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Spatial and temporal patterns of foot and mouth disease outbreaks (2011–2022) in cattle export-sourcing areas of southeastern Ethiopia

Daniel Gizaw[1,3*], Gashaw Beyene[2], Hagos Ashenafi[3], Mengistu Legesse[3] and Tesfu Kassa[3]

Abstract

Background Foot-and-mouth disease (FMD) is a highly contagious viral infection that infects cloven-hoofed animals, including cattle, sheep, goats, swine, and various wildlife species. Ethiopia is found in pool four where Serotype A, Serotype O, SAT1 and SAT2 are endemic. A retrospective study was conducted to analyse the spatial and temporal patterns of FMD outbreaks in export-sourcing areas of Southeastern Ethiopia over 12 years (from January 2011 to December 2022), using reported FMD outbreak data. Geographically, the area extending from Borana to East Shoa, along the main road connecting Moyale to Adama, was identified as the primary FMD outbreak zone within the cattle export-sourcing areas of southeastern Ethiopia.

Results The data on Foot-and-mouth disease (FMD) outbreaks over the past twelve years (from January 2011 to December 2022) obtained from the Ministry of Agriculture's, Ethiopia database were retrieved and analyzed. There were a total of 58,426 cases across 247 outbreaks in 11 zones and 89 districts within the cattle export-sourcing areas of southeastern Ethiopia. On average, there were 20.3 outbreaks per year, with a median of 18 outbreaks annually, corresponding to approximately 4.6 outbreaks per month. The highest incidence occurred in January. The year with the most reported outbreaks was 2011, which had 54 outbreaks, followed by 2020 with 39 outbreaks and 2015 with 30 outbreaks In contrast, there were very few outbreaks recorded in 2014 and 2019. The case fatality rate was 1.02%, and an estimated 4,775,124 cattle were at risk of FMD infection. A time-series decomposition of the FMD outbreak data revealed seasonal trends. The trend analysis indicated that FMD outbreaks occurred in a cycle of two to five years, with peaks observed in 2011, 2012, 2015, and 2021. The incidence of FMD outbreaks varied across different zones, being lowest in the Afder and Gedeo zones and highest in the Arsi zone. An analysis using a space-time permutation probability model within the SaTScan software, with a maximum cluster size of 50%, identified five high-risk clusters and four low-risk clusters that were statistically significant ($P < 0.05$).

Conclusions These spatial and temporal cluster analyses highlighted regions and periods with significantly higher-than-expected FMD outbreaks. The spatiotemporal and cluster analysis of FMD outbreaks provides critical insights for prioritizing control, prevention, and prophylactic measures in cattle export-sourcing areas of southeastern Ethiopia.

*Correspondence:
Daniel Gizaw
nebiyudan@yahoo.com
Full list of author information is available at the end of the article

Keywords Foot and mouth disease, Outbreaks, Cattle, Export sourcing areas, Spatiotemporal, Clusters

Background

Foot-and-mouth disease (FMD) is a highly contagious viral infection that infects cloven-hoofed animals, including cattle, sheep, goats, swine, and various wildlife species [1]. The temporal and spatial dynamics of the FMD virus make it the most economically significant infectious disease of animals [2]. FMD is a prominent transboundary animal disease (TAD) that severely impacts livestock production and disrupts regional and international trade in animals and animal products [3, 4]. In addition, FMD affects food security and the economic development of smallholder farmers as well as organized production chains that supply urban and export markets [4].

Animals infected with the FMD virus usually show symptoms such as fever, lameness, and vesicular lesions on the tongue, snout, feet, and teats [5]. In severe cases, the epithelial tissue may slough off, causing the vesicles to rupture and release significant viral load. [6]. While FMD rarely leads to death in adult animals, it can be much more severe in young animals, particularly in very young calves [5, 7].

The classification of FMD virus serotypes into geographical virus pools is based on genetic sequences encoding the variable capsid protein (VP1) [8, 9]. In Africa, three distinct virus pools have been identified: Pool 4, which covers East and North Africa and is predominantly associated with serotypes A, O, SAT1, and SAT2; Pool 5, which is restricted to West and North Africa and includes serotypes O, A, SAT1, and SAT2; and Pool 6, which is primarily found in Southern Africa and is associated with serotypes SAT1, SAT2, and SAT3 [4].

Over the past decade, multiple outbreaks of FMD in livestock have been reported in Africa [3]. Ethiopia is found in pool four where Serotype A, Serotype O, SAT1 and SAT2 are endemic [10, 11]. The temporal patterns in FMD outbreaks indicate a clear seasonality of the disease, with the season itself considered a risk factor [12]. In bigger cities such as Addis Ababa and Adama outbreaks of FMD occur throughout the year. because of the influx of animals from various regions of the country [13]. The adaptation of pastoralists to seasonal climate and grazing trends plays a crucial role in the distribution of the viruses and may result in livestock coming into contact with susceptible wildlife [14].

The temporal distribution of FMD outbreaks based on when they are identified or reported tends to differ both between and within countries [15] Analyzing these outbreaks serves as a foundation for epidemic intelligence, helping to identify disease hotspots and enhancing the design, tailoring or implementation of timely evidence-based surveillance and response strategies [16].

The Ethiopian government has developed a national strategic control plan for FMD, to enhance the trade of meat and live animals in the export-sourcing areas of the country, where the Boran breed of cattle considered a good source of meat originated. The targeted areas include Borana, Guji, Bale, West Arsi, Arsi and East Shao zones in the Oromia regional state, as well as Liban, Dawa and Afder zones in the Somali region and Sidama and Gedeo zones [17]. The national control plan recommends measures like control of animal movements, vaccination at farms and livestock markets, and strict biosecurity control in slaughterhouses. FMD control requires a comprehensive understanding of the spatiotemporal distribution of FMD outbreaks, which involves analyzing the monthly, yearly, and geographical clusters to indicate hotspot areas. Hence this study was aimed at describing the FMD outbreaks in cattle export-sourcing areas of Ethiopia from 2011 to 2022 focusing on evaluating the spatiotemporal distribution of FMD outbreaks.

Results

The FMD outbreak data from January 2011 to December 2022 in the cattle export-sourcing areas of southeastern Ethiopia revealed a total of 58,426 cases from 247 outbreaks where cattle populations were predominantly affected, with limited data available for other species. On average, there were 20.3 outbreaks per year during this period, with a median of 18 and a mode of 8 outbreaks per year. The peak outbreak occurred in 2011 with 54 outbreaks, followed by 39 outbreaks in 2020 and 30 in 2015, while 2014 and 2019 had the lowest recorded number of outbreaks.

In 2015, the highest number of cases ($n = 22014$) was reported, while 2017 had the lowest number of cases ($n = 129$) with a cumulative percentage of 0.2%, as detailed in Table 1. The average case fatality rate among cattle was 1.02%., and ranges from 0.0 to 7.8%. There was an estimated, population of cattle at risk of 4,775,124. The overall morbidity rate was 1.22%, while the mortality rate was 0.01%.

Spatial distribution of FMD cases in export sourcing areas

Although FMD is endemic in Ethiopia, the increasing incidence of FMD cases in areas that supply cattle for export has generated significant concerns. The Arsi zone in Oromia recorded 80 outbreaks over the past 12 years, making up 32.4% of the total outbreaks in the region, while Borana reported 67 outbreaks, constituting 27.1% of the cumulative total, as highlighted in Table 2. However, Gedeo and Afder zones reported very few outbreaks during the study periods. The number of outbreaks

Table 1 Annual outbreak of FMD in export-sourcing areas of Ethiopia (2011–2022)

Year	Total outbreak	Total case	Cumulative percentage (%)	Total death	Population at risk	Case fatality rate (%)	Morbidity rate (%)	Mortality rate (%)
2011	54	4604	7.9	116	826,686	2.52	0.56	0.01
2012	26	9665	16.5	79	545,908	0.82	1.77	0.01
2013	8	1293	2.2	38	121,542	2.94	1.06	0.03
2014	4	185	0.3	3	43,500	1.62	0.43	0.01
2015	30	22,014	37.7	41	705,418	0.19	3.12	0.01
2016	18	5758	9.9	2	472,169	0.03	1.22	0.00
2017	8	129	0.2	0	60,296	0.00	0.21	0.00
2018	10	1381	2.4	108	73,300	7.82	1.88	0.15
2019	3	311	0.5	7	35,150	2.25	0.88	0.02
2020	39	6031	10.3	112	564,869	1.86	1.07	0.02
2021	22	1867	3.2	34	920,113	1.82	0.20	0.00
2022	25	5188	8.9	56	406,173	1.08	1.28	0.01
Total	247	58,426	100.0	596	4,775,124	1.02	1.22	0.01

Table 2 Spatial distribution of FMD outbreaks in zones of export sourcing areas (2011–2022)

Region	Export sourcing Zone	Outbreak	Cumulative (%)	case	Death	PAR	Case fatality rate (%)	Morbidity rate (%)	Mortality Rate (%)
Oromia	Arsi	80	32.4	14,843	84	1,623,427	0.57	0.91	0.01
	Bale	8	3.2	568	10	93,320	1.76	0.61	0.01
	Borana	67	27.1	35,934	368	1,124,456	1.02	3.20	0.03
	East Shoa	21	8.5	2600	27	822,207	1.04	0.32	0.00
	Guji	27	10.9	1113	39	714,738	3.50	0.16	0.01
	West Arsi	8	3.2	191	2	40,679	1.05	0.47	0.00
SNNPR	Gedeo	1	0.4	1	0	72,000	0.00	0.00	0.00
	Sidama	26	10.5	1675	10	216,967	0.60	0.76	0.00
Somali	Afder	1	0.4	82	32	6090	39.02	1.35	0.53
	Dawa	4	1.6	106	16	36,810	15.09	0.29	0.04
	Liban	4	1.6	1313	8	24,430	0.61	5.37	0.03
Total		247	100.0	58,426	596	4,775,124	1.02	1.22	0.01

ranges from 1 to 6 in some outbreak areas in the same year.

Temporal distribution of FMD outbreaks in export-sourcing areas

Throughout the study period, the peak number of FMD outbreaks was in January, having 46 outbreaks (mean = 4.6), followed by December which had 38 outbreaks (Mean = 6.3). The months with the fewest reported outbreaks were April, May, June and July with occurrences of 12, 8, 7, and 4 outbreaks, respectively. The monthly index of the number of outbreaks was demonstrated in Fig. 1.

The number of FMD outbreaks was above average from October to December, while it was below average from March to August. The outbreaks showed a seasonal pattern, with fewer incidences occurring from June to August and a higher frequency from October to February. This pattern is typical for export-sourcing areas. The monthly distribution of the cumulative outbreak varied throughout the year, as shown in Fig. 2. The occurrence of FMD outbreaks over time is not random. The annual outbreak trend line shows that 2011, 2012, 2015, 2016, 2019, 2020, 2021, and 2022 had a significantly above-average trend line. An analysis of the trend component reveals that FMD outbreaks tend to follow a cycle of two to five years, with notable peaks occurring in 2011, 2012, 2015, and 2021 (Fig. 3).

The decomposed FMD outbreak occurrence pattern shows a slight increase in the number of monthly outbreaks (Fig. 2). The seasonal pattern of FMD outbreaks is clearly illustrated in Fig. 3. The occurrence of these outbreaks tends to be high at the end of the rainy season (June to August) in highlands and continues through the dry season. Notably, there is a greater frequency of FMD outbreaks during the dry season compared to the wet season.

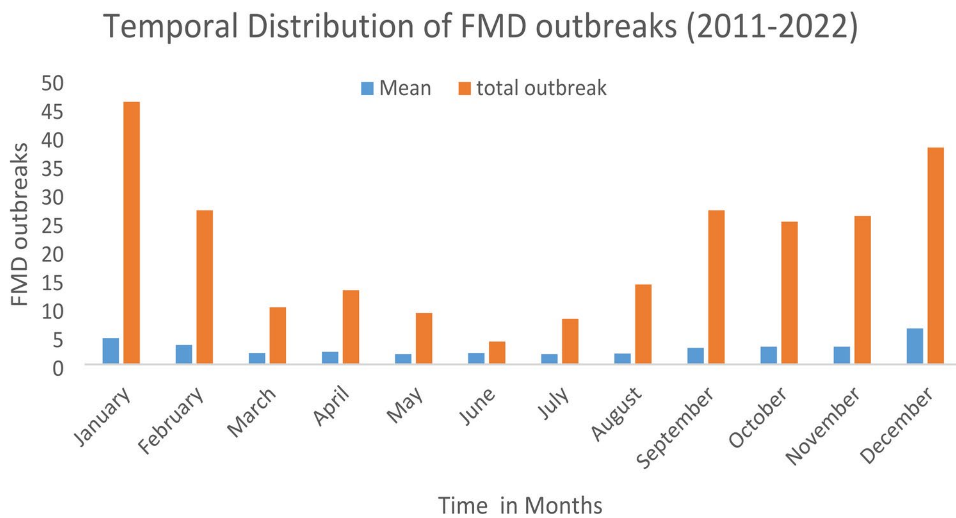


Fig. 1 Monthly distribution of FMD outbreaks in export-sourcing areas (2011–2022)

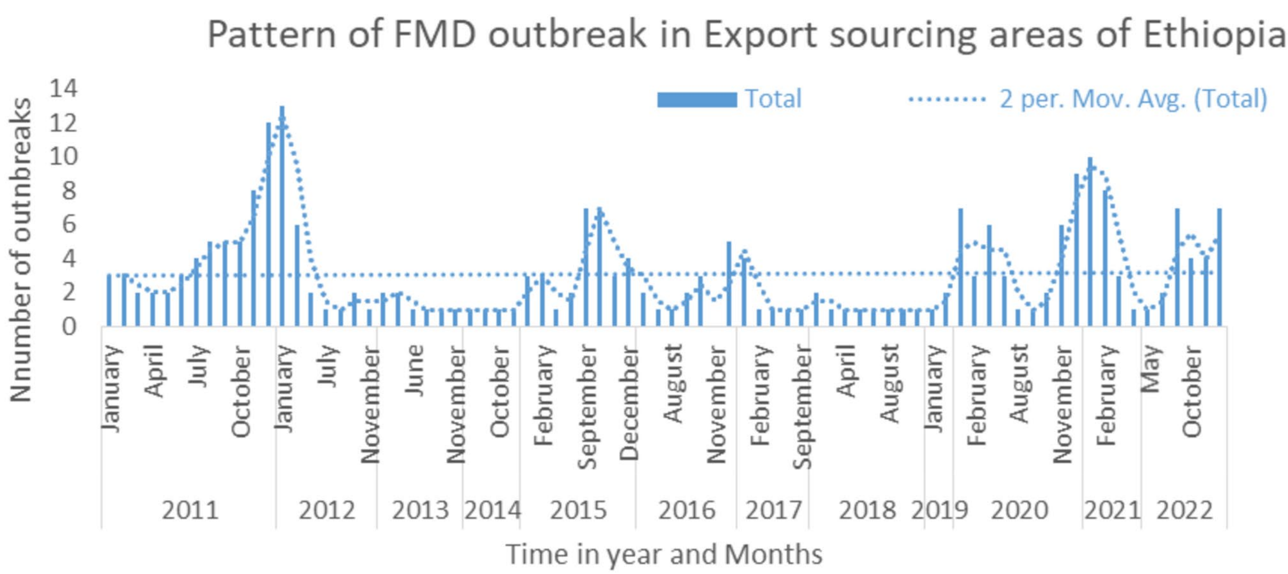


Fig. 2 Monthly FMD outbreak trends and moving average from 2011 to 2022 in export sourcing areas of southeastern Ethiopia

Space-time cluster analysis of FMD outbreak from 2011 to 2022 in export sourcing areas

Analysis of spatial and temporal dependencies revealed 9 significant clusters during the study period (Table 3). This spatial and temporal cluster analysis identifies regions and time frames with higher FMD outbreaks than what would have occurred by chance. Five most likely clusters were observed in export-sourcing areas having a minimum radius of 1.21 and a maximum radius of 238.23 km while four secondary clusters were also described in (Table 3). Five primary clusters and four secondary clusters are illustrated in Fig. 4 below. Combined locations are represented by a single location where disease cases concentrate in specific geographic regions and time intervals. Temporal cluster analysis in Fig. 5 below showed that the red line indicates a significant increase in FMD outbreaks over 12 years, surpassing the expected frequency based on historical data.

Discussion

This retrospective study reported the spatial and temporal distribution of FMD outbreaks in export-sourcing areas of southeastern Ethiopia from January 2011 to December 2022. The findings indicated that FMD outbreaks did not occur randomly; rather, they exhibited distinct spatial and temporal patterns. Our study identified a high frequency of FMD outbreaks in export-sourcing regions of southeastern Ethiopia, particularly in the Arsi highland areas and Borana zones, which are predominantly pastoral. These two areas reported the highest number of outbreaks, with 80 in Arsi and 67 in Borana. The high incidence of FMD outbreaks in the

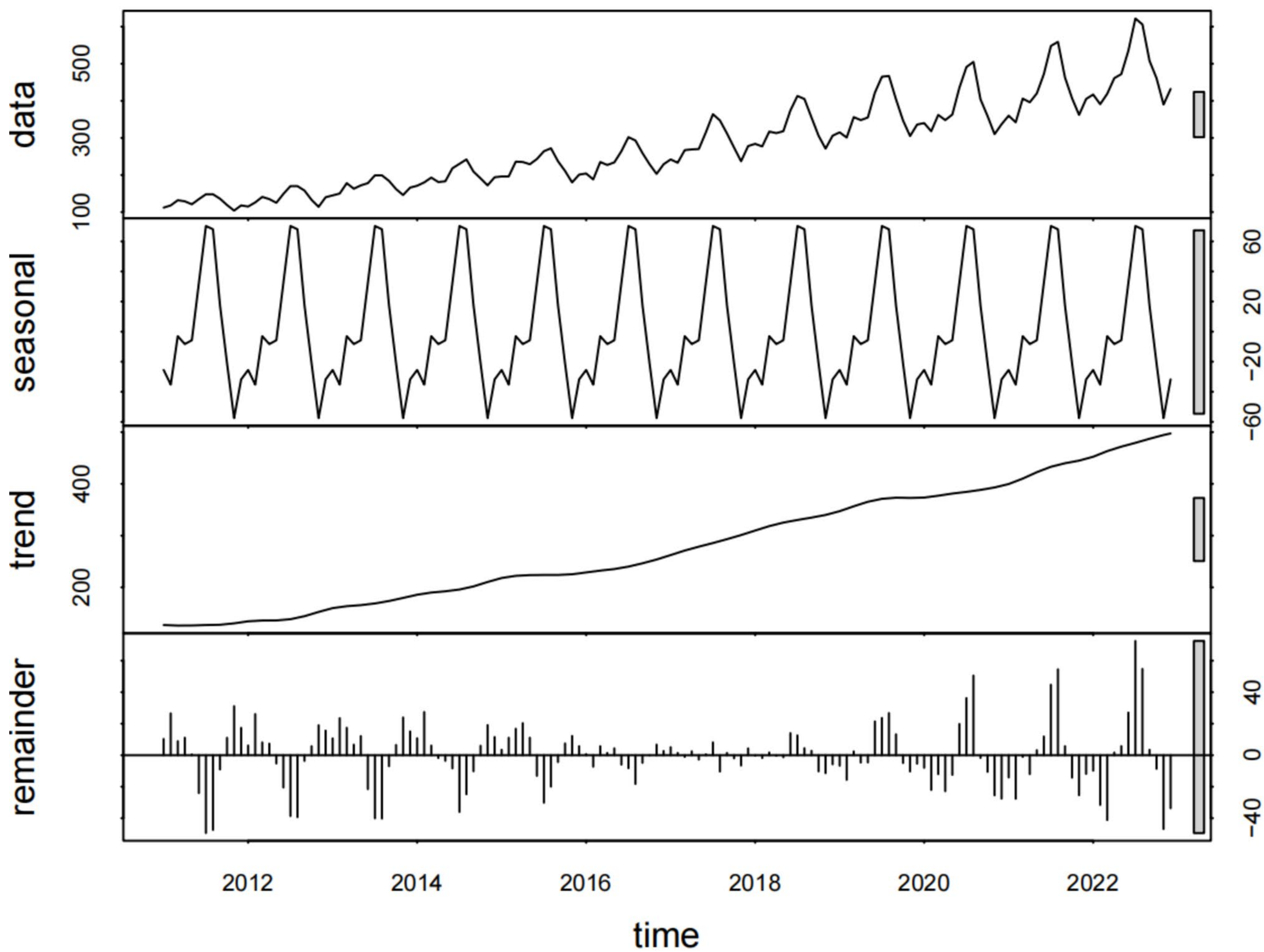


Fig. 3 Decomposed time series of the observed temporal pattern of FMD outbreaks from 2011 to 2022 into three components: seasonality, trend, and remainder

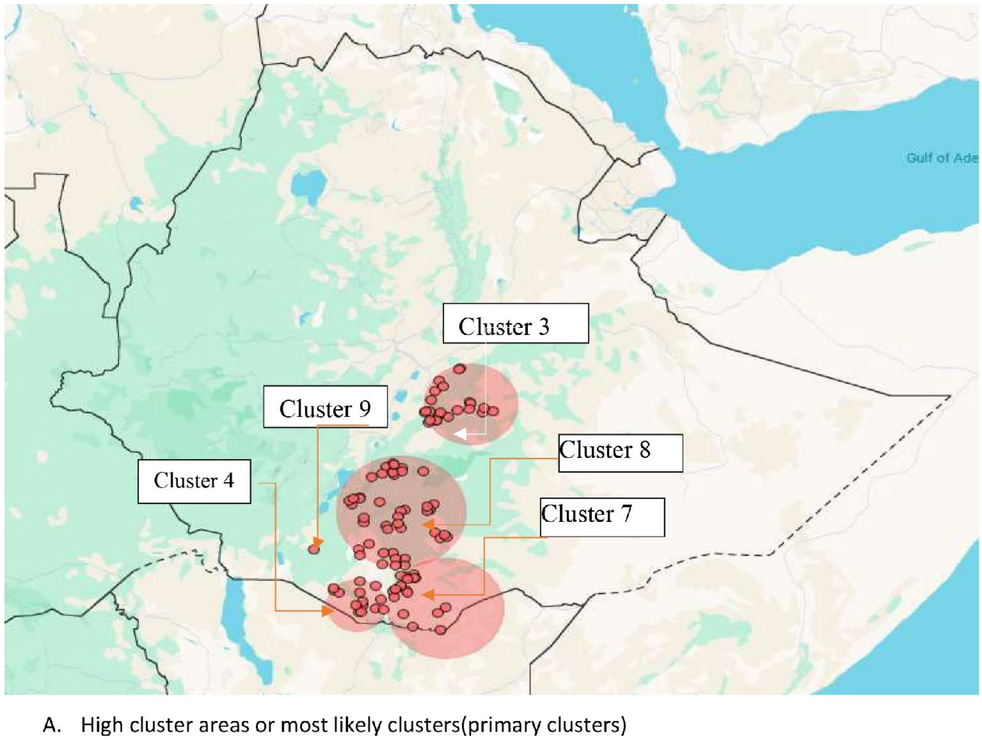
Table 3 Space-Time clusters of FMD outbreak identified using SaTScan analysis

Cluster	Type	Radius (km)	Location	Time frame	Observed	Expected	RR/LLR	*P*-value
Cluster 1	SC	238.23 km	7.702200 N, 39.799860 E	2015/1/1 to 2020/12/31	186	9269.7	0.0	0.001
Cluster 2	SC	113.66 km	3.471610 N, 39.502030 E	2011/1/1 to 2014/12/31	0	5637.0	0.0	0.001
Cluster 3	MLC	129.65 km	7.832120 N, 40.004340 E	2011/1/1 to 2012/12/31	8257	2147.5	3.9	0.001
Cluster 4	MLC	103.59 km	3.951260 N, 38.100540 E	2019/1/1 to 2020/12/31	2815	345.9	8.1	0.001
Cluster 5	SC	1.21 km	3.738040 N, 38.573740 E	2017/1/1 to 2020/12/31	0	2760.4	0.0	0.001
Cluster 6	SC	126.91 km	4.195730 N, 37.815240 E	2013/1/1 to 2016/12/31	7	2186.8	0.0	0.001
Cluster 7	MLC	138.01 km	3.897780 N, 39.586290 E	2017/1/1 to 2020/12/31	1947	280.1	7.0	0.001
Cluster 8	MLC	218.98 km	5.762300 N, 38.841820 E	2011/1/1 to 2014/12/31	3766	1275.4	3.0	0.001
Cluster 9	MLC	0	5.033960 N, 37.395367 E	2013/1/1 to 2014/12/31	500	12.7	39.5	0.001

MLC (Most Likely Cluster), SC (Secondary Cluster), Radius (distance between the center of the cluster and its borders)

Location (Geographic coordinates of the center of the cluster). RR (Relative risk inside the cluster, compared to the rest of the study area), LLR (Log likelihood ratio)

Arsi and Borana Zones varied by geographical location; whereas Arsi is in the highland, Borana is pastoral and lowland. The higher FMD outbreaks in Arsi, as observed in our study, align with a prior report indicating that a higher prevalence of FMD in central Ethiopia [16], where Arsi, is situated, serves as a location that verifies this trend. High FMD occurrence is associated with the dry season extending from October to March. The dry season might be considered the ideal time for the occurrence of an FMD outbreak in pastoral [18]. High numbers of livestock are mixing at water points, grazing areas, and markets, which increases the occurrence of FMD [19]. Overall, there were 247 FMD outbreaks documented during the study period. During this period, an average



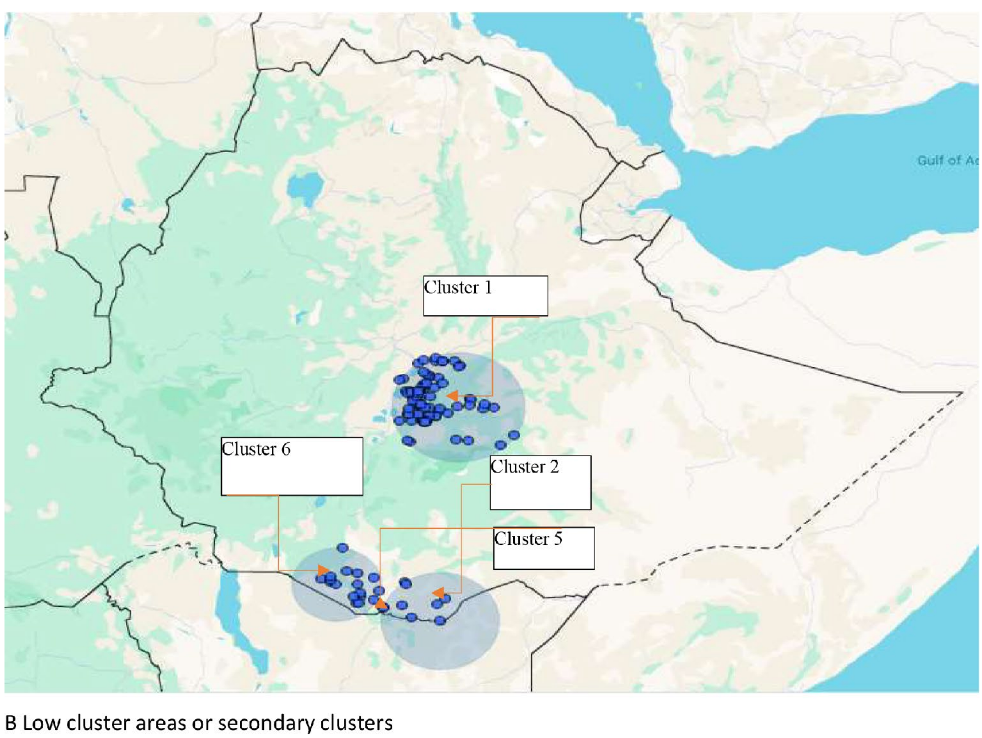


Fig. 4 Map showing Space-Time clusters of FMD outbreaks identified using SaTScan analysis. **A**: High cluster areas and **B**: Low Cluster areas

of 20.3 outbreaks of FMD were reported annually from cattle export sourcing areas. The highest number of outbreaks occurred in 2011, with 54 cases, while the lowest was in 2019, with only 3 occurrences. Our study identified cyclical, seasonal, and long-term trends in FMD outbreaks within these export-sourcing areas, which is consistent with findings from Lina et al. [15]. In contrast to our study, a low report of 4.5 outbreaks per year was documented in the west Hararghe zone, Ethiopia [20].

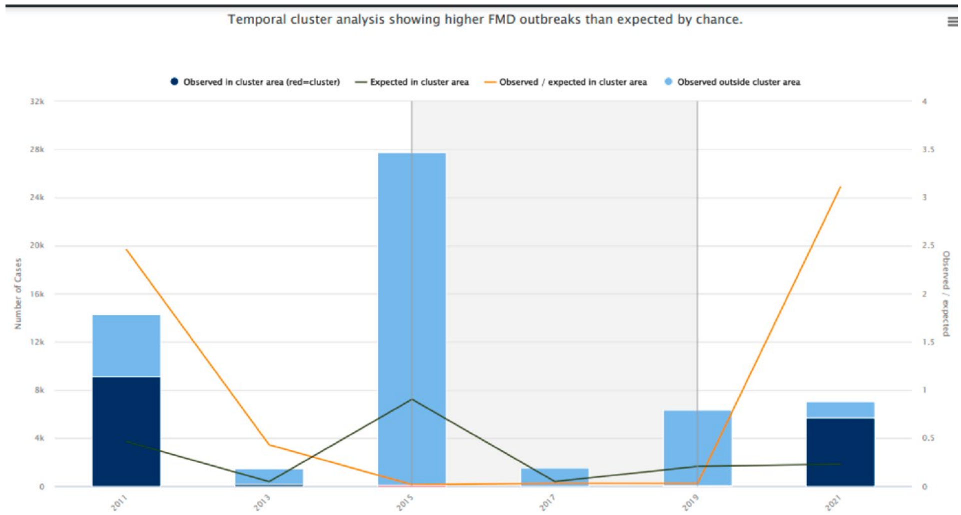


Fig. 5 Temporal cluster analysis showing higher FMD outbreaks than expected by chance

Outbreaks of FMD exhibit a distinct seasonal pattern, with variations in the timing of the epidemics throughout the year. The peak periods for FMD outbreaks occurred in October, November, and January, while lower in June, July, and August, correspond, respectively, to the dry and wet seasons in export-sourcing areas. A similar study of the seasonality of FMD outbreaks was reported from the Amhara Region [21] and the West Hararghe zone [20] Study in Kenya from passive report data indicated seasonal variation in FMD outbreaks [22]. The seasonality of an FMD outbreak may result from the introduction, transmission, and dynamics of the at-risk population, including environmental factors that influence the virus's survival [23, 24]. Factors such as religious festivals and cultural practices may influence the seasonal mobility of livestock in export-sourcing areas [16, 21]. The circulation of the FMD virus across cattle markets, densely populated cities, and slaughterhouses showed an epidemiological linkage [23, 25, 26]. Many studies have shown that temporal trends of outbreak clusters and hotspot detection reveal hidden causes of excess disease incidence, which contributes to its endemicity [15, 16, 21].

Our study revealed that pastoral areas such as Afder, Liban, and Dawa zones had fewer FMD outbreaks. This variation could impact the accurate understanding of disease patterns due to the common underreporting in pastoral settings. Disease notification through passive surveillance systems in pastoral areas is infrequently done. This was supported by a report by Woldmariam et al. [16], which indicated that report levels did not exceed 40% in pastoral areas, especially in remote regions. A study in Cambodia demonstrated a connection between spatial accessibility and reporting especially in remote areas [27]. Abattoirs and feedlots for livestock export are primarily located in the East Shoa zone of our study areas, which may contribute to FMD outbreaks due to significant cattle movements for slaughter. Many researchers have reported that FMD outbreaks are associated with regions where livestock markets are located or near areas of high human consumption, as indicated by their proximity to abattoirs and densely populated cities [15, 21, 23]. FMD is endemic in Ethiopia and reported throughout the year from all regions [28].

The study identified a primary cluster of outbreaks in export-sourcing areas. Through spatial and temporal cluster analysis, nine clusters were identified, along with periods that experienced higher-than-expected FMD outbreaks. The scanning window with the highest value of the likelihood ratio test statistic was defined, and secondary clusters with significant test statistic values were also reported from January 1, 2011, to December 31, 2022, involving 230 locations and 58,426 cases.

Cluster analysis showed 9 cluster periods with six high clusters and three low clusters. The high clusters were (2011/01/01 to 2014/12/31, 2019/01/01 to 2020/12/31, 2017/01/01 to 2020/12/31, 2011/01/01 to 2014/12/31, and 2013/01/01 to 2014/12/31). These most likely clusters showed different temporal span sizes (129.65 km, 103.59 km, 138.01 km, 218.98 km and 0 km) for clusters 3, 4, 7, 8, and 9, respectively. In our study, cluster 9 had a log-likelihood ratio (LLR) of 39.53, with clusters 4, 7, 3, and 8 having LLR of 8.14, 6.95, 3.85, and 2.95, respectively.

The analysis revealed several low clusters spanning different periods: Cluster 1 (from January 1, 2015, to December 31, 2020), Cluster 2 (from January 1, 2011 to December 31, 2014), Cluster 5 (from January 1, 2017 to December 31, 2020), and Cluster 6 (from January 1, 2013 to December 31, 2016). Among these, Cluster 1 exhibited the largest area coverage at 238.23 km^2, followed by Cluster 6 at 126.91 km^2 and Cluster 2 at 113.66 km^2. In contrast, the smallest cluster was Cluster 5, measuring just 1.21 km^2. The largest cluster covered the Arsi zone which had the most FMD outbreaks in our study. Woldemariyam and colleagues [17] similarly found seven clusters of FMD outbreaks in their studies in the central highlands of Ethiopia.

Most of these outbreaks were not confirmed using laboratory tests. The report focused on cattle; other species such as sheep, goats, and wildlife affected by FMD were not captured in the monthly report. Cross-border movements of animals are significant for FMD circulation, particularly along the border between Kenya and Somalia, where our study areas, (Boran, Dawa, Liban, and Afder zones), reported FMD outbreaks. There was a relatively low number of outbreak reports coming from the pastoral areas in our study, which has a vague situation there.

Conclusion

The spatial and temporal distribution of FMD outbreaks in our study showed that FMD is an important disease in the cattle export-sourcing areas of southeastern Ethiopia. Timely information on the spread of cases in space and time can facilitate action to be taken. Early detection and immediate responses to active investigations and surveillance have paramount importance for FMD control. The temporal distribution in the export-sourcing areas revealed higher FMD incidences from October to February, with lower incidences occurring from June to August. There will be a need to enhance surveillance systems by expanding coverage and utilizing cutting-edge technologies, which facilitate real-time reporting, early detection and response. The existing national FMD prevention and control strategies in export sourcing areas should be revised with the current situation.

Methods

Study area

This study was conducted in export-sourcing regions in the southeastern part of the country. These areas primarily include areas identified in the national FMD control strategy, as illustrated in Fig. 6 below [17]. The areas encompass Borana, Guji, Bale, East Shoa, West Arsi, Arsi, Liban, Dawa and Afder, Sidama and Gedeo Zone. Each district in these zones is mandated to report FMD outbreaks to either regional veterinary laboratories or the Ministry of Agriculture monthly [17]. These monthly reports of the district in the country for the period of study time were obtained from the Ministry of Agriculture. These national data contain information on the number of cases, animal species (cattle, goats, and sheep), estimated outbreaks, and geographical locations. Seasons were defined as follows: the rainy season occurs from June to August in highland areas; the short rainy season lasts from October to November in pastoral (Borana, Guji, Liban, Afder and east Bale areas), and the dry season spans from December to March. Most cases were diagnosed based on clinical observations made by local animal health professionals, while some were confirmed through laboratory tests conducted at the Animal Health Institute.

Study design

This study was retrospective, where FMD data were collected from previous outbreak reports spanning 12 years (January 2011 to December 2022). The data were analyzed for the spatiotemporal patterns of FMD outbreaks, identifying long-term, cyclical, and seasonal trends.

Data collection

The information extracted from the FMD outbreak report contained variables like the district location, species affected, index date, number of cases, number of outbreaks, number of deaths, number of animals vaccinated, number of animals treated, and number of animals at risk. An outbreak is defined as one or more cattle, sheep, or goats exhibiting signs of FMD in a district and reported to the Ministry of Agriculture or regional veterinary laboratories. Consequently, the incidence of FMD outbreaks was assessed at both the zonal and district levels using data spanning 12 years, from January 2011 to December 2022. Given the socioeconomic status of cattle and less susceptibility of sheep and goats, FMD in cattle was of primary interest.

Data analysis

The FMD outbreak report data were organized based on importance and validity. Long-term trends, seasonality, and irregularities were examined by decomposing the FMD outbreak time series. To assess the seasonality of FMD outbreaks, 12-month moving averages were estimated and plotted using the outbreak numbers over the 12-year study period. The moving averages helped to minimize random fluctuations and more effectively identify underlying trends. A randomness test was conducted to verify the pattern of monthly FMD outbreak occurrences in the study area [29].

The morbidity rate was calculated by dividing the number of reported FMD cases in each district during an outbreak by the total population of susceptible cattle at risk. The mortality rate was calculated by dividing the total number of deaths from FMD in each district during a specific outbreak by the total number of susceptible cattle reported in that period, which represents the population at risk. The case fatality rate was calculated as the total number of reported deaths from FMD in each district during a specific outbreak, divided by the total

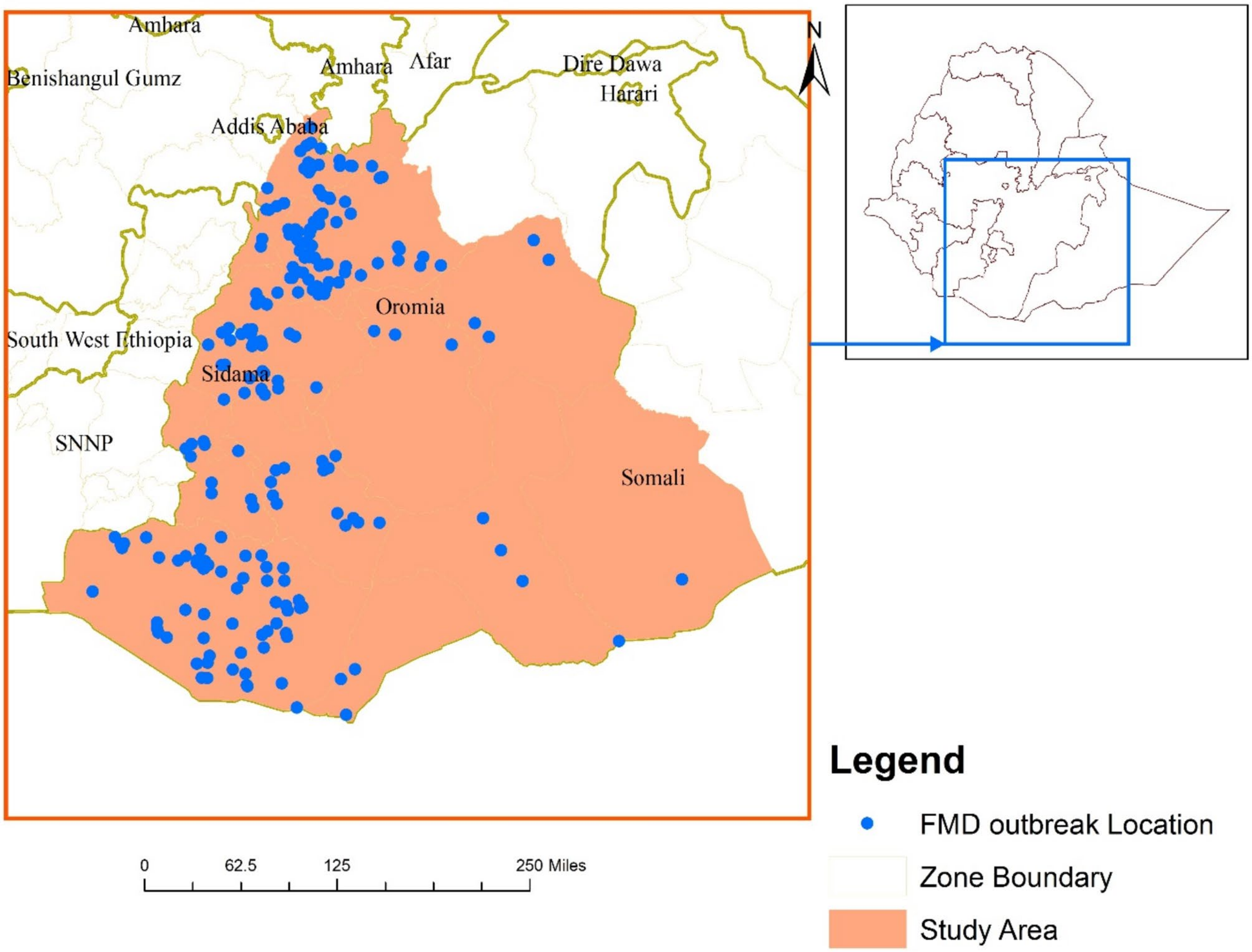


Fig. 6 Map of cattle export sourcing areas of southeastern Ethiopia

number of reported cattle cases in the population at risk during that period.

The clustering of FMD outbreaks in export-sourcing areas was evaluated through a retrospective space-time analysis that scanned for clusters with high/low rates using SaTScan version 10.2.5 (https://www.satscan.org/) assessed on 20/12/24 [30, 31]. The maximum spatial cluster size was set to be 50% of the outbreaks, and the maximum temporal cluster size was set to be 50% of the study period of 12 years from (2011/1/1 to 2022/12/31). The observed/expected cases were calculated in the circular window, which is movable across each centroid of locations, assuming they are randomly distributed in space. The clusters were identified by dividing the observed cases in the outbreak by the population-at-risk as expected cases, assuming no clustering of the null hypothesis. The optimal temporal aggregate period was set as 3 years. The likelihood ratio's sampling distribution was assessed using a Monte Carlo test with 999 repetitions. A spatial coordinate system was utilized for geo-referencing the cases based on the available outbreak events. A p-value of less than 0.05 was considered statistically significant to reject the null hypothesis, which stated that the cases were randomly distributed in space [30]. The relative risk (RR) compared risk inside and outside these areas [32].

Abbreviations

FMD	Foot and mouth disease
TAD	Transboundary Animal Disease
SAT	South African Territories
Km	Kilometer
SNNPR	South Nation, Nationalities and People Regional State
No	Number
AHI	Animal Health Institute
PAR	Population at risk
SC	Secondary cluster
MLC	Most likely cluster
LLR	Log likelihood ratio
RR	Relative risk

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Author contributions
DG: Contributed to the conception of the research idea, data analysis and interpretation of data, writing, and editing of the manuscript. TK, HA and ML: Contributed to the conception of the research idea, designing, interpretation of data, and editing of the manuscript. GB: Contributed to interpretation of data, editing or reviewing of the manuscript. All authors read and approved the final manuscript.

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Data availability
The datasets used and analysed during the current study are available from the corresponding author on request.

Declarations

Ethics and consent to participate
Not applicable.

Consent for publication
The consent for publication is not applicable.

Competing interests
The authors declare no competing interests.

Author details
[1]Animal Health Institute (AHI), Sebeta, Ethiopia
[2]Ministry of Agriculture, Addis Ababa, Ethiopia
[3]Aklilu Lemma Institute of Health Research, Center for Pathobiology Research, Addis Ababa University, Addis Ababa, Ethiopia

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References

1. Knowles N, Samuel A. Molecular epidemiology of foot-and-mouth disease virus. Virus Res. 2003;91(1):65–80.
2. OIE/FAO. The global foot-and-mouth-disease control strategy: strengthening animal health systems through improved control of major diseases [Internet]. FAO ISBN 9. 2012. 253 p. Available from: http://www.fao.org/docrep/015/an390e/an390e.pdf
3. Rweyemamu M, Maree F, Kasanga C, Scott K, Opperman P, Chitray M et al. Challenges and prospects for the control of foot-and-mouth disease: an African perspective. Vet Med Res Rep. 2014;119.
4. Mashinagu MM, Wambura PN, King DP, Paton DJ, Maree F, Kimera SI, et al. Challenges of controlling Foot-and-Mouth disease in pastoral settings in Africa. Transbound Emerg Dis. 2024;2024:1–14.
5. Li K, Wang C, Yang F, Cao W, Zhu Z, Zheng H. Virus-Host interactions in Foot-and-Mouth disease virus infection. Front Immunol. 2021;12(February):1–18.
6. Firestone SM, Hayama Y, Bradhurst R, Yamamoto T, Tsutsui T, Stevenson MA. Reconstructing foot-and-mouth disease outbreaks: a methods comparison of transmission network models. Sci Rep [Internet]. 2019;9(1):1–12. Available from: https://doi.org/10.1038/s41598-019-41103-6
7. Stenfeldt C, Arzt J. The carrier conundrum; a review of recent advances and persistent gaps regarding the carrier state of foot-and-mouth disease virus. Pathogens. 2020;9(3).
8. Paton DJ, Sumption KJ, Charleston B. Options for control of foot-and-mouth disease: knowledge, capability and policy. Philos Trans R Soc B Biol Sci. 2009;364(1530):2657–67.
9. Lycett S, Tanya VN, Hall M, King DP, Mazeri S, Mioulet V, et al. The evolution and phylodynamics of serotype A and SAT2 foot-and-mouth disease viruses in endemic regions of Africa. Sci Rep. 2019;9(1):1–11.
10. Gizaw D, Tesfaye Y, Wood BA, Di Nardo A, Shegu D, Muluneh A et al. Molecular characterization of foot-and-mouth disease viruses circulating in Ethiopia between 2008 and 2019. Transbound Emerg Dis [Internet]. 2020;67(6):2983–92. Available from: https://onlinelibrary.wiley.com/doi/https://doi.org/10.1111/tbed.13675
11. Ayelet G, Mahapatra M, Gelaye E, Egziabher BG, Rufeal T, Sahle M et al. Genetic characterization of foot-and-mouth disease viruses, Ethiopia, 1981–2007. Emerg Infect Dis [Internet]. 2009;15(9):1409–17. Available from: http://wwwnc.cdc.gov/eid/article/15/9/09-0091_article.htm
12. Abdela N. Sero-prevalence, risk factors and distribution of foot and mouth disease in Ethiopia. Acta Trop [Internet]. 2017;169:125–32. Available from: https://doi.org/10.1016/j.actatropica.2017.02.017
13. Wudu TJ. Bioeconomic Modelling of Foot and Mouth Disease and Its Control in Ethiopia. Wageningen: Wageningen University PhD thesis. 2016.
14. Di Nardo A, Knowles NJ, Paton DJ. Combining livestock trade patterns with phylogenetics to help understand the spread of foot and mouth disease in sub-Saharan Africa, the middle East and Southeast Asia. OIE Rev Sci Tech. 2011;30(1):63–85.
15. Lina, Porphyre T, Muhanguzi D, Muwonge A, Boden L, Bronsvoort BM. d. C. A scoping review of foot-and-mouth disease risk, based on Spatial and spatio-temporal analysis of outbreaks in endemic settings. Transbound Emerg Dis. 2022;69(6):3198–215.
16. Woldemariyam FT, Leta S, Assefa Z, Tekeba E, Gebrewold DS, Paeshuyse J. Temporal and Spatial patterns and a Space–Time cluster analysis of Foot-and-Mouth disease outbreaks in Ethiopia from 2010 to 2019. Viruses. 2022.
17. MOA. Ministry of Agriculture National FMD control plan, Addis Ababa Ethiopia. 2017.
18. Jemberu WT, Mourits MCM, Hogeveen H. Farmers' Intentions to Implement Foot and Mouth Disease Control Measures in Ethiopia. Parida S, editor. PLoS One [Internet]. 2015;10(9):e0138363. Available from: https://doi.org/10.1371/journal.pone.0138363
19. Woldemariyam FT, Kariuki CK, Kamau J, De Vleeschauwer A, De Clercq K, Lefebvre DJ, et al. Epidemiological dynamics of Foot-and-Mouth disease in the Horn of Africa: the role of virus diversity and animal movement. Viruses. 2023;15(4):1–18.
20. Bekere HY, Ahmed R, Anne AA, Bristy FF, Kumar S. Spatial and Temporal distribution of foot and mouth disease (FMD) outbreaks. Am J Pure Appl Biosci. 2023;5(2):28–44.
21. Aman E, Molla W, Gebreegizabher Z, Jemberu WT. Spatial and Temporal distribution of foot and mouth disease outbreaks in Amhara region of Ethiopia in the period 1999 to 2016. BMC Vet Res. 2020.
22. Dn M, Pm K. Epidemiological analysis of passive surveillance data on foot and mouth disease occurrence in Nakuru. 2017;6(3):298–300.
23. Colenutt C, Brown E, Nelson N, Paton DJ, Eblé P, Dekker A, et al. Quantifying the transmission of foot-and-mouth disease virus in cattle via a contaminated environment. MBio. 2020;11(4):1–13.
24. Mumford JA. Vaccines and viral antigenic diversity. Rev Sci Tech Off Int Epiz. 2007;26(1):69–90.
25. Di Nardo A, Libeau G, Chardonnet B, Chardonnet P, Kock RA, Parekh K et al. Serological profile of foot-and-mouth disease in wildlife populations of West and Central Africa with special reference to Syncerus caffer subspecies. Vet Res [Internet]. 2015;46(1):1–16. Available from: https://doi.org/10.1186/s13567-015-0213-0
26. Jemberu WT, Mourits MCM, Sahle M, Siraw B, Vernooij JCM, Hogeveen H. Epidemiology of foot and mouth disease in Ethiopia: a retrospective analysis of district level outbreaks, 2007–2012. Transbound Emerg Dis. 2016;63(6):e246–59.
27. Young JR, Suon S, Andrews CJ, Henry LA, Windsor PA. Assessment of financial impact of foot and mouth disease on smallholder cattle farmers in Southern Cambodia. Transbound Emerg Dis. 2013;60(2):166–74.
28. Jemberu WT, Mourits M, Rushton J, Hogeveen H. Cost-benefit analysis of foot and mouth disease control in Ethiopia. Prev Vet Med [Internet]. 2016;132:67–82. Available from: https://doi.org/10.1016/j.prevetmed.2016.08.008
29. Casey-bryars M, Reeve R, Bastola U, Knowles NJ, Auty H, Bachanek-bankowska K et al. Waves of endemic foot-and-mouth disease in vaccination approaches. Nat Ecol Evol [Internet]. 2018;2(September):1449–57. Available from: https://doi.org/10.1038/s41559-018-0636-x
30. Mostashari F, Kulldorff M, Heffernan R, Hartman J, Assunc R. PLoS MEDICINE A Space-Time permutation scan statistic for disease outbreak detection. PLOS Med. 2005;2(3):e59.
31. Kulldorff M, Jacobs JH. PLoS MEDICINE A Space-Time permutation scan statistic for disease outbreak detection. PLOS Med. 2005;2(3):e59.

32. Sirdar MM, Fosgate GT, Blignaut B, Mampane LR, Rikhotso OB, Du Plessis B, et al. Spatial distribution of foot-and-mouth disease (FMD) outbreaks in South Africa (2005–2016). Trop Anim Health Prod. 2021;53(3):0–3.

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