Network analysis of pig movements in Ecuador: strengthening surveillance of classical swine fever

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Abstract

The analysis of domestic pig movements have became useful in the understanding of disease spread patterns and epidemiology, which facilitates the development of more effective animal diseases control strategies. The aim of this work was to analyse the static and spatial characteristics of the pig network, to identify its trading communities and to analyse the contribution of the network to the transmission of classical swine fever. Pig movement data were extracted from the national veterinary service database (2017-2019), using social network analysis and spatial analysis we constructed a network with registered premises as nodes and their movements as edges, and also a network of parishes as its nodes aggregating their premises movements as edges. The annual network metrics showed in average a diameter of 20.33, a number of neighbours of 2.61, a shortest path length of 4.39 and a clustering coefficient of 0.38 (small-world structure). The most frequent movements were to or from markets (57%). Backyard producers made up 89% of the network premises, and the top 2% of parishes (highest degree) contributed to 50% of the movements. The highest frequencies of movements between parishes were in the centre of the country, while the highest frequency of movements to abattoirs was in the south-west. Finally, the pattern of CSF disease outbreaks within the Ecuador network was likely the result of network transmission processes. In conclusion, our results represent the first exploratory analysis of domestic pig movements at premise and parish levels. These results could be taken into account by the surveillance system to improve its procedures and update the disease control and management policy, allowing the implementation of targeted or risk-based surveillance.

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KEYWORDS: Classical swine fever; Social network analysis; Ecuador; Spatial analysis; Surveillance system; Policy.

SUMMARY

The analysis of domestic pig movements have became useful in the understanding of disease spread patterns and epidemiology, which facilitates the development of more effective animal diseases control strategies. The aim of this work was to analyse the static and spatial characteristics of the pig network, to identify its trading communities and to analyse the contribution of the network to the transmission of classical swine fever. Pig movement data were extracted from the national veterinary service database (2017-2019), using social network analysis and spatial analysis we constructed a network with registered premises as nodes and their movements as edges, and also a network of parishes as its nodes aggregating their premises movements as edges. The annual network metrics showed in average a diameter of 20.33, a number of neighbours of 2.61, a shortest path length of 4.39 and a clustering coefficient of 0.38 (small-world structure). The most frequent movements were to or from markets (57%). Backyard producers made up 89% of the network premises, and the top 2% of parishes (highest degree) contributed to 50% of the movements. The highest frequencies of movements between parishes were in the centre of the country, while the highest frequency of movements to abattoirs was in the south-west. Finally, the pattern of CSF disease outbreaks within the Ecuador network was likely the result of network transmission processes. In conclusion, our results represent the first exploratory analysis of domestic pig movements at premise and parish levels. These results could be taken into account by the surveillance system to improve its procedures and update the disease control and management policy, allowing the implementation of targeted or risk-based surveillance.

1. INTRODUCTION

Classical swine fever (CSF) is one of the most important viral diseases affecting pig production, the disease has multiple manifestations that depend on the host and viral factors, also is highly contagious (Blome et al., 2017) (OIE, 2020). Most countries have regulatory control measures in place, although the effectiveness of these measures depends on the state of development of their veterinary services and laboratory capacities (Edwards et al., 2000). In South America, CSF is endemic in Bolivia, Guyana, Peru, Suriname and Venezuela. In Brazil, Colombia and Ecuador, the disease is still present but limited by recognised OIE free zones (OIE-WAHIS, 2021).

Pig movements are linked to the national and international spread of pig (*Sus scrofa*) pathogens (VanderWaal and Deen, 2018) (Beltran-Alcrudo et al., 2019). Indeed, they represent one of the most important pathways for disease spread between premises (Nöremark et al., 2011) (Fritzemeier, 2000) (Moon et al., 2019), their link with CSF outbreaks has been documented in Colombia (Pineda et al., 2020), Germany (Fritzemeier, 2000), Spain (Allepuz et al., 2007), and the Netherlands (Elber et al., 1999). A better comprehension of pig movement network may improve the mitigation strategies used to reduce the risk of disease spread (Moon et al., 2019).

Relations have been previously analysed between the movement of live animals and the introduction of swine diseases to Ecuador: CSF from Peru (neighbouring country) (Garrido Haro et al., 2018) and porcine epidemic diarrhoea from Chile and the US (Barrera et al., 2017). However, the internal livestock movement registry was historically focused mainly in cattle, for the control of foot and mouth disease.

In 2016, the compulsory vaccination campaign against CSF started, along with individual identification of animals by official ear tags, stricter mobilisation regulations and a web-based control system (Acosta et al., 2019).

A contact network or graph is a set of nodes and connecting edges representing complex systems, such as animal movements (Dubé et al., 2009) (Newman, 2010). Indeed, the description of livestock movement patterns provides essential information to understanding the observed distribution of infectious diseases (Crescio et al., 2020). Detection of trade communities has proven useful in identifying clusters of premises with a high frequency of interactions, which can be targeted at intervention strategies or prioritized by surveillance systems (Gorsich et al., 2016).

To implement prevention and control programs, network analysis can help explain some of the epidemiological patterns underlying the spread of diseases (Salathé and Jones, 2010) (Tillett, 1992), it can also contribute to implement more efficient disease monitoring and control strategies (Knific et al., 2020) (Cannon, 2009). For example: in Argentina, the network structure of movements provided information to build cost-effective surveillance (Baron et al., 2020); In Brazil, a network-based risk index was created to prioritise the surveillance actions at the municipality level (Cespedes et al., 2021); In Peru, network analysis was used to quantify the risk of CSF associated with movements from districts that had recently experienced outbreaks (Gomez-Vazquez et al., 2019). However, in other low-income Andean countries, such as Venezuela, Colombia, Ecuador and Bolivia, information and analysis on livestock movements remains limited (Todaro and Smith, 2009).

The pig sector in Ecuador is an important source of protein (ASPE, 2016) linked to a strong cultural heritage and traditional cuisine (Procel, 2019). Mainly in backyard premises, pigs are used by producers for self-consuption and also for profit selling them on markets (Lowenstein et al., 2016).

In this paper, we present the first exploratory network analysis of the pig trade network at premise and parish levels, using the official trade data (2017–2019) and Social network analysis (SNA). The aim of this paper was to explore the characteristics of the pig network, detect network communities, unravel the spatial structure of movements and analyse the contribution of the network to CSF transmission.

2. MATERIALS AND METHODS

We obtained population and pig movement data from the Veterinary Service from 2017 to 2019 (*www.guia.agrocalidad.gob.ec*). The cadastral and movement data were registered by producers, accessing individual accounts in the official system. Producers required a registry of their farm, and their pigs identified by official ear tags applied when vaccinated against CSF. The categories of pigs were piglets <30 days, barrows and gilts of 31–250 days, and boars and sows >250 days. The system updates the categories of pigs on a daily basis, taking into account their birth date. The cadastral dataset contained the identification of the premise and owner, number and category of animals. The movement dataset contained the movement ID, date and hour of validity (certificates have a validity of 14 hours), number of animals grouped by age and sex categories, premise and farmer ID, type of premise and administrative location (province, canton and parish) of origin and destination.

The surveillance dataset contained the CSF outbreaks in the study period (n=134), outbreak ID, date of occurrence, owner identification, farm location, farm type and number of pigs. This information was recorded in a parallel system and database, separate from the cadastral and movements (*www.sistemas.agrocalidad.gob.ec/sizse*). Map layers were obtained from the Institute of Statistics and Census of Ecuador INEC (*http://www.geoportaligm.gob.ec/*).

2.1 Descriptive analysis of movements

Swine movements in each study year were described (2017–2019), as well as their productive categories by age and sex. Then, we analysed the number of pigs and movements according to their type of premise in every year, the annual averages and the number of pigs per batch (movement) and the issuance of movement certificates directly by producers (using their individual accounts) and through the service's officials.

2.2 Seasonal activity of movements

Time series were constructed with the sum of the monthly number of active premises, movements, and animals in the study period (36 months). The absence of serial correlations was then assessed using partial autocorrelation plots. A Mann-Kendall seasonal trend test (Pohlert, 2020) was applied to determine the statistical significance of the overall (full time series) and seasonal trends (months). Pettitt's test (Pettitt, 1979) was performed to detect a single point of change in the time series.

2.3 Network characterisation

We created a contact network where premises (farms, traders, industrials, and markets) became the nodes and movements as their edges, excluding movements to abattoirs as they are dead-ends for disease transmission (Guinat et al., 2016). The network was represented by its adjacency matrix, where the number of neighbours of a node (degree), and its value was calculated directly from the adjacency matrix (A), where $A_{ij} = 1$ if there was a connection between nodes i and j; otherwise, $A_{\mathrm{ij}} = 0$ (Newman, 2010). Swine movements were represented as a directed network (networks in which the direction of movement was taken into account).

Annual and monthly networks of premises were created and computed the following metrics: betweenness, closeness, clustering coefficient, degree, density, diameter, average shortest path, and giant weakly and strongly connected components (Table 1). Then, we analysed seasonal activity in network metrics and features such as shortest path length and small-world characteristics (highly clustered networks) (Strogatz, 2001) (James et al., 2009) that may facilitate rapid disease transmission.

Table 1. Network terminology used to characterise the Ecuadorian pig movement network.

Metric	**Definition**
Betweenness	The frequency of a node is in the shortest path between others in the netwo
Closeness	Reciprocal average shortest path length between a node and all other nodes
Clustering coefficient	The proportion of neighbours who are also neighbours of another.
Degree	The number of edges attached to a node. In directed networks *in-degree* an
Density	The density of a graph is the ratio of the number of edges and the number
Diameter	The longest geodesic between any pair of nodes in the network (maximum s
Average shortest path length	Average steps to go from two randomly chosen nodes.
Giant strongly connected component (GSCC)	Subset of nodes mutually accessible to each other via a series of links, is an
Giant weakly connected component (GWCC)	Contains a strongly connected component as well as nodes that are linked i

2.4 Community detection

Communities are sets of nodes (modules) that are densely interconnected compared to other nodes in the network, sharing common properties. This definition leads to a function called modularity, used to describe the quality of the partitions and the modular structure of the network. We computed the optimal partition from the network of premises summarised by parishes using the simulated annealing (SA) algorithm (Grisi-Filho et al., 2013) based on LinkRank (Kim et al., 2010) derived from Google's PageRank (Page and Brin, 1998).

2.5 Spatial movement analysis

In this analysis, we constructed networks of premises and abattoirs summarised by parish and then computed the Euclidean distance of the movements (Karney, 2013) based on parish centroids (1,032 polygons). Afterwards, we plotted the spatial movements on annual maps, representing the source and target by a vector between parish centroids and the direction of movement by an arrow, and added the frequency of movements by colours: $<$100 green, 101–500 blue and $>$500 red. From the network of premises, we summarise the total incoming and outgoing movements and calculate their balance to detect the most influential parishes, plotting the result on the map, looking for the areas with higher risk of disease spread.

Using network metrics and spatial movements, we plotted images and converted them into annual animations using six frames for every month, showing the monthly status of the centrality network metrics. The video sections contains A: representation of weighted origin/destiny movements on the map, vectors are plotted according with movement weights, parishes coloured by monthly In/Out/balance degree. B: Ingoing-outgoing mobilised pigs (parishes codes). C: percentage of accumulated active nodes. D: monthly movement weights. E: Active edges. Videos are available in the supporting information.

2.6 Epidemiological relevance of the network

To analyse the causality of the direct pathway transmission, we used the k-test, comparing the observed connectivity between cases with the expected distribution of the k-statistic, which is the average number of observed cases, occurring within one step of an infected case in the network (k=1) (VanderWaal et al., 2016) . We assessed whether it was possible that the pattern of observed disease outbreaks (cases) could be the result of network transmission, thus evaluating its *epidemiological relevance* . We used a network of premises specifying the status of their nodes (not infected=0, infected=1) for every year and the cumulative period. We then compared the observed k-statistic with its permuted distribution, where case locations are randomly reassigned within the network through 1,000 iterations.

Cleaning of the datasets was performed to homogenize premises classification, and remove inconsistencies, also match outbreaks with movements between databases. We computed all analyses using R V.3.6.3 (*https://cran.r-project.org/*) and software gephi v0.9.2 (*https://gephi.org/*).

3. RESULTS

3.1 Descriptive analysis of pig movements in Ecuador

The Ecuadorian pig chain is organised into two production structures: traditional producers (farms, traders, and markets) and industrial producers (industrial). Premises are classified as farms: traditional producers, mainly backyards (subsistence); traders: individuals who buy/sell animals on the same day and/or groups of animals for one or two days, transporting and selling them to final destinations such as abattoirs, markets and farms; industrials: industrial pork producing companies; markets: licenced facilities where live pig are marketed (Ecuador's Official Record, 2016). Live animal markets represent vestiges of indigenous tradition, marketing and culture, acting mainly in the highland Andean region (Benitez and Sanchez, 2001).

The dataset contained 9,904,714 pigs involved in 1,190,991 movements, geographically distributed in 945 (92%) of the 1,032 Ecuadorian parishes. The movement dataset contained domestic movements and included 721 imported animals from Chile, Canada and the United States (for breeding purposes from industrial farms). The number of movements analysed averaged 396,997 per year. In the study period, there was an increase in the number of movements, pigs and premises of 53.23%, 32.38% and 51.32%, respectively. Considering the categories of premises, there was an increase of 53% farms, 46% traders, 4% abattoirs, 8% industrial markets, and 15% markets. Pig producers used their individual web accounts to issue 94.72% of the movement certificates in the study period, compared to 9.43% in 2015.

The annual average proportion between premises types was from farms to markets (26.66%), followed by farms to abattoirs (23.33%). The less frequent were from industrial to markets (0.17%) and between markets (0.28%). Markets as origins or destinations accounted for 55.37% of the movements (Table 2). Only 5% of the premises had geographical coordinates, using instead the centroid of their parish, the median distance of the movements was 11 km. The number of movements for each study year is available in SI1.

Table 2. Average number of movements and animals by origin, destination and distance grouped by type of premises in Ecuador (2017-2019).

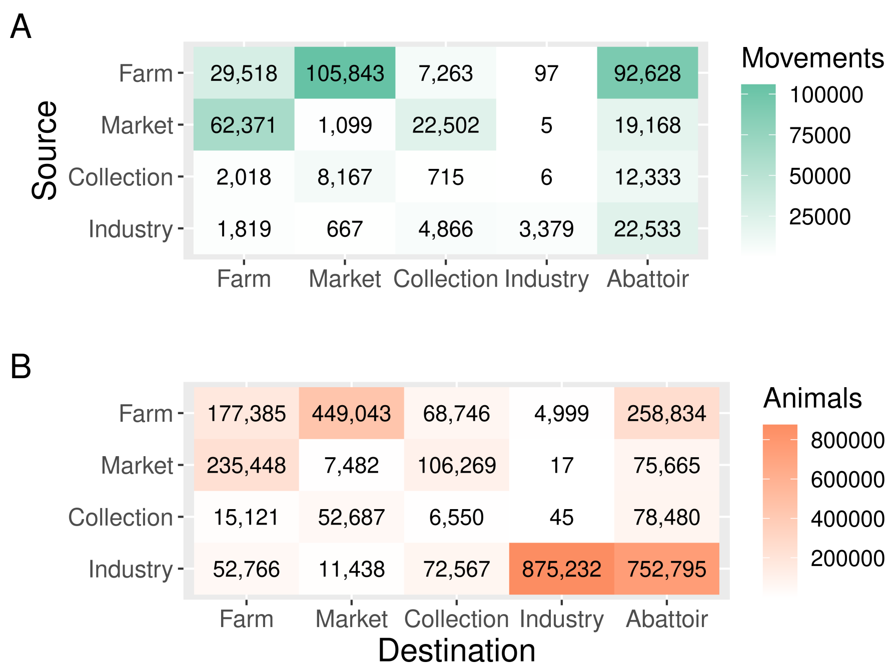
Type of premise	Number of movements Annual Average	Number of movements Proportion (%)	Number of animals Annual Average	Number of animals Proportion (%)	Distance (km)+ Median (Q1–Q3)++	Distance (km)+ Max
From farm to:	From farm to:	From farm to:	From farm to:	From farm to:	From farm to:	From farm to:
Trader	7,263	1.83	68,746	2.08	55 (19–123)	541
Abattoir	92,628	23.33	258,834	7.84	0 (0–15)	598

Market	105,843	26.66	449,043	13.6	11 (0–26)	478
Industry	97	0	4,999	0.15	17 (0–58)	493
Farm	29,518	7.44	177,385	5.37	13 (0–42)	564
From industry to:	From industry to:	From industry to:	From industry to:	From industry to:	From industry to:	From industry to:
Trader	4,866	1.23	72,567	2.2	68 (28–107)	424
Abattoir	22,533	5.68	752,795	22.8	26 (0–72)	441
Market	667	0.17	11,438	0.35	127 (43–135)	399
Industry	3,379	0.85	875,232	26.5	27 (0–68)	440
Farm	1,819	0.46	52,766	1.6	47 (22–78)	517
From market to:	From market to:	From market to:	From market to:	From market to:	From market to:	From market to:
Trader	22,502	5.67	106,269	3.22	14 (0–37)	514
Abattoir	19,168	4.83	75,665	2.29	13 (0–36)	417
Market	1,099	0.28	7,482	0.23	39 (24–49)	287
Industry	5	0	17	0	49 (49–58)	258
Farm	62,371	15.71	235,448	7.13	13 (0–28)	468
From trader to:	From trader to:	From trader to:	From trader to:	From trader to:	From trader to:	From trader to:
Trader	715	0.18	6,550	0.2	48 (11–121)	456
Abattoir	12,333	3.11	78,480	2.38	0 (0–15)	405
Market	8,167	2.06	52,687	1.6	13 (0–27)	417
Industry	6	0	45	0	79 (40–143)	412
Farm	2,018	0.51	15,121	0.46	16 (0–47)	465
Total	396,997	100	3,301,569	100	11(0–28) §	597
+The distance was calculated using the centroids of the corresponding parish. ++Q1: first quartile. Q3: third quartile. § 0 corresponds to movements within the same parish.	+The distance was calculated using the centroids of the corresponding parish. ++Q1: first quartile. Q3: third quartile. § 0 corresponds to movements within the same parish.	+The distance was calculated using the centroids of the corresponding parish. ++Q1: first quartile. Q3: third quartile. § 0 corresponds to movements within the same parish.	+The distance was calculated using the centroids of the corresponding parish. ++Q1: first quartile. Q3: third quartile. § 0 corresponds to movements within the same parish.	+The distance was calculated using the centroids of the corresponding parish. ++Q1: first quartile. Q3: third quartile. § 0 corresponds to movements within the same parish.	+The distance was calculated using the centroids of the corresponding parish. ++Q1: first quartile. Q3: third quartile. § 0 corresponds to movements within the same parish.	+The distance was calculated using the centroids of the corresponding parish. ++Q1: first quartile. Q3: third quartile. § 0 corresponds to movements within the same parish.

The average annual number of pigs moved, grouped by age and sex categories were 71,606 (2.03%) sows, 26,606 (0.76%) boars, 1.37 million gilts (38.70%), 1.60 million barrows (45.37%), 258,290 male piglets (7.31%) and 206,223 female piglets (5.83%), the average considered only 2018 and 2019.

The number of movements (110,932) in Figure 1A is related to the number of animals (474,116) in Fig. 1B. In contrast, when analysing the industrial premises, the relation is inverted, and few movements (3,379) in Fig. 1A account for the higher number of animals (875,232) in Fig. 1B. The number of animals transported by the industrials, which averages 51.99 pigs per movement, clearly explains this observation, which contrasts with an average of 5.94 pigs in the other type of premises.

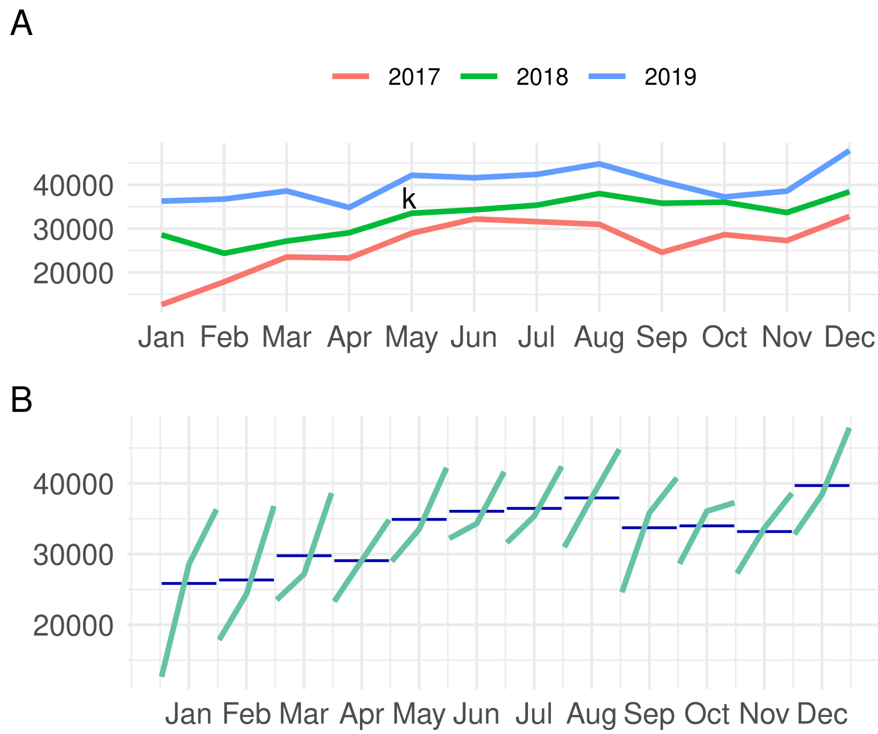
Figure 1. Number of movements (A) and number of animals (B) between types of premises in Ecuador, expressed as the average of the three-year study period (2017–2019).



3.2 Seasonal activity of movements on the network

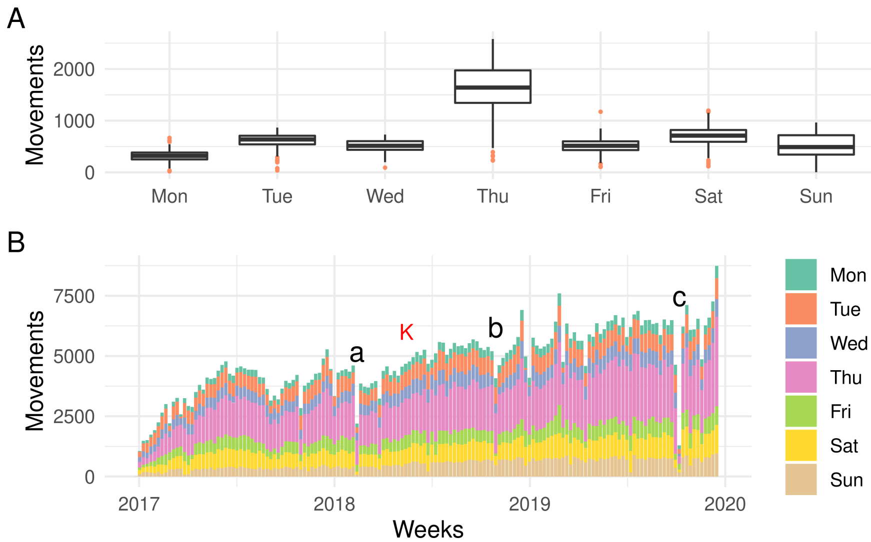
The average number of monthly movements was 26,212 (2017), 32,872 (2018), and 40,165 (2019). According to the Mann-Kendall seasonal test, the overall time series of the monthly number of movements increased over time ($p<0.001$). There was also a shift in the central trend, detected by a change point (k) (Pettit's test), which corresponded to May 2018 ($k=17$, $p<0.001$) (Fig. 2A) (SI 2). The monthly average seasonal activity of the movements was highest from May to August and December and less frequent from January to April and from September to November (Fig. 2B).

Figure 2. Seasonal plots of movements in the Ecuadorian pig network. (A) Monthly number of movements in separate years, shift in central tendency (k). (B) Graph of the subseries as a separate mini time series; the blue line represents the mean of the observations within each season (month).



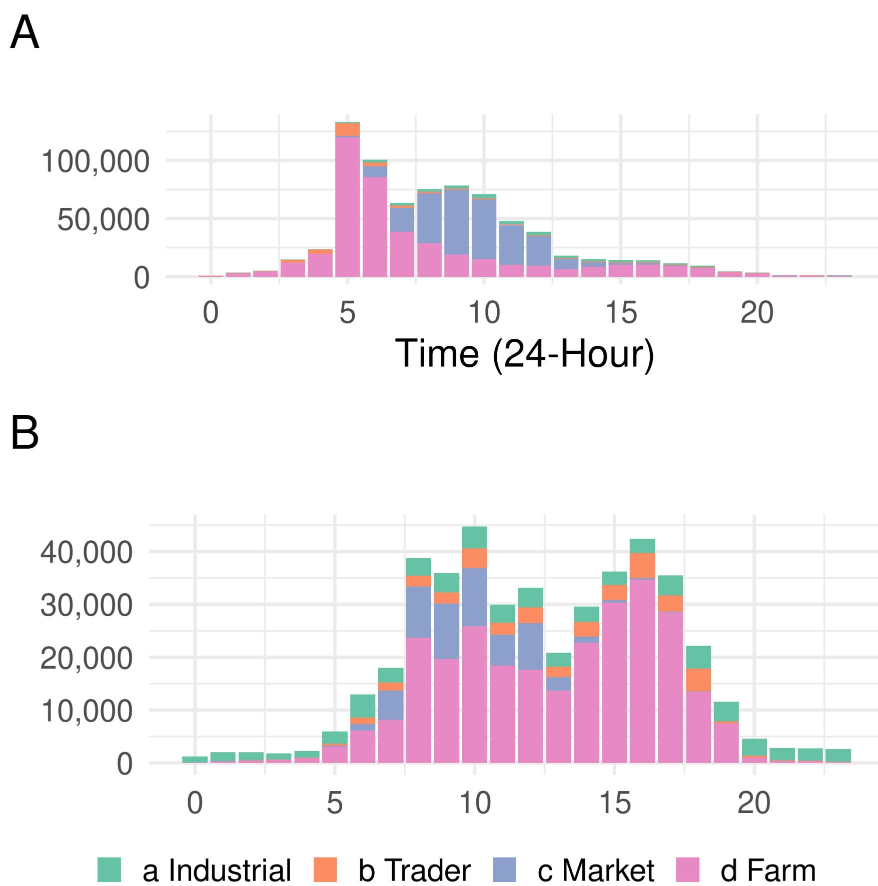
The average number of daily pig movements was 682, with Thursdays being 2.44 times higher than the average, related to preparation for the higher demand over the weekends and the higher activity of markets (Fig. 3A). In Fig. 3B, we plot the frequency of movements by week. Furthermore, over the years, the mean number of weekly movements grew from 3,599 in 2017 to 5,973 in 2019, which is supported by an increasing trend over time (S=144, $p<0.01$ Mann-Kendall test) and the detection of a change point ($p=<0.001$) on week 73 corresponding to May 2018 (K on Fig. 3B), related to the adoption of stricter vaccination and movement policy. Cultural and political influence affected the network, identified by weekly reductions from the average of movements; -53.8% due to the celebration of Carnival holiday (a in Fig 3B), 14% due to a extended national holiday (b in Fig 3B) and 73% due to road blockades during a national strike led by indigenous groups (c in Fig. 3B).

Figure 3. Representation of pig movements in different time aggregations. (A) Box plots of the number of movements grouped by day of the week. (B) Movements grouped by week and filled by days of the week; Pettit's change point (k) at week 72, and highest reductions in the weekly movements marked with letters a (carnival holiday), b (extended holiday) and c (national strike).



Most of the movements from farms and traders start early (05H00); subsequently, a large part of them originate from markets (09H00 to 14H00) (Fig. 4A). On average, the time of the day with the highest movement activity was 07H30 for traders, 07H37 for markets, 10H54 for industrials and 07H40 for farms, which also had a second peak of activity at approximately 16H00, related to afternoon movements to traders that intermediate the next day's early mobilisations to markets and abattoirs (Fig. 4B). The average time to abattoirs by type of producer was 13H06 for traders, 09H48 for markets and 12H30 for industrials and farms (Fig. 4B).

Figure 4. Description of the number of pig movements and the occurring time, grouped by type of origin premises in Ecuador (2017–2019). (A) Destination to other premises. (B) Destination to abattoirs.



3.3. Network Characterisation

Excluding movements to abattoirs, the dataset comprised 751,003 movements. The annual average networks had 76,205 nodes and 250,334 edges. Table 3 summarises the results obtained from the exploratory network characterisation of the static networks. The annual and monthly networks were highly clustered, and their metrics were stronger in the annual networks (0.38) than in the monthly networks (0.15). The network diameter (maximum shortest path length) was 20.33 steps in the annual networks and 17.47 steps for monthly networks, meaning that a maximum of 20 steps in the annual network separated any two premises. The average number of neighbours was similar in the annual (2.61) and monthly (2.19) networks, meaning that each node in the network was connected on average to 2.6 other nodes. The shortest path length ranged from 4.29–4.47, meaning that it took approximately 4 steps to go between two randomly chosen nodes in the annual networks and between 3 and 6 steps in the monthly networks.

In the annual networks, the GWCC contained 98.49% of the active premises, meaning that trade connections reached almost all nodes. The GSCC in the annual networks contained 17.62% of the active premises and 10.17% in the monthly networks; in this subset of nodes, there was a direct path between all pairs of nodes, forming the backbone of the network and ensuring its overall connectivity.

Table 3. Summary of global metrics of the annual and monthly pig movement networks in Ecuador (2017–2019).

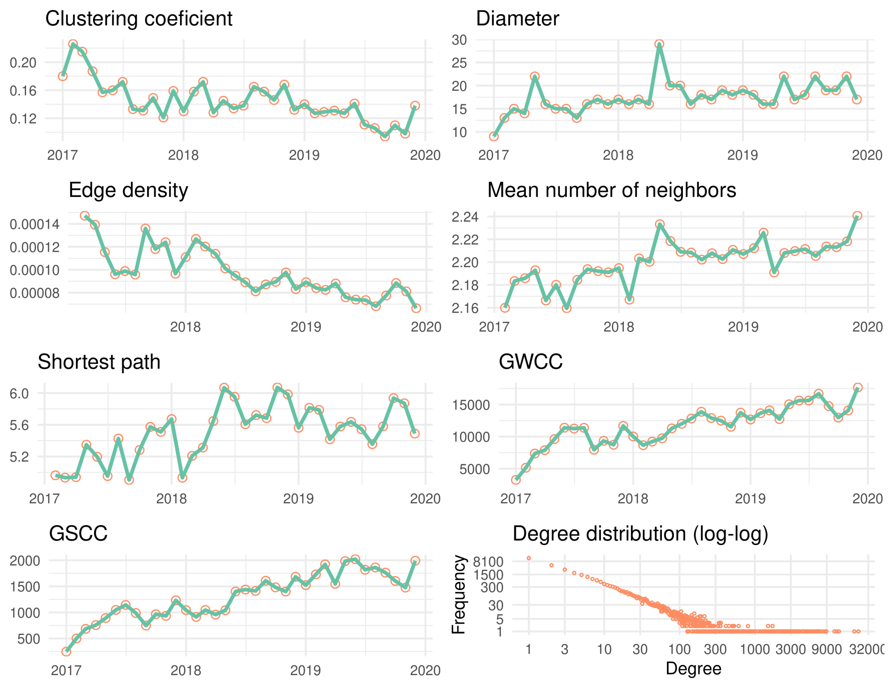
Metric	**Yearly Networks** Mean [Min-Max]	**Yearly Networks** Mean [Min-Max]	**Monthly Networks** Mean [Min-Max]	**Monthly Networks** Mean [Min-Max]

Active premises (nodes)	76,205.66	[59,689–93,707]	1,2457.03	[3,861–18,420]
Movements (edges)	250,334.33	[187,149–314,385]	20,861.19	[6,390–31,176]
Degree	6.53	[6.271–6.71]	3.35	[3.19–3.47]
Betweenness	81,947.53	[57,260.56–106,570.83]	12,578.41	[1,057.94–21,024.99]
Closeness	3.55 e-10	[2.1 e-10–5.3 e-10]	1.32 e-08	[4.7 e-09–8.0 e-08]
Clustering coefficient	0.3766	[0.34–0.44]	0.1448	[0.094–0.226]
Diameter	20.33	[19–21]	17.47	[9–29]
Edge density	1.98 e-05	[1.6 e-05–2.4 e-05]	1.06 e-04	[6.6e-05–2.9e-04]
Mean number of neighbours	2.61	[2.54–2.65]	2.19	[2.09–2.24]
Average path length	4.39	[4.29–4.47]	5.45	[3.57–6.07]
Size of GSCC (%)	13,673.33 (17.6%)	[9,076–18,387]	1,299.92 (10.2%)	[247–2021]
Size of GWCC (%)	75,061.66 (98.5%)	[58,745–92,284]	11,631.36 (93.0%)	[3,247–17,659]

The average path length and clustering coefficient were 4.39 and 0.37 respectively, showing characteristics of a small-world structure. The monthly network size grew steadily over the study period, reaching its maximum value in the last study month (December 2019) with 31,176 nodes and 18,420 edges. The analysis of the global time series for network metrics using the trend test increased significantly over time ($p<0.001$) for betweenness, diameter, mean number of neighbours, shortest paths, and giant weakly and strongly connected components; on the other hand, we found a significant decreasing tendency ($p<0.001$) for closeness, clustering coefficient and edge density (Fig. 5).

Visualizing the Ecuadorian network metrics videos (Supporting information) help to understand the network dynamics for each study year (2017-2019), along with the spatial distribution of movements.

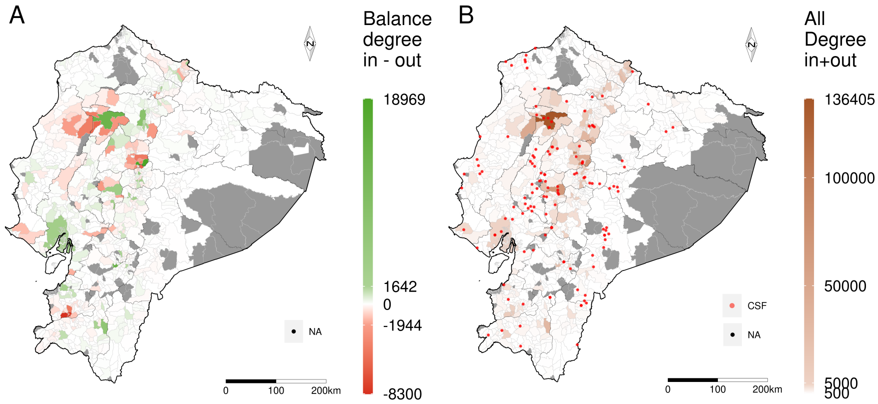
Figure 5. Temporal distribution of monthly networks metrics characterising the 2017–2019 pig movements in Ecuador.



When analysing individual seasons (months) with the Mann-Kendall trend test, there were no significant differences in the monthly trends, but there were significant shifts ($p<0.001$) in the central trend, corresponding to April 2018 ($k=16$) for diameter, mean number of neighbours, and shortest path according to Pettit's test (Fig. 5).

Three parishes shared the highest value of in-degree and out-degree centrality (Santo Domingo, Saquisili and Guaranda). The 21 most influential parishes (top 2% degree) accounted for 53.73% of the movements in Ecuador. The parishes with the highest balance (Marcabeli, Balsas, San Andres and Puerto Limon) accounted for -47.44% (SI 3). It is possible to visualise the parishes of Marcabeli and Balsas in the south-western part of the country near the Peru border with a balance of -8,300 (Fig. 6A). Parishes without pig movements in gray are especially visible in 18 parishes concentrated in the Amazon rainforest (east on map), and 77 are distributed in the other regions of the country. The degree on a colour scale showed the highest value in Santo Domingo parish at the western centre of the country. The distribution of cases of CSF all around the country represents the endemic situation well; note that the higher degree concentration is also related to high concentration of cases, especially in the Andean zone (strip from north to south) Fig. 6B.

Figure 6. Map representing the study area showing the degree and cases of CSF in Ecuador (2017–2019). The gray polygonal lines are the boundaries of the parishes, the darker gray the boundaries of provinces. (A) Representing the parish balance between the ingoing and outgoing movements. (B) Representing the aggregated parish degree and the red dots representing the location of CSF outbreaks. The network of parishes contains 1,032 vertices (parishes) and 751,003 edges (movements). Parishes without movements as NA.



3.4 Community detection.

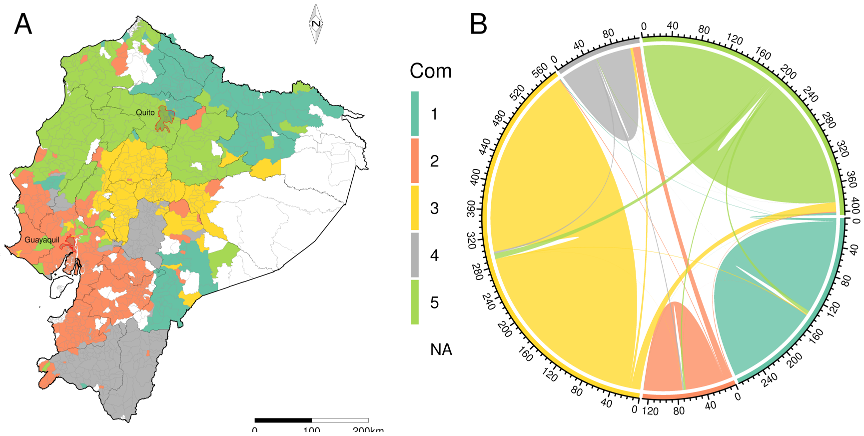
We identified 5 trading communities with a modularity value of 0.338. A strong community structure is usually in the range of 0.3–0.7 (Newman and Girvan, 2004); a high proportion (92.29%) of intra-community movements and a lower proportion (7.71%) of intercommunity ones, represented as the few connecting lines between communities coloured in the circular plot (Table 4, Fig. 7B).

Table 4. Number of trade connections within and between trade communities in Ecuador (2017–2019).

ID	**N parishes**
C 3	164
C 5	184
C 1	182
C 2	237
C 4	178
InC +	
Total	1032
+ (InC) Inter-community movements represented in Fig. 7B	+ (InC) Inter-community movements represented in Fig. 7B

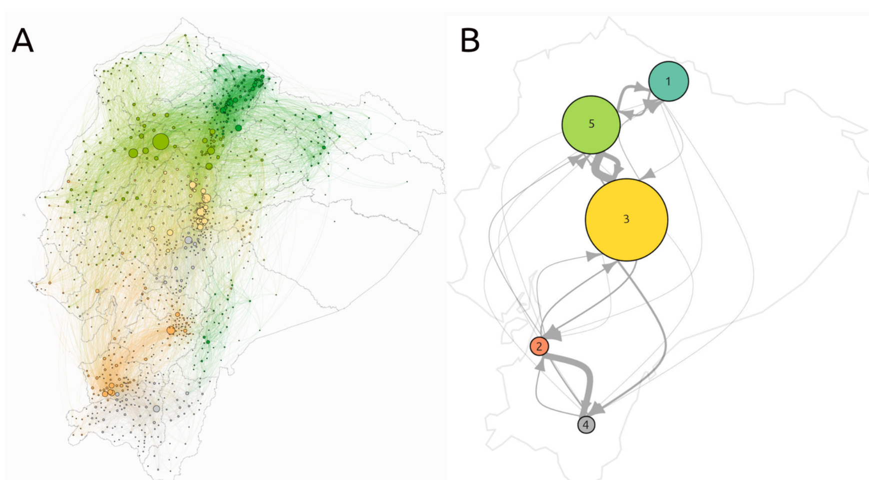
Community 3 (C3) is located in the central Andean zone, well known for its small traditional producers (backyard) with intensive transit to local markets directly or mediated by traders; important markets are located in its centre (Cotopaxi and Bolivar provinces). C5 comprises coastal and Andean areas related to medium and industrial producers, with the largest pig market in the province of Santo Domingo. C1 in the northern Andean zone on the border with Colombia showed the largest negative degree balance (-7.967) (Table 4). C2 comprises the southern Andean areas and the littoral bordering Peru. C4 as bordering Peru shows the highest positive degree balance (10,124). The main consumption centres Guayaquil and Quito (largest cities in Ecuador), are in C2 and C5, respectively (Fig. 7A).

Figure 7. (A) Map of Ecuador showing the spatial distribution of identified communities at parish level. Province boundaries in darker grey and parish in light grey. White area without movement information. Mayor consumption centres boundaries in red (main cities). (B) Circular diagram of intra and inter-community trade movement flow; the circumference represents movements between and within communities scaled in thousands of movements.



We represented in Fig. 8 the parishes (as circles) according to their degree value and community: Santo Domingo (degree 136,405), visible as the largest green circle belonging to community 5 in the northwest, and Saquisili (degree 88,093), the largest yellow circle located in the centre of the country, belonging to community 3. The province boundaries shown in Fig. 8A do not coincide with the communities. The highest intercommunity boundaries were identified from communities 3 to 5 (weight 6,700), connecting the central highlands with the northeastern coastal zone, and the second from communities 2 to 4, connecting the southern coastal zone with the southern highlands (weight 5,184), visible in Fig. 8B.

Figure 8. Representation of nodes and edges of the Ecuadorian parish network and its communities (2017–2019). (A) Movements between parish centroids, node size by aggregate degree, province boundary in gray. (B) Intra-community movement represented as node size (community degree value), edge size proportional to aggregate movements between communities, nodes located at the approximate centroid of the community.

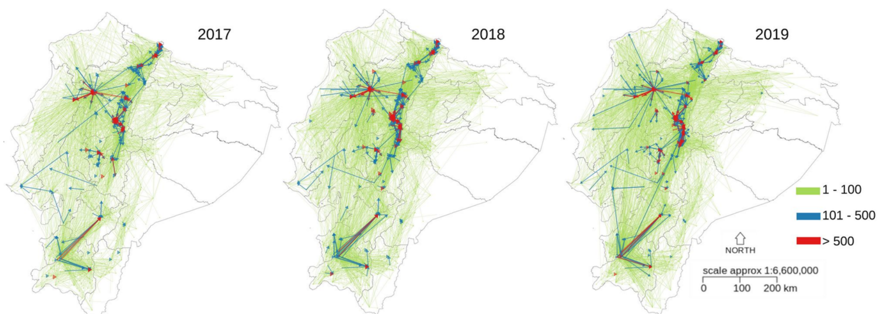


3.5 Spatial movements analysis.

3.5.1 Movements between premises.

Animals are moved in a single day across the country, highly interconnected by roads. The majority (96%) of movement frequencies aggregated by parish were between 1–100 (green arrows), 3.24% between 101–500 (blue arrows), and 0.76% > 500 (red arrows). The directed edges depicted in Figure 9 evidenced the high parish interrelationship across movements throughout the country. Movements occurred within the same parish with an average distance of 23.83 km and a maximum of 597.86 km. The median distances travelled between parishes were 13 km, between markets 39 km, and 11 km from farms to markets (Table 2). The most intense frequencies of movements (> 500) were at the centre of the country (Cotopaxi province with 31.17%), in the north near the Colombian border (Carchi with 16.39%) and in the northwest (Santo Domingo with 13.11%). Considering the number of movements, Cotopaxi concentrates 21.04% as origin and 20.29% as destination, followed by Santo Domingo with 11.79% as origin and 11.18% as destination, followed by Pichincha (SI 4) (Fig. 9).

Figure 9. Spatial representation of pig movement frequencies between parishes in Ecuador. Province boundaries on map.

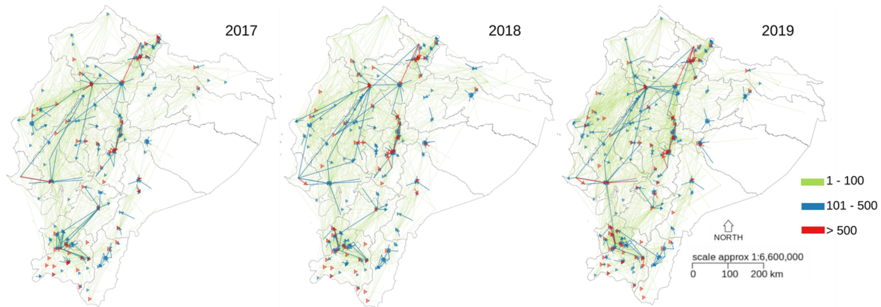


Considering the number of animals moved, Santo Domingo is the province that concentrates 38.28% as origin and 36.77% as destination; followed by Cotopaxi with 8.58% as origin and 8.20% as destination; and El Oro with 8.19% as origin and 5.55% as destination (Fig. 9) (SI 5).

3.5.2 Movements to abattoirs.

Local abattoir was the most frequent movement depicted in Fig. 10, with a frequency of annual movements greater than 500 within the same parishes; these movements are represented as red arrowheads without vectors. Inter-parish movements were more frequent in the southwestern provinces (bordering Peru) of Loja (16.45%) and El Oro (12.65%) and in the central province of Chimborazo (7.59%) in 2019 (Fig. 10). Considering the frequency of annual movements, 89.52% were between 1–100 movements (green arrows), 7.6% were between 101–500 (blue arrows), and 2% >500 (red arrows) (Fig. 10). Movements to abattoirs originated 63.15% from farms, 15.36% from industrials, 13.06% from markets, and 8.41% from traders. The largest senders of movements to abattoirs were the southwestern provinces of Loja (12.71%) and El Oro (12.07%) (SI 6). The provinces with the highest number of animals transported to abattoirs were Santo Domingo, with 29.81% as the origin and 36.77% as the destination; Cotopaxi, with 8.58% as the origin and 8.20% as the destination; and El Oro, with 8.19% as the origin and 5.55% as the destination (Fig. 10) (SI 7).

Figure 10. Spatial representation of the frequencies of pig movements to abattoirs in Ecuador between 2017 and 2019 (province boundaries on map).

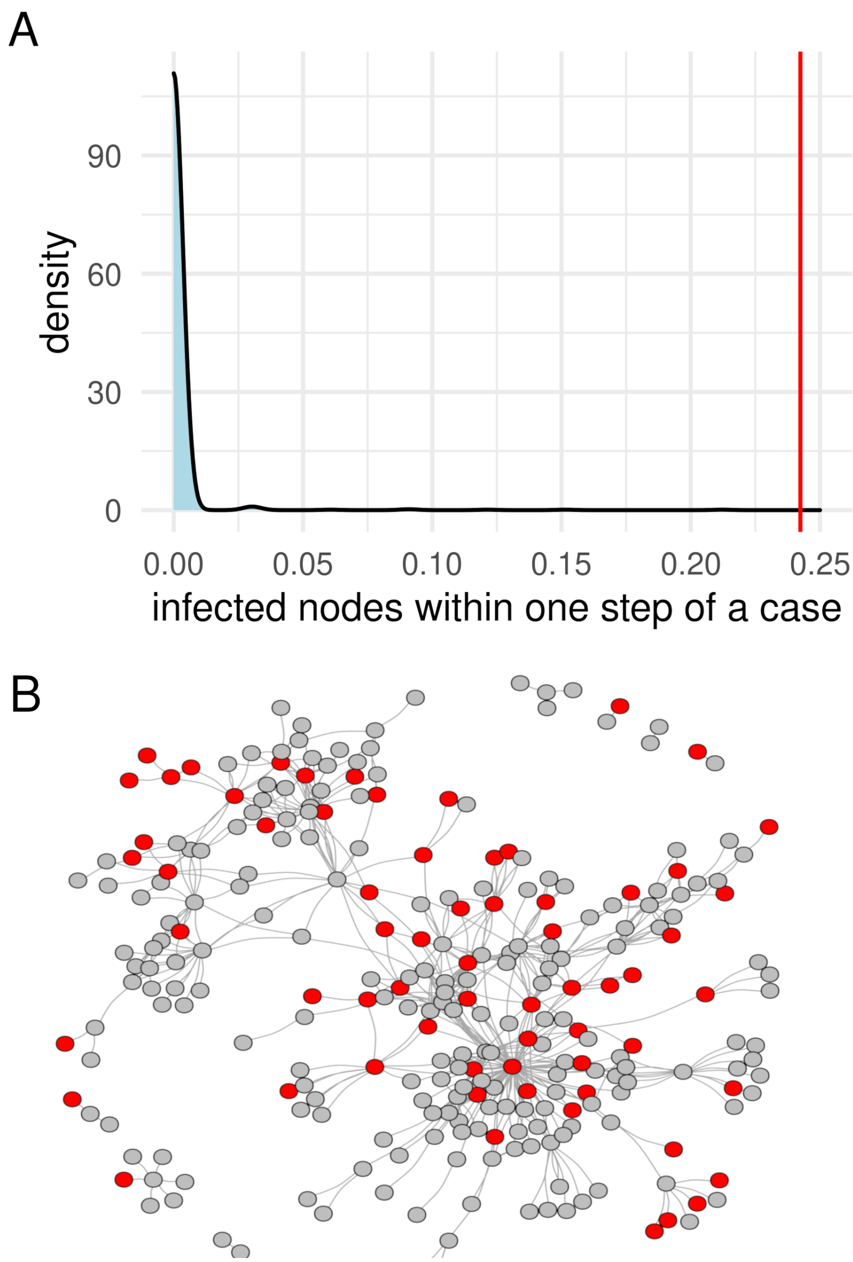


3.6 Epidemiological relevance of the network.

The recorded number of CSF outbreaks in each year was 2017 (n=39), 2018 (n=60), and 2019 (n=35). Only 75 of 134 outbreaks were identified in the network, 9 were excluded because they were movements to abattoirs, and 66 were final outbreaks with 204 immediate neighbours.

The k-test results showed that infected premises were connected to a mean of 0.246 other infected premises in the 3-year cumulative network (mean test value was 0.0013) (Fig. 11); therefore, the k-test rejected the null hypothesis that cases were strewn in the network ($p<0.001$). CSF outbreaks were connected with annual means of 0.13 ($p=0.002$) and 0.38 ($p<0.001$) positive premises in 2017 and 2018. The mean values of the permutations were 0.0027 and 0.0084 for 2017 and 2018, respectively. The year 2019 showed no significant relationships.

Figure 11. (A) K-test graphical results where the blue region under the curve represents the null distribution of the k-statistic when the location of the infected nodes was randomised on the network. The red line indicates the number of observed cases with one step of a case. (B) Representation of the CSF outbreaks (66 red nodes in the network) and limited only to their immediate neighbours for visualisation purposes (Fruchterman-Reingold layout).



4. DISCUSSION

The Ecuadorian network presents small world properties, strong community structure and a steadily growing tendency over the years, contributing to CSF transmission; these characteristics, as well as the spatial and temporal trends, could be considered by the surveillance system to improve their procedures and update the disease control and management policy, enabling the application of targeted or risk-based surveillance. These results provide a framework for future exploration, relevant to the Veterinary service and stakeholders implementing prevention and control strategies for CSF or any other infectious disease.

Although the Ecuadorian pig network is of medium size (83.000 nodes, 396,000 edges), compared to others, such as those in Slovenia (Knific et al., 2020), Germany (Lentz et al., 2016) and Italy (Crescio et al., 2020), network metrics such as graph density, diameter and small-world properties match those observed in these countries. However, compared to studies in Latin America, it is more similar to that of the state of Rio-Grande-do Sul, Brazil (11,800 nodes, 445,000 edges) (Machado et al., 2021) and larger than networks reported in Argentina (6,300 nodes, 22,000 edges) (Baron et al., 2020), Peru (500 nodes, 25,000 edges) (Gomez-Vazquez et al., 2019), and the state of Santa Catarina, Brazil (10,000 nodes, 50,000 edges) (Cespedes et al., 2021). Although each network is completely different, their size shows the importance of this sector for the Ecuadorian economy and the potential hazards for the spread of diseases across the country or even the region.

More than half of the movements (57%) originated from or were destined for markets, network analysis of cattle shares a similar proportion (53%) (Vinueza et al., 2022), apparently markets have a central influence in the organization of trade in both species, which could be related to the Andean marketing structure (Benítez and Sánchez, 2001) and the livestock population dynamics within the economy (Vernon and Keeling, 2009). This emphasises the high risk of markets as potential spreaders of any animal disease and the need to prioritise them in the prevention and control policies, further analysis could be useful to asses the risks of individual markets and the sales held (Robinson and Christley, 2007), also the possibility of monitoring strategies in this facilities.

Backyard producers constituted 89% of the premises in the network, facing major technological constraints and a lack of biosecurity practices, making them a population at higher risk of CSF infection (Martínez-López et al., 2013). Network metrics such as degree could be used to select those at higher risk and implement target surveillance. Parishes with the top degree centrality contributing with 50% of pig movements, could be prioritised by allocating more human and financial resources, focusing movement supervision on the most likely places to encounter disease (Cameron, 2012).

Higher seasonal movement activity was observed from May to August and December; the last could be related to traditional celebrations, also evidenced in Peru and related to Christmas and New-year festivities (Gomez-Vazquez et al., 2019) when pork meat dishes are highly consumed; in addition, lower seasonal movement activity was observed from January to April, and September to November, with a general behaviour that is repeated across the study years. Thus, the veterinary service could prioritise its actions, modulating their activities according to seasonal network activity rather than administrative or historic decisions.

The communities computed could be important to implement the zoning strategy considered in the Ecuadorian CSF eradication project and implemented in the zoning strategy in Colombia (Pineda et al., 2020) (ICA, 2016). The eradication strategy could be divided into steps, focusing on one community at a time, analysing the risks of infection by incoming movements (Grisi-Filho et al., 2013). The veterinary service has a preponderant role in disease management, closing borders between communities or differentiating requirements for intercommunity movements could be valid strategies, without significant effects on trade (Cardenas et al., 2019), rather than the traditional approach of managing only administrative divisions (provinces).

Some communities showed spatially disconnected parishes due to commercial activity, where producers buy piglets in distant markets and sell them at higher prices than local ones after fattening; also irregular movement schemes could be related.

The border provinces of Loja and El Oro contributed a quarter of the origin and destination of national movements to abattoirs; this proportion is higher than mass marketing centres such as Santo Domingo and Cotopaxi and the major consumption centres in Guayaquil (largest Ecuadorian city) and Quito (capital). We could attribute this result to the underestimation of production, also informal trade along the extensive borders (Terán et al., 2004).

Previous molecular findings from 2015 CSF outbreaks, showed a close relation with strains isolated in 2010 in Peru (Garrido Haro et al., 2018); moreover, the largest Peruvian pig trading community extended close to the border with Ecuador, which is reported to be of higher risk of CSF occurrence (Gomez-Vazquez et al., 2019). Further studies that take these variables into account could be necessary to assess the risk of regional disease spread in border areas.

The network of pig movements contributed to the CSF transmission process; supporting the fact that movement networks are more important than spatial proximity in the spread of CSF (VanderWaal et al., 2020), (Lee et al., 2017), (Rosendal et al., 2014). Pig farming is generally practised indoors (Rodríguez-Estévez et al., 2010), feral pigs could mediate transmission, but in Ecuador they are not commonly seen and no records are kept of them to analyse any relationship. Currently, traders and markets provide the best conditions (direct contact) for CSF transmission and should be prioritised in monitoring and control activities, without underestimation of mechanical transmission and irregular movements.

The lack of unique identification codes for premises in the outbreak database, and the lack of geographic coordinates in the premises database was a limitation in this study.

5. ACKNOWLEDGMENTS

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6. CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflict of interests.

7. REFERENCES

Acosta, A., L. Pisuna, S. Vasquez, and F. Ferreira, 2019: Space-time cluster analysis to improve classical swine fever risk-based surveillance in Ecuador. *Front. Vet. Sci.* **6** , DOI: 10.3389/conf.fvets.2019.05.00108.

Allepuz, A., J. Casal, J. Pujols, R. Jové, I. Selga, J. Porcar, and M. Domingo, 2007: Descriptive epidemiology of the outbreak of classical swine fever in Catalonia (Spain), 2001/02. *Vet Rec* **160** , 398–403, DOI: 10.1136/vr.160.12.398.

ASPE, 2016: Asociación de porcicultores del Ecuador, Swine porcine stats [Online] Available at http://www.aspe.org.ec/index.php/informacion/estadisticas/datos-porcicola-2011 (accessed August 21, 2020).

Baron, J.N., M.N. Aznar, M. Monterubbianesi, and B. Martínez-López, 2020: Application of network analysis and cluster analysis for better prevention and control of swine diseases in Argentina. *PLOS ONE***15** , e0234489, DOI: 10.1371/journal.pone.0234489.

Barrera, M., A. Garrido-Haro, M.S. Vaca, D. Granda, A. Acosta-Batallas, and L.J. Pérez, 2017: Tracking the Origin and Deciphering the Phylogenetic Relationship of Porcine Epidemic Diarrhea Virus in Ecuador.*BioMed Research International* **2017** , 1–7, DOI: 10.1155/2017/2978718.

Beltran-Alcrudo, D., J.R. Falco, E. Raizman, and K. Dietze, 2019: Transboundary spread of pig diseases: the role of international trade and travel. *BMC Veterinary Research* **15** , 64–64, DOI: 10.1186/s12917-019-1800-5.

Benitez, W., and M.D. Sanchez, 2001: Los Cerdos Locales En Los Sistemas Tradicionales de Producción, 1st edn. p. 208. *Estudio FAO produccion y sanidad animal 148* . Roma: Organización de las Naciones Unidas para la Agricultura y la Alimentación.

Benítez, W., and M.D. Sánchez, 2001: Los Cerdos Locales En Los Sistemas Tradicionales de Producción, 1st edn.*Estudio FAO produccion y sanidad animal 148* . Roma: Organización de las Naciones Unidas para la Agricultura y la Alimentación.

Blome, S., C. Staubach, J. Henke, J. Carlson, and M. Beer, 2017: Classical swine fever—an updated review. *Viruses* **9** , 1–24, DOI: 10.3390/v9040086.

Cameron, A.R., 2012: The consequences of risk-based surveillance: Developing output-based standards for surveillance to demonstrate freedom from disease. *Preventive Veterinary Medicine***105** , 280–286, DOI:

10.1016/J.PREVETMED.2012.01.009.

Cannon, R.M., 2009: Inspecting and monitoring on a restricted budget—where best to look? *Preventive Veterinary Medicine***92** , 163–174, DOI: 10.1016/j.prevetmed.2009.06.009.

Cardenas, N.C., J.O.A. Galvis, A.A. Farinati, J.H.H. Grisi-Filho, G.N. Diehl, and G. Machado, 2019: Burkholderia mallei : The dynamics of networks and disease transmission. *Transboundary and Emerging Diseases* **66** , 715–728, DOI: 10.1111/tbed.13071.

Cespedes, N., K. VanderWaal, F.P. Veloso, J.O.A. Galvis, M. Amaku, and J.H.H. Grisi-Filho, 2021: Spatio-temporal network analysis of pig trade to inform the design of risk-based disease surveillance.*Preventive Veterinary Medicine* **189** , 105314, DOI: 10.1016/j.prevetmed.2021.105314.

Crescio, M.I., G. Mastrantonio, S. Bertolini, C. Maurella, A. Adkin, F. Ingravalle, R.R.L. Simons, M. DeNardi, K. Stark, A. Estrada-Pena, and G. Ru, 2020: Using network analysis to identify seasonal patterns and key nodes for risk-based surveillance of pig diseases in Italy.*Transboundary and Emerging Diseases* **n/a** , DOI: 10.1111/tbed.13960.

Dube, C., C. Ribble, D. Kelton, and B. McNab, 2009: A Review of Network Analysis Terminology and its Application to Foot-and-Mouth Disease Modelling and Policy Development. *Transboundary and Emerging Diseases* **56** , 73–85, DOI: 10.1111/j.1865-1682.2008.01064.x.

Ecuador's Official Record Resolution 125. (2016), Reglamento zoosanitario para el funcionamiento de centros de concentracion de animales de produccion 1–8. Ecuador's Official Journal.

Edwards, S., A. Fukusho, P.-C. Lefevre, A. Lipowski, Z. Pejsak, P. Roehe, J.J. Westergaard, P.-C. Lefe Avre, A. Lipowski, Z. Pejsak, P. Roehe, and J.J. Westergaard, 2000: Classical swine fever: the global situation. *Veterinary Microbiology* **73** , 103–119, DOI: 10.1016/S0378-1135(00)00138-3.

Elber, A.R., A. Stegeman, H. Moser, H.M. Ekker, J.A. Smak, and F.H. Pluimers, 1999: The classical swine fever epidemic 1997-1998 in The Netherlands: descriptive epidemiology. *Prev Vet Med* **42** , 157–184, DOI: 10.1016/s0167-5877(99)00074-4.

Fritzemeier, J., 2000: Epidemiology of classical swine fever in Germany in the 1990s. *doi.org* 29–41, DOI: 10.1016/s0378-1135(00)00254-6.

Garrido Haro, A.D., M. Barrera Valle, A. Acosta, and F. J. Flores, 2018: Phylodynamics of classical swine fever virus with emphasis on Ecuadorian strains. *Transboundary and Emerging Diseases* **65** , 782–790, DOI: 10.1111/tbed.12803.

Gomez-Vazquez, J.P., M. Quevedo-Valle, U. Flores, K. Portilla Jarufe, and B. Martinez-Lopez, 2019: Evaluation of the impact of live pig trade network, vaccination coverage and socio-economic factors in the classical swine fever eradication program in Peru. *Preventive Veterinary Medicine* **162** , 29–37, DOI: 10.1016/j.prevetmed.2018.10.019.

Gorsich, E.E., A.D. Luis, M.G. Buhnerkempe, D.A. Grear, K. Portacci, R.S. Miller, and C.T. Webb, 2016: Mapping U.S. cattle shipment networks: Spatial and temporal patterns of trade communities from 2009 to 2011.*Preventive Veterinary Medicine* **134** , 82–91, DOI: 10.1016/j.prevetmed.2016.09.023.

Grisi-Filho, J.H.H., M. Amaku, F. Ferreira, R.A. Dias, J.S.F. Ferreira Neto, R.L. Negreiros, and R. Ossada, 2013: Detecting livestock production zones. *Preventive Veterinary Medicine* **110** , 304–311, DOI: 10.1016/j.prevetmed.2012.12.013.

Guinat, C., A. Relun, B. Wall, A. Morris, L. Dixon, and D.U. Pfeiffer, 2016: Exploring pig trade patterns to inform the design of risk-based disease surveillance and control strategies. *Nature Publishing Group* DOI: 10.1038/srep28429.

ICA Resolution 11138. (2016), Colombian Agriculture and Livestock Institute (ICA). Colombia's Official Journal.

James, R., D.P. Croft, and J. Krause, 2009: Potential banana skins in animal social network analysis. *Behav Ecol Sociobiol* **63** , 989–997, DOI: 10.1007/s00265-009-0742-5.

Kao, R.R., D.M. Green, J. Johnson, and I.Z. Kiss, 2007: Disease dynamics over very different time-scales: foot-and-mouth disease and scrapie on the network of livestock movements in the UK. *Journal of The Royal Society Interface* **4** , 907–916, DOI: 10.1098/rsif.2007.1129.

Karney, C.F.F., 2013: Algorithms for geodesics. *J Geod***87** , 43–55, DOI: 10.1007/s00190-012-0578-z.

Kim, Y., S.W. Son, and H. Jeong, 2010: Finding communities in directed networks. *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics* **81** , 016103–016103, DOI: 10.1103/PhysRevE.81.016103.

Knific, T., M. Ocepek, A. Kirbiš, and H.H.K. Lentz, 2020: Implications of Cattle Trade for the Spread and Control of Infectious Diseases in Slovenia. *Frontiers in Veterinary Science* **6** , 454–454, DOI: 10.3389/fvets.2019.00454.

Lee, K., D. Polson, E. Lowe, R. Main, D. Holtkamp, and B. Martínez-López, 2017: Unraveling the contact patterns and network structure of pig shipments in the United States and its association with porcine reproductive and respiratory syndrome virus (PRRSV) outbreaks.*Preventive Veterinary Medicine* **138** , 113–123, DOI: 10.1016/j.prevetmed.2017.02.001.

Lentz, A. Koher, P. Hövel, J. Gethmann, C. Sauter-Louis, T. Selhorst, and F.J. Conraths, 2016: Disease spread through animal movements: A static and temporal network analysis of pig trade in Germany. (Thierry Boulinier, Ed.)*PLoS ONE* **11** , e0155196–e0155196, DOI: 10.1371/journal.pone.0155196.

Lowenstein, C., W.F. Waters, A. Roess, J.H. Leibler, and J.P. Graham, 2016: Animal Husbandry Practices and Perceptions of Zoonotic Infectious Disease Risks among Livestock Keepers in a Rural Parish of Quito, Ecuador. *Am. J. Trop. Med. Hyg* **95** , 1450–1458, DOI: 10.4269/ajtmh.16-0485.

Machado, G., J.A. Galvis, F.P.N. Lopes, J. Voges, A.A.R. Medeiros, and N.C. Cárdenas, 2021: Quantifying the dynamics of pig movements improves targeted disease surveillance and control plans. *Transboundary and Emerging Diseases* **68** , 1663–1675, DOI: 10.1111/tbed.13841.

Martínez-López, B., B. Ivorra, A.M. Ramos, E. Fernández-Carrión, T. Alexandrov, and J.M. Sánchez-Vizcaíno, 2013: Evaluation of the risk of classical swine fever (CSF) spread from backyard pigs to other domestic pigs by using the spatial stochastic disease spread model Be-FAST: The example of Bulgaria. *Veterinary Microbiology* **165** , 79–85, DOI: 10.1016/j.vetmic.2013.01.045.

Moon, S.A., T. Ferdousi, A. Self, and C.M. Scoglio, 2019: Estimation of swine movement network at farm level in the US from the Census of Agriculture data. *Sci Rep* **9** , 6237, DOI: 10.1038/s41598-019-42616-w.

Newman, and M. Girvan, 2004: Finding and evaluating community structure in networks. *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics* **69** , DOI: 10.1103/PhysRevE.69.026113.

Newman, M., 2010: Networks: An Introduction. Oxford: Oxford University Press.

Nöremark, M., N. Håkansson, S.S. Lewerin, A. Lindberg, and A. Jonsson, 2011: Network analysis of cattle and pig movements in Sweden: Measures relevant for disease control and risk based surveillance.*Preventive Veterinary Medicine* **99** , 78–90, DOI: 10.1016/j.prevetmed.2010.12.009.

OIE, 2020: OIE - World Organisation for Animal Health, Terrestrial Manual Online Access [Online] Available at https://www.oie.int/en/what-we-do/standards/codes-and-manuals/terrestrial-manual-online-access/ (accessed December 14, 2020).

OIE-WAHIS, 2021: OIE-WAHIS [Online] Available at https://wahis.oie.int/#/report-info?reportId=5912 (accessed August 4, 2021).

Page, L., and S. Brin, 1998: The anatomy of a large-scale hypertextual Web search engine. *Computer Networks* **30** , 107–117, DOI: 10.1016/s0169-7552(98)00110-x.

Pettitt, A.N., 1979: A Non-Parametric Approach to the Change-Point Problem. *Journal of the Royal Statistical Society. Series C (Applied Statistics)* **28** , 126–135, DOI: 10.2307/2346729.

Pineda, P., A. Deluque, M. Peña, O.L. Diaz, A. Allepuz, and J. Casal, 2020: Descriptive epidemiology of classical swine fever outbreaks in the period 2013-2018 in Colombia. *PLOS ONE* **15** , e0234490, DOI: 10.1371/journal.pone.0234490.

Pohlert, T., 2020 (17. September): Non-Parametric Trend Tests and Change-Point Detection [R package trend version 1.1.4] [Online] Available at https://CRAN.R-project.org/package=trend (accessed May 19, 2021). Comprehensive R Archive Network (CRAN).

Procel, C., 2019: Estudio del Cerdo local ecuatoriano, importancia gastronómica y cultural. *Tesis (Licenciado en Arte Culinario), Universidad San Francisco de Quito, Colegio de Hospitalidad, Arte Culinario y Turismo; Quito, Ecuador, 2019* .

Robinson, S.E., and R.M. Christley, 2007: Exploring the role of auction markets in cattle movements within Great Britain. *Preventive Veterinary Medicine* **81** , 21–37, DOI: 10.1016/j.prevetmed.2007.04.011.

Rodríguez-Estévez, V., M. Sánchez-Rodríguez, A.G. Gómez-Castro, and S.A. Edwards, 2010: Group sizes and resting locations of free range pigs when grazing in a natural environment. *Applied Animal Behaviour Science* **127** , 28–36, DOI: 10.1016/j.applanim.2010.08.010.

Rosendal, T., C. Dewey, R. Friendship, S. Wootton, B. Young, and Z. Poljak, 2014: Spatial and temporal patterns of porcine reproductive and respiratory syndrome virus (PRRSV) genotypes in Ontario, Canada, 2004–2007. *BMC Veterinary Research* **10** , 83, DOI: 10.1186/1746-6148-10-83.

Salathé, M., and J.H. Jones, 2010: Dynamics and control of diseases in networks with community structure. *PLoS Computational Biology* **6** , DOI: 10.1371/journal.pcbi.1000736.

Strogatz, S.H., 2001: Exploring complex networks. *Nature* **410** , 268–276, DOI: 10.1038/35065725.

Terán, M.V., N.C. Ferrat, and J. Lubroth, 2004: Situation of Classical Swine Fever and the Epidemiologic and Ecologic Aspects Affecting Its Distribution in the American Continent. *Annals of the New York Academy of Sciences* **1026** , 54–64, DOI: 10.1196/annals.1307.007.

Tillett, H.E., 1992: Infectious Diseases of Humans: Dynamics and Control. R. M. Anderson, R. M. May, Pp. 757. Oxford University Press; 1991 (£50.00). *Epidemiology & Infection* **108** , 211–211, DOI: 10.1017/S0950268800059896.

Todaro, M.P., and S.C. Smith, 2009: Economic Development. Pearson Addison Wesley.

VanderWaal, K., and J. Deen, 2018: Global trends in infectious diseases of swine. *PNAS* **115** , 11495–11500, DOI: 10.1073/pnas.1806068115.

VanderWaal, K., E.A. Enns, C. Picasso, C. Packer, and M.E. Craft, 2016: Evaluating empirical contact networks as potential transmission pathways for infectious diseases. *Journal of The Royal Society Interface* **13** , 20160166–20160166, DOI: 10.1098/rsif.2016.0166.

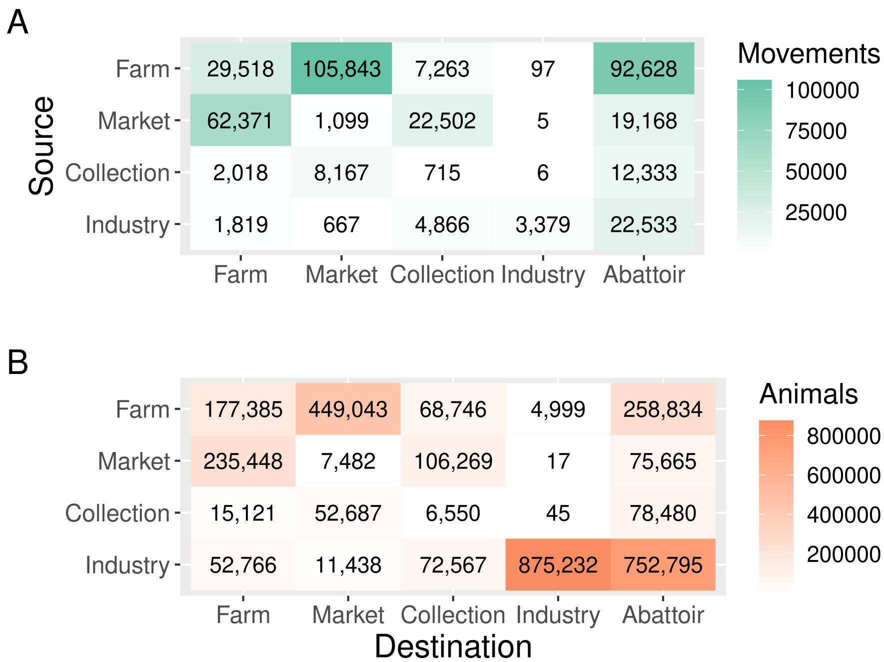
VanderWaal, K., I.A.D. Paploski, D.N. Makau, and C.A. Corzo, 2020: Contrasting animal movement and spatial connectivity networks in shaping transmission pathways of a genetically diverse virus. *Preventive Veterinary Medicine* **178** , 104977, DOI: 10.1016/j.prevetmed.2020.104977.

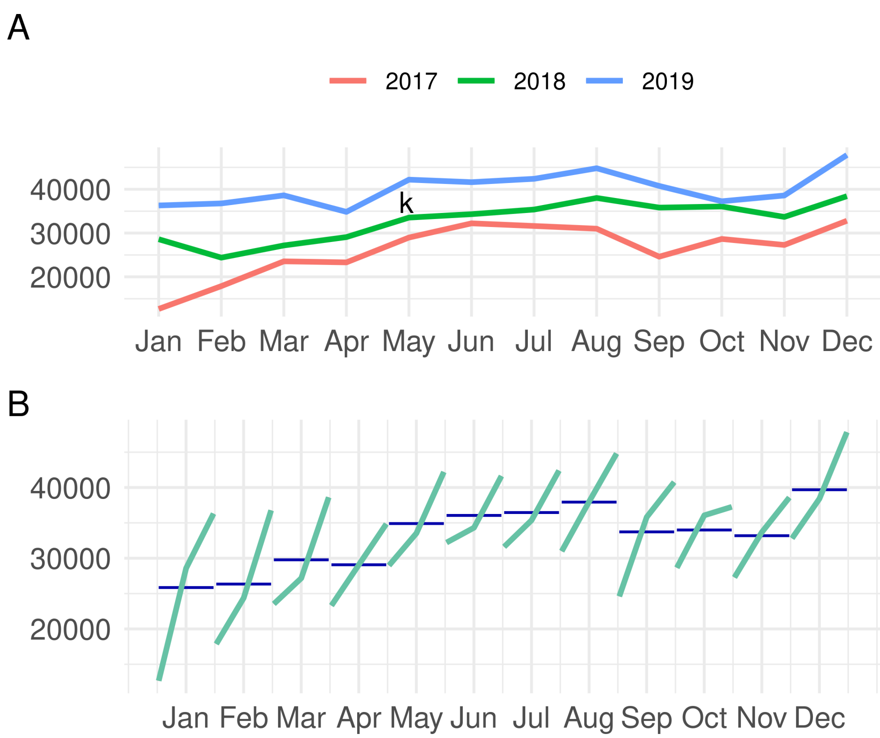
Vernon, M.C., and M.J. Keeling, 2009: Representing the UK's cattle herd as static and dynamic networks. *Proceedings of the Royal Society B: Biological Sciences* **276** , 469–476, DOI: 10.1098/rspb.2008.1009.

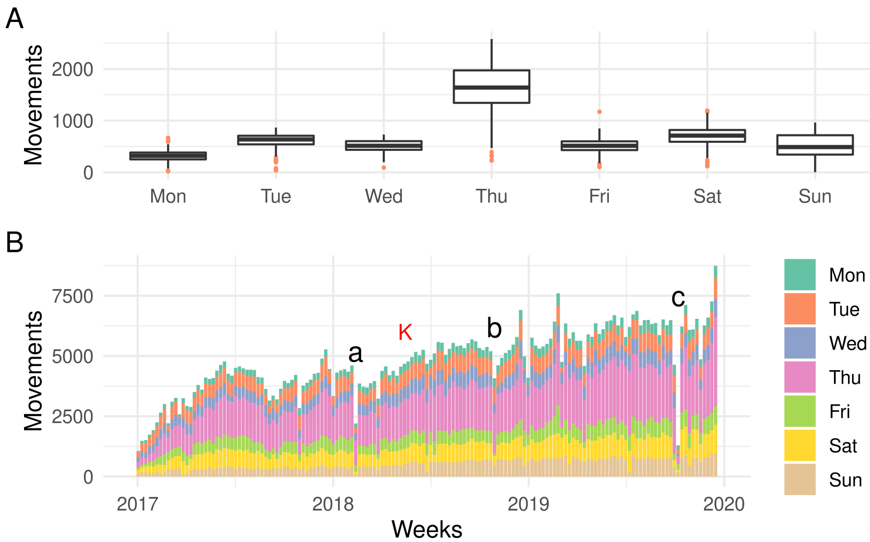
Vinueza, R.L., B. Durand, and G. Zanella, 2022: Network analysis of cattle movements in Ecuador. *Preventive Veterinary Medicine* **201** , 105608, DOI: 10.1016/j.prevetmed.2022.105608.

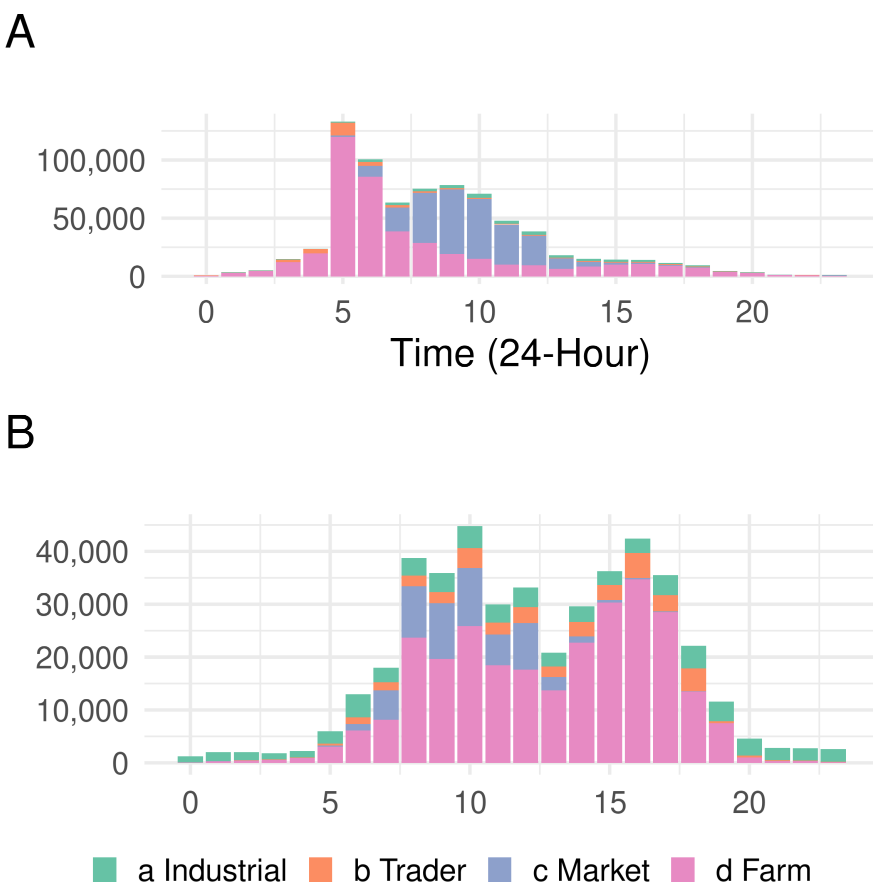
Wasserman, S., S. (University of I.W. Urbana-Champaign), and K. Faust, 1994: Social Network Analysis: Methods and Applications. Cambridge University Press.

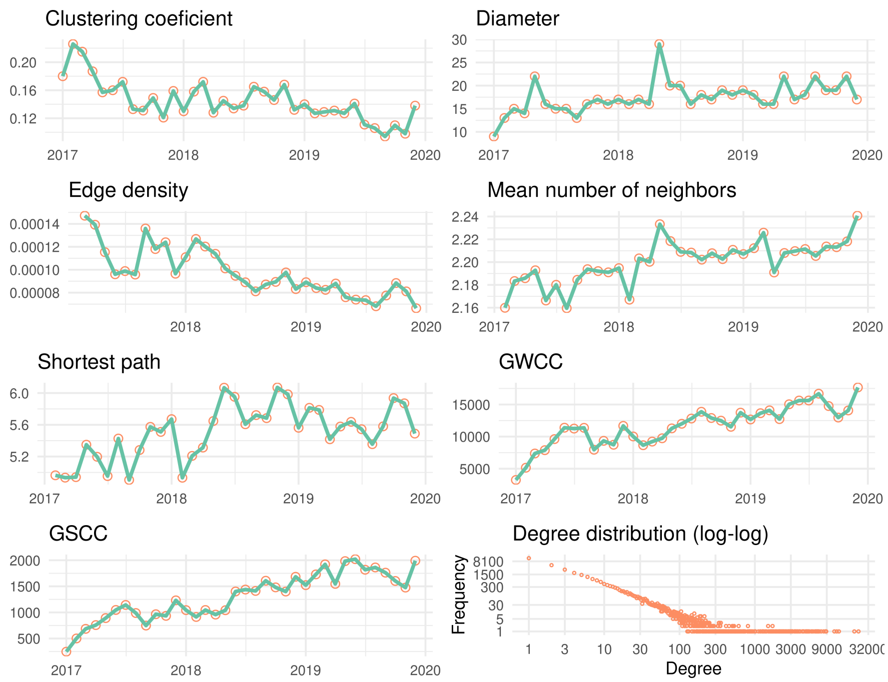
Watts, D.J., and S.H. Strogatz, 1998: Collective dynamics of ‘small-world’ networks. *Nature* **393** , 440–442, DOI: 10.1038/30918.



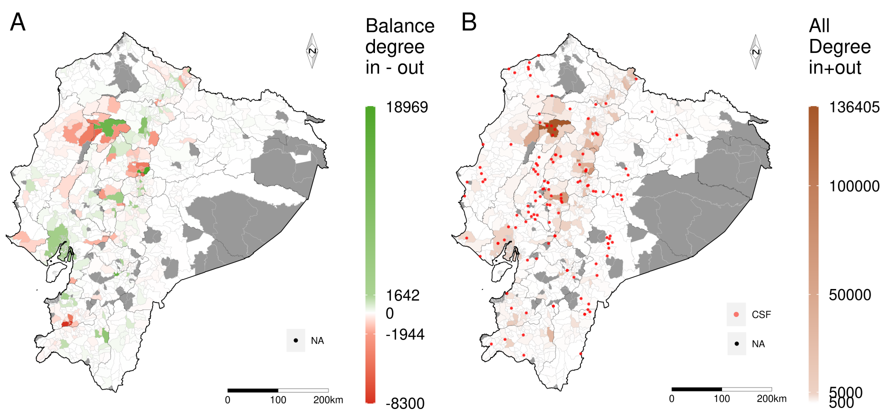



A
Movements
2000
1000
0
Mon
Tue
Wed
Thu
Fri
Sat
Sun
B
Movements
7500
5000
2500
0
a
K
b
c
2017
2018
2019
2020
Weeks
Mon
Tue
Wed
Thu
Fri
Sat
Sun

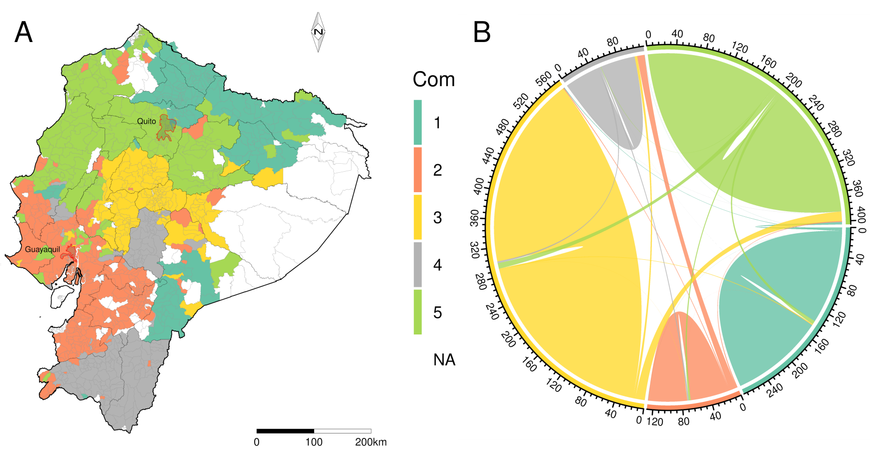

A
100,000
50,000
0
0
5
10
15
20
Time (24-Hour)
B
40,000
30,000
20,000
10,000
0
0
5
10
15
20
a Industrial
b Trader
c Market
d Farm



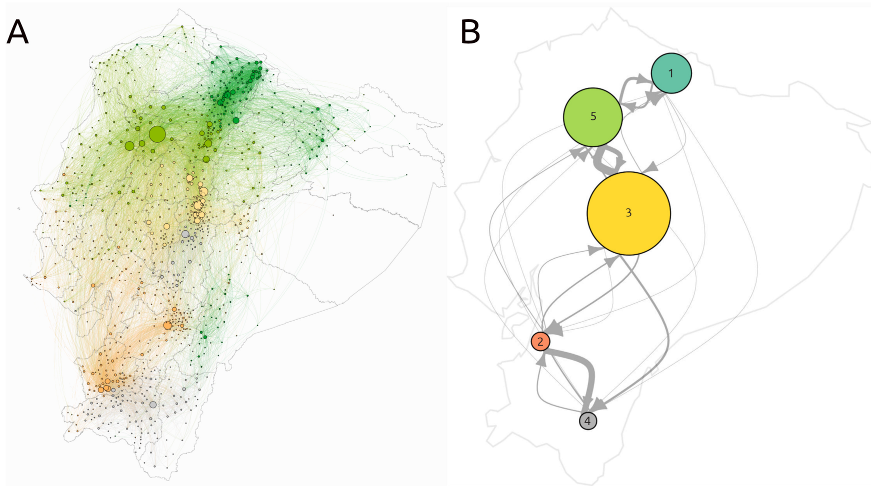
Clustering coeficient
0.20
0.16
0.12
2017
2018
2019
2020
Diameter
30
25
20
15
10
Edge density
0.00014
0.00012
0.00010
0.00008
Mean number of neighbors
2.24
2.22
2.20
2.18
2.16
Shortest path
6.0
5.6
5.2
GWCC
15000
10000
5000
GSCC
2000
1500
1000
500
Degree distribution (log-log)
Frequency
8100
1500
300
30
5
1
1 3 10 30 100 300 1000 3000 9000 32000
Degree

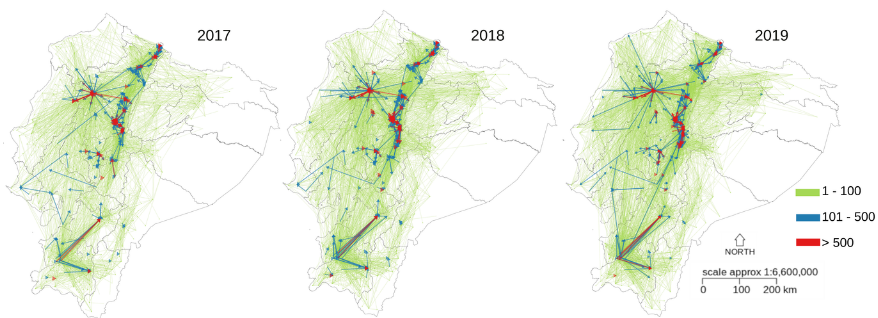


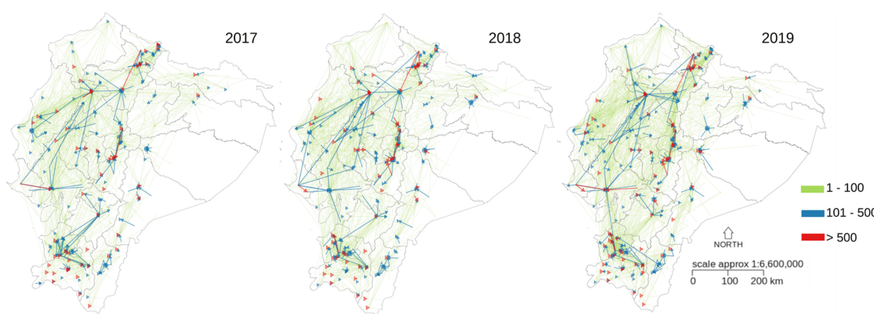
A
Balance degree in - out
18969
1642
0
-1944
-8300
NA
0 100 200km
B
All Degree in+out
136405
100000
50000
5000
500
CSF
NA
0 100 200km

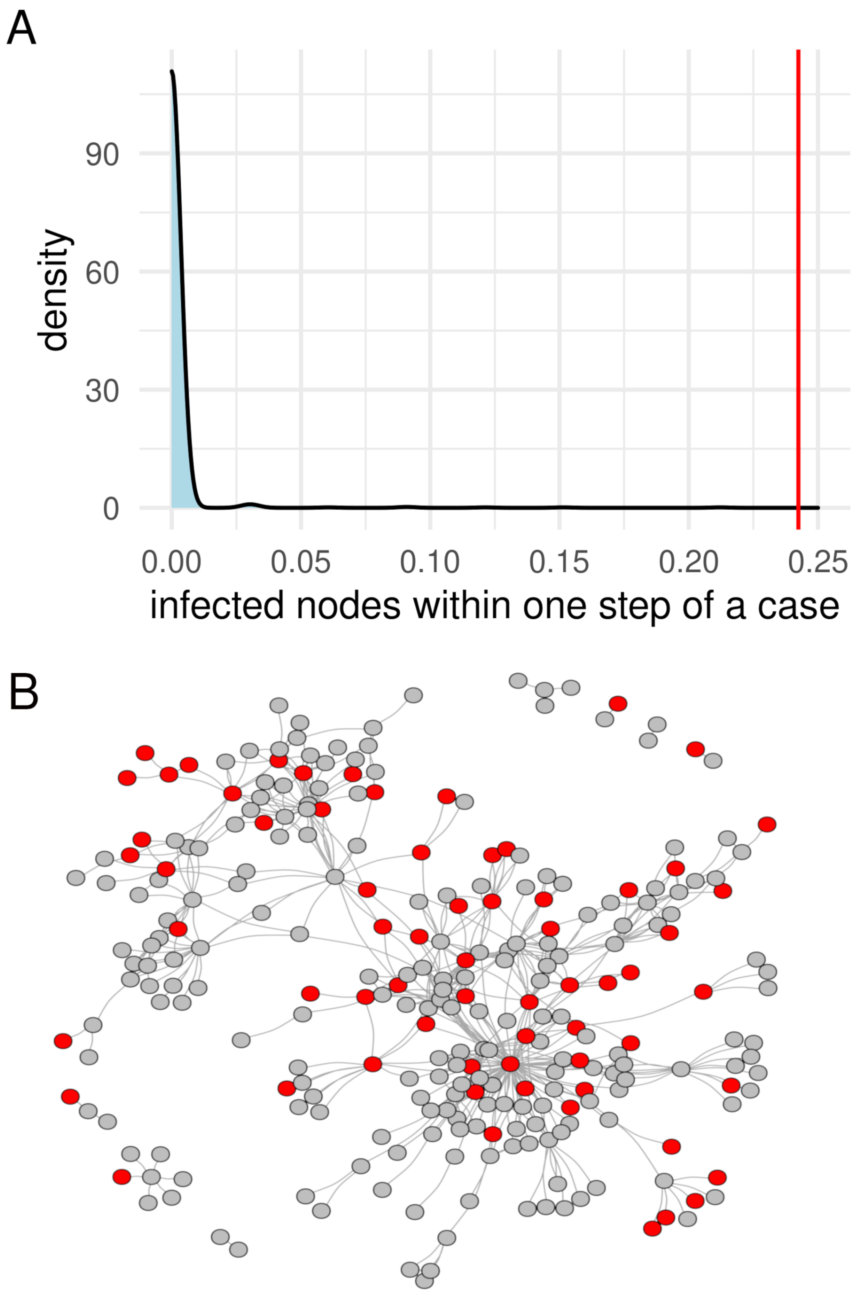


A
Quito
Guayaquil
Com
1
2
3
4
5
NA
0 100 200km
B


A
B
1
5
3
2
4


2017
2018
2019
1 - 100
101 - 500
> 500
NORTH
scale approx 1:6,600,000
0 100 200 km


2017
2018
2019
1 - 100
101 - 500
> 500
NORTH
scale approx 1:6,600,000
0 100 200 km



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