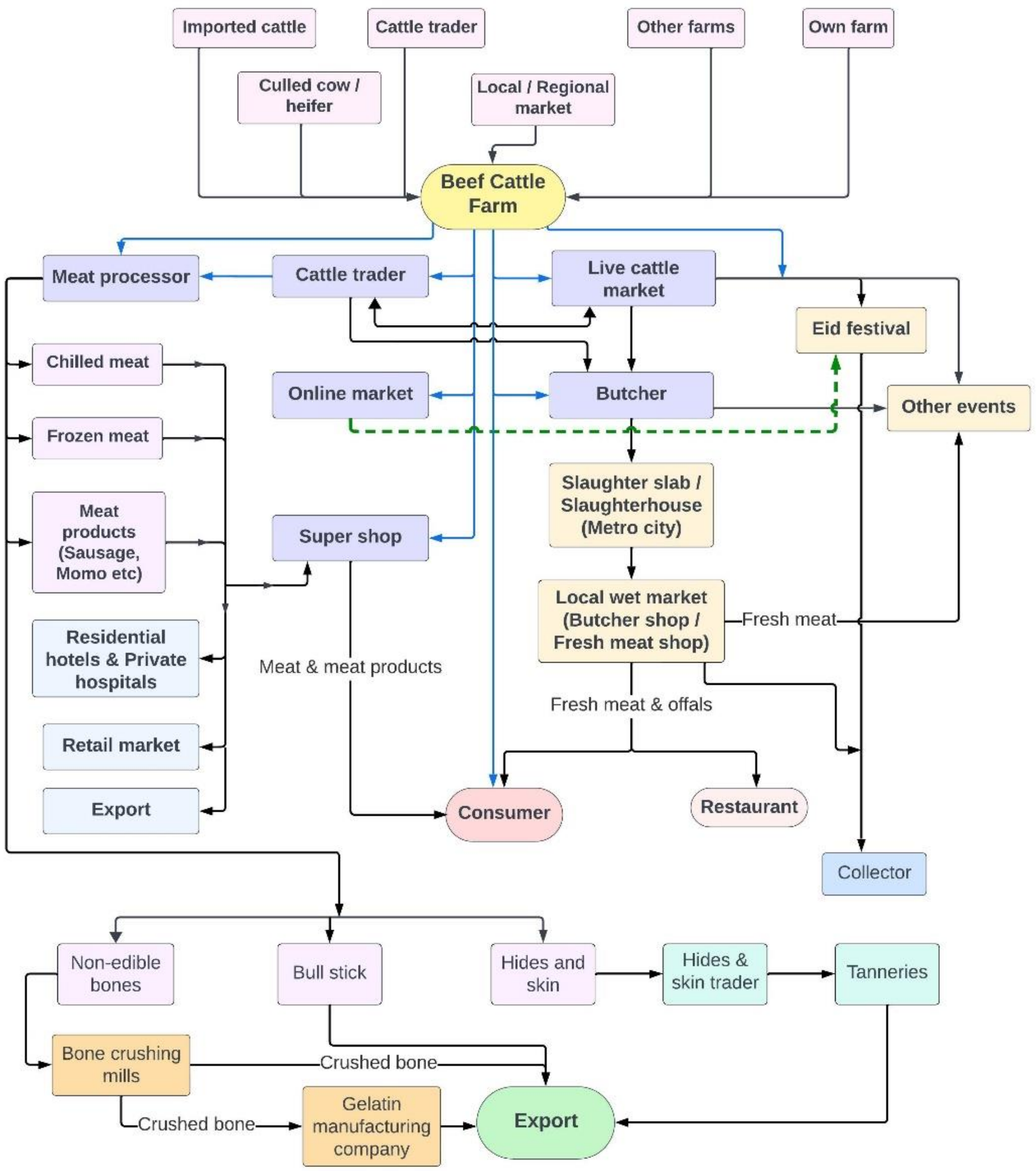

Figure C4. A diagram showing the beef cattle value chain from the constitution of the farms to the marketing of meat and meat products

Discussion

Dairy Cattle Value Chain

The dairy cattle value chain in the studied area exhibits several interesting dynamics. Firstly, the majority of dairy farmers procure their cattle from other dairy farms, local or regional markets, emphasizing the interconnectedness within the local dairy industry. The prevalence of crossbred dairy cattle highlights a deliberate effort towards enhancing milk production through selective breeding. However, the coexistence of indigenous cattle signifies the importance of traditional breeds in local dairy farming practices. The widespread adoption of AI among dairy farmers underscores the integration of modern reproductive technologies to improve breeding efficiency and genetic quality. Nevertheless, a notable percentage of farmers still rely on natural service or a combination of AI and natural methods, indicating a diversity of approaches across different farms.

The primary output of dairy farms is milk, with additional outputs including culled cows, male calves, and manure. The distribution channels for raw milk involve various stakeholders such as Milk Vita Dairy Co-operative, individual milkmen, local markets, household processors, and sweetmeat shops. This diversification in distribution channels reflects the adaptability of dairy farmers to cater to different consumer preferences and market demands.

Beef Cattle Value Chain

In contrast to the dairy cattle value chain, the beef cattle value chain exhibits different characteristics shaped by cultural practices and market dynamics. Beef cattle are predominantly sourced from local and regional markets, cattle traders, neighboring farms, and occasionally from international sources. The influx of cattle during festivals, particularly Eid-ul-Adha, highlights the seasonal nature of beef consumption and the strategic planning of farmers to capitalize on festive demand.

The marketing of beef cattle involves multiple stakeholders including producers/farmers, cattle traders, meat processors, and butchers. Producers engage in targeted cultivation of beef cattle for specific market opportunities, such as Eid festivals, demonstrating a proactive approach to meet festival demand fluctuations. Cattle traders play a pivotal role in facilitating transactions between farmers and consumers, ensuring the smooth flow of cattle within the value chain.

Meat processors play a crucial role in value addition by converting raw beef into various products tailored to urban consumer preferences. The distribution of meat and meat products extends beyond local markets to residential hotels, private hospitals, super shops, and even international markets through exports. Additionally, the utilization of hides, skins, and bones underscores the holistic approach towards resource optimization within the beef value chain, contributing to both economic and environmental sustainability.

Cross-Comparison of Value Chains

An investigation of the dairy and beef cattle value chains reveals both similarities and differences in their structure and operation. While both chains involve multiple stakeholders from production to consumption, the dairy value chain exhibits a more diversified distribution network catering to various consumer segments. In contrast, the beef value chain demonstrates a stronger emphasis on seasonal demand patterns and value addition through processing and export.

Impact of LSD on cattle value chains

This study focused on the identification and ranking of key stakeholders involved in the beef and dairy cow value chains, with regards to the outbreak, spread, prevention, and management of LSD. The ranking process considered the stakeholders' degree of interest and impact in things linked to LSD. The results emphasize the primary actors accountable for the occurrence and spread of LSD, such as cattle traders, farmers, live cattle markets, veterinarians and other health care providers. Furthermore, individuals involved in the transportation of animals and animal feed dealers are also considered contributors to the transmission of LSD because of the inherent hazards associated with their respective jobs.

The LSD outbreak had a great impact on the livestock industry. The diverse clinical signs, loss of production of both milk and meat, persistence of the clinical signs for a long time in some cases, permanent scar on skin of animals, and death of animals greatly various aspects of the value chain. The animals exhibiting clinical signs were deemed unfit for trading by cattle traders and/or butchers. The cost of raising animals has also increased due to the inclusion of expenses for medications such as antibiotics, antipyretics, anti-inflammatory treatments, and immune modulators. This has negatively impacted farmers, who are the primary stakeholders. The decrease in milk yield results in an elevated cost per liter of milk and has repercussions on the milk supply chain. The impact was experienced by the producers, dairy co-operative authorities, and the stakeholders that are directly involved in the milk value chain.

The efficiency of the beef value chain was also hindered due to a drop in the population of healthy and fit live cattle. The rise in live cattle prices led to a corresponding increase in the market price of meat per kilogram. This had an impact on the cattle trader, butcher, internet market, supermarkets, restaurants, hotels, and consumers as a whole. LSD primarily impacts the integumentary system of animals, resulting in potentially irreversible harm to their skins. Consequently, the tannery industry was also adversely affected by the disease outbreak.

In the survey, it was noted that although there was no formal coordination specifically aimed at LSD prevention and control among veterinarians, dairy cooperatives, the Department of Livestock Services (DLS), and farmers, the Upazila Livestock Office and Veterinary Hospital took proactive measures. They organized training sessions, conducted meetings, and arranged free vaccination campaigns to raise awareness among farmers and control LSD outbreaks. Additionally, personnel from dairy cooperatives provided advice to farmers regarding vaccination and vector control.

Specific Aim#2: To assess the economic impact of LSD outbreaks in selected dairy farming area

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Summary

- In the study areas, the majority of cattle owners are smallholders, typically having 2-15 cattle per household. The fatality of LSD-infected cattle imposes a significant economic burden, as losing even a few cattle can result in disproportionately high losses.
- The primary economic losses result from the decline in milk production and the expenses incurred for treating LSD-affected cattle.
- Despite the high treatment expenses, only 4% of respondents reported vaccination costs, indicating limited adoption of LSD vaccination among cattle owners.
- Factors contributing to low vaccination coverage include limited vaccine availability, cost considerations, and oversight in vaccination practices.
- Less than 20% of cattle owners reported expenses for insecticide use, and fewer than 15% disclosed costs for disinfectant usage, highlighting a lack of investment in disease prevention.

Materials and Methods

A questionnaire survey was conducted in the study areas. All respondents have experienced with LSD outbreak.

Results

Figure D1 displays the total number of cattle in each herd and the corresponding total number of cattle affected by LSD. The mean and median values of total number of LSD affected cattle were 1.04 and 0.5, respectively.

The costs and losses related to lumpy skin disease outbreaks for LSD outbreak farms are presented as mean ± standard deviation (Mean ± SD) in Table 1. Figure D2 illustrates costs and losses by farm.

Table D1. Cost and losses due to lumpy skin disease outbreak farms

Item	Frequency*	BDT (Mean ± SD)	USD
Treatment cost	100	5618.80 ± 6553.71	51.25±59.78
Insecticide cost	33	751.51 ± 606.89	65.17±55.28
Disinfectant cost	25	472.00 ± 399.50	4.30±3.64
Vaccination Cost	9	644.44 ± 598.15	5.87±5.45
Milk yield loss	34	14168.38 ± 33648.95	129.13±306.67
Loss due to animal died	19	116842.11 ± 90142.03	1064.90±821.56
Losses due to hide or skin damage	2	750 ± 353.55	6.84±3.22

*Frequency values indicate the number of respondents reporting the cost or losses for each category. The mean and standard deviation (SD) are calculated based on the frequency, not the total number of respondents for each group.

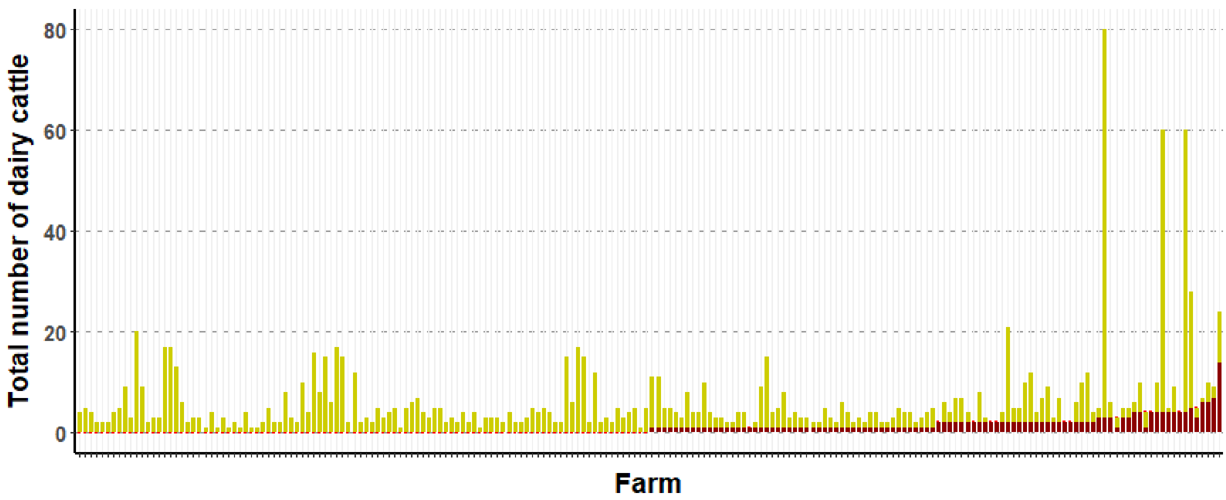

Figure D1. The total number of cattle in each herd (yellow bar) and the corresponding total number of cattle affected by LSD (red bar).

The results of this investigation, presented in Table 1, elucidate the frequency of costs and losses related to disease outbreaks among the surveyed farms. Significantly, treatment costs were exclusively reported by 100 respondents from farms experiencing disease outbreaks. In the case of insecticide costs, 33 respondents from outbreak farms acknowledged the expenses associated with insecticide use.

Similarly, disinfectant costs were reported by 25 respondents from outbreak farms disclosed the costs linked to disinfectant use. Noteworthy is the fact that vaccination costs were reported by 9 respondents out of 100 respondents who owned farms experiencing LSD outbreaks. These costs showed variation among the farms, averaging BDT 644.44 (5.87 USD).

Furthermore, milk yield losses were reported by 34 respondents, while losses due to animal deaths were noted by 19 respondents from outbreak farms. Additionally, losses attributed to hide or skin damage were reported by 2 respondents.

The highest cost was the treatment of LSD affected cattle followed by insecticide and disinfectant costs. The major loss was due to losses in milk followed by mortality of cattle.

Furthermore, the heatmap clearly indicates that the predominant trend among respondents who had LSD in their animals is the payment for treatment (Figure D3). A notable portion of respondents incurred expenses for both treatment and losses resulting from cattle fatality. Additionally, the main pattern observed among respondents was the losses attributed to a decline in milk production.

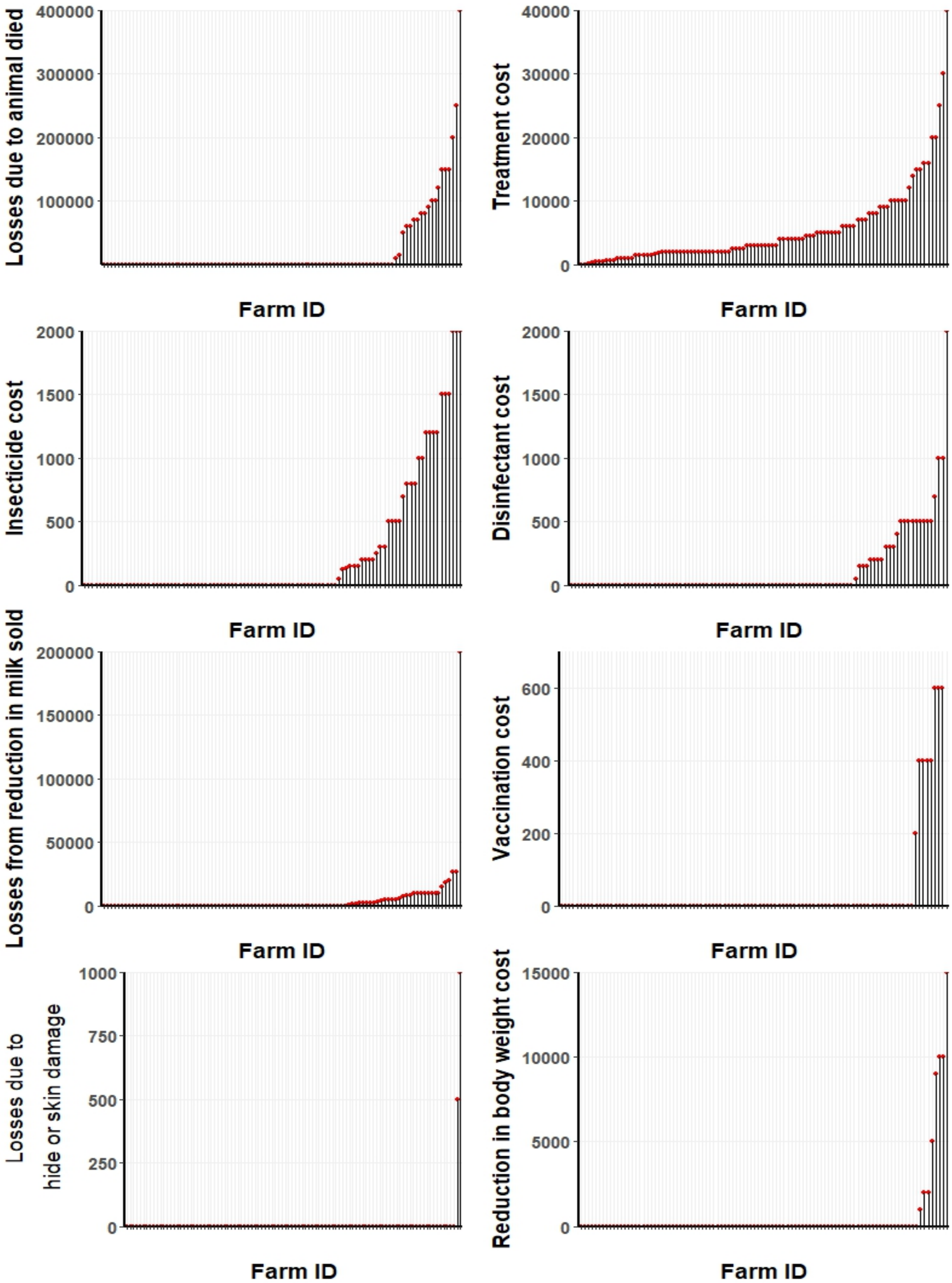

Figure D2. Costs and losses in relation to lumpy skin disease outbreaks in dairy farms

Figure D3. A heatmap depicting costs and losses reported by respondents experiencing LSD outbreaks.

Discussion

The majority of cattle owners are smallholders raising cattle in household areas, which aligns with previous reports indicating that each household typically had 2-15 cattle.

The fatality of cattle affected by LSD poses a significant economic burden for the cattle owner. Due to the small herd size, the loss of only a few cattle can result in a disproportionately high percentage of overall losses. For instance, in a herd with 10 cattle, the fatality of 1-2 cattle would contribute to a 10-20% reduction in the total herd size. Consequently, this loss in cattle also leads to a decrease in milk production. These aforementioned losses could result in economic hardships, especially for small-scale cattle herd owners.

Most cattle owners incur expenses for treating LSD-affected cattle. The treatment cost typically applies to around one cattle, as the average number of LSD-affected cattle in the surveyed herds was one. Nevertheless, the overall treatment expenses exceeded other costs, highlighting that preventing the disease proves to be more cost-effective than treating it.

Only 4% of the respondents reported that they had the vaccination cost. It was possible that vaccines were financial supported by the government or relevant organizations. However, there were 49 out of 200 farms had a history of LSD vaccination indicating that a limited adoption of LSD vaccination by cattle owners. Possible reasons for this low adoption rate could include limited availability of vaccines or other factors. For example, cattle herd owners might assume that certain herds have not experienced LSD outbreaks even without vaccination, leading to oversight in vaccination practices. Additionally, the cost of the vaccine may be a determining factor for cattle owners in deciding whether to purchase and administer vaccines. Given that unimmunized cattle face a heightened risk of LSD infection, future investigations should prioritize exploring the factors contributing to the low coverage of LSD vaccination in order to address this circumstance more comprehensively.

The number of cattle owners willing to invest in control measures was not substantial, as less than 20% reported expenses related to insecticide use and fewer than 15% disclosed costs associated with disinfectant usage. Furthermore, the incurred expenses for insecticide and disinfectant varied, indicating a diverse range of investments in disease prevention. In cases of low vaccination coverage, households with cattle unimmunized by the LSD vaccine should prioritize LSD prevention. Furthermore, the implementation of vaccination should also be given priority to control LSD outbreaks or prevent the re-emergence of LSD.

The surveyed cattle herds are representative of small-holder cattle production in the Asian context. This study addresses knowledge gaps by providing insights into how LSD impacts smallholders.

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Rationale and comparative results from Thailand and Bangladesh

In the country study framework, Thailand and Bangladesh were chosen to represent Southeast Asia (SEA) and South Asia, respectively. Thailand stands out for having the highest number of LSD outbreak reports in SEA, with widespread LSD outbreaks across the nation. Meanwhile, Bangladesh holds the distinction of being the first country in Asia to report LSD outbreaks. Moreover, both nations have provided a wealth of reports and research publications compared to their regional counterparts.

Thailand's climate and cattle production system make it representative of countries in Southeast Asia such as Vietnam, Laos, and Cambodia. Similarly, Bangladesh's production system aligns closely with those of South Asian countries like India and Nepal. Regarding production systems, Thailand's dairy industry operates on a more extensive scale with larger herd sizes compared to Bangladesh, although beef herd sizes are comparable between the two.

Given the variations in management practices, environments, cultures, LSD outbreak control strategies, and other factors, conducting studies in these two countries presents a compelling opportunity to enhance our understanding of LSD epidemiology and refine prevention and control strategies in response to LSD outbreaks.

The study found that LSD outbreaks in Bangladesh and Thailand formed separate spatio-temporal clusters, reflecting their distinct geographic and temporal characteristics. However, it's worth noting that one cluster identified by the model included LSD outbreaks in both Bangladesh and Myanmar, a neighboring country to Thailand. This observation supports the directional trend findings, indicating the spread of LSD outbreaks from South Asia to Southeast Asia. Additionally, it aligns with the phylogenetic tree results, which show similarities between the lumpy skin disease viruses isolated in Bangladesh and those in Myanmar.

Thailand has extensively documented nationwide LSD vaccination efforts carried out by the livestock authority, while similar interventions in other Asian countries, including Bangladesh, have not been acknowledged. However, while mass vaccination campaigns in countries other than Thailand have not been formally documented, reports indicate that vaccination efforts have been undertaken in various regions of these countries.

The comparative analysis of risk factors for LSD outbreaks in Thailand and Bangladesh reveals similar findings, with absent or insufficient control of insect vectors posing a significant risk for LSD outbreaks in naïve cattle herds in both countries. Economic losses estimated from LSD outbreaks are higher in Thailand due to its larger cattle herd size. Additionally, there are differences in vaccination coverage between the study areas. The analysis of the value chain also highlights both similarities and differences, reflecting variations in cattle production systems, consumer behavior, religious beliefs, and socio-economic factors between the two countries.

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