Preventive Veterinary Medicine 204 (2022) 105644

Contents lists available at ScienceDirect

Preventive Veterinary Medicine

journal homepage: www.elsevier.com/locate/prevetmed

Network analysis of cattle movements in Chile: Implications for pathogen spread and control

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A B S T R A C T

Livestock movement between herds is one of the main routes for a pathogen to spread between herds. Understanding the contact structure, patterns and importance of specific individuals and classes can help assess dissemination risk, control, and surveillance measures. In this study, the cattle herd's contact structure in southern Chile was characterized based on the study of movement within one of the most important geographical regions for livestock production. Using Social Network Analysis, network measures of centrality, network cohesion and contact chains were estimated to identify essential features that can influence disease transmission among premises. Static and disaggregated by season networks were built for the entire set of nodes and for the Los Rios region animal flow only. For all networks, it was found that most nodes had a few movements; meanwhile, a small number of them were highly connected. Livestock markets have a powerful influence over the networks, being the most connected and central nodes, appearing as candidates for surveillance because of their possible role as super spreaders. Nodes attributes were associated with the likelihood of having high contact chains measures, such as herd class, location, and presence of markets anywhere on the contact chain. This work is the first deep analysis in livestock flows in Chile and shows the importance of animal movement data interpretation to assess pathogen risk spread in the country.

1. Introduction

Cattle movements and how they shape the contact structure between farms is a critical factor that determines pathogen spread in a district or a country (Christley et al., 2005), because it is the way that infectious animals can move between different units, hence influencing the size and timing of an outbreak (Volkova et al., 2010). Therefore, traceability of cattle shipments plays a crucial role in understanding the underlying mechanisms of pathogen transmission, control, and prevention of infectious diseases outbreaks (Caporale et al., 2001). Several countries have implemented regulations that obligate farmers to report cattle movement to their respective authorities (Dubé et al., 2009; Nöremark et al., 2011; Frössling et al., 2012).

Social network analysis (SNA) is used to measure relationships between social entities, and it has been used to study the influence of cattle movement in the spread of infectious diseases and animal surveillance (Christley et al., 2005; VanderWaal et al., 2016), forecasting disease dynamics (Dubé et al., 2011; Tinsley et al., 2012; Widgren et al., 2016), and to inform disease interventions and control at metapopulation level (Gates and Woolhouse, 2015; Marquetoux et al., 2016).

SNA provides a methodology to assess the role that a node can play in a network, for example, identifying holdings that connect with a significant number of nodes or holdings with high centrality measures, which can be responsible for super-spreading events and can be aimed for surveillance to improve detection of pathogens (Dubé et al., 2011). Furthermore, estimating the cohesiveness measures, which assess the connectedness level of the network, allows us to explore how fast or slow a pathogen can spread (Dubé et al., 2011).

Animal movements might be significant for the beef and dairy industry in Chile, where the commercialization of cattle is concentrated in relatively few cattle auctions. In addition, there are many movements between units within and between provinces and regions that imply long distances between origin and destination.

In 2005, Chile established the National Program of Livestock Traceability (NPLT), which has a significant objective: identifying all animal premises and implementing a national traceability system for all cattle. Previously, Verdugo (2004) characterized the Chilean cattle movements finding that markets and slaughterhouses have a significant role in animal flow. The animal trade showed a seasonal pattern, in which there is an increase in cattle auctions during autumn and summer,

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https://doi.org/10.1016/j.prevetmed.2022.105644
Received 12 September 2021; Received in revised form 9 January 2022; Accepted 2 April 2022
Available online 5 April 2022

driven by cattle sales to face the scarcity of pasture in winter and the end of the fattening process, respectively. Calves were the most interchanged animal group in cattle auctions, increasing the risk of pathogen spread by movement of youngstock between herds primarily for fattening purposes.

Herd movements as a potential route for pathogen spread have not yet been analyzed in the country. Currently, control and eradication programs exist in Chile for pathogens that can spread through animal movements, such as Bovine Tuberculosis and Bovine Brucellosis; however, no control and eradication programs exist for diseases like Bovine Viral Diarrhea (BVD), which is highly prevalent in southern Chile (Alocilla and Monti, 2022) and is primarily spread by animal movement. Given the significance of the Los Rios Region in Chilean dairy and beef industry, and the possibility of accessing the information, we analyzed the contact structure of bovine holdings in southern Chile, emphasizing the analysis of within-region movement dynamics and incoming connectivity with other regions.

The study aimed to describe and characterize flows of animal movements between herds for the Los Ríos Region, especially those that could be important to consider for BVD spread between herds. In addition, this information could be used to develop further mathematical models for infectious disease dynamics.

2. Material and methods

2.1. Main characteristics of the study area

The comparatively great production concentration in a very small number of geographical regions is one of the characteristics of the Chilean cattle industry, and one of these spots is the Los Rios Region in southern Chile. This region is also home to 16% of the country's bovine population, contributing 30% of national milk output and 11% of national meat production, respectively (the country's second-largest milk producing region) (INE, 2007). The Region is divided into two provinces (Valdivia and Ranco) and twelve communes, which are surrounded by two additional Regions (Araucania to the north and Los Lagos to the south) (Fig. 1), that together account for 60% of all cattle in the country (INE, 2007). The region's production method is predominantly pasture-based, with few beef herds that reach the final stages of fattening in confinement, primarily outside the Region. Market auctions and direct sales to retailers from a herd were the most important commercialization channels for cattle in the Los Rios Region in 2015, accounting for 53% and 34% of the herds, respectively. Private herd auctions, livestock dealers, direct sales to slaughterhouses, and exports were used to market the remainder (INE, 2015). The analysis was limited to the Los Rios region in order to obtain data for future studies of Bovine Viral Diarrhea Virus control and eradication strategies in the named region; thus, the characteristics of within-region movement dynamics as well as the impact of incoming movement from other regions were used.

2.2. Data and population description

Records of cattle movements within Los Rios and incoming to the Los Rios Region were obtained for 2016 and 2017 from the National Program of Livestock Traceability databases. They included identification of the origin and destination, movement date, and the number of animals for every movement. In addition, herds attributes (location, class, size) were derived from another file from the same source and related to the movement file by a unique identification number that all herds possess. We excluded movement to slaughterhouses for this analysis because those movements were an endpoint and represented no risk of infection to another herd.

A total of 17.219 holdings and 170.789 shipments, which included movements within the Los Rios Region and movements from other Regions to the Los Rios Region, were used for this study. Movements from the Los Rios Region that has destination other country regions were removed from the analysis because they do not represent a risk for pathogen spread within the Los Rios Region. The cattle premises were categorized within the following attributes:

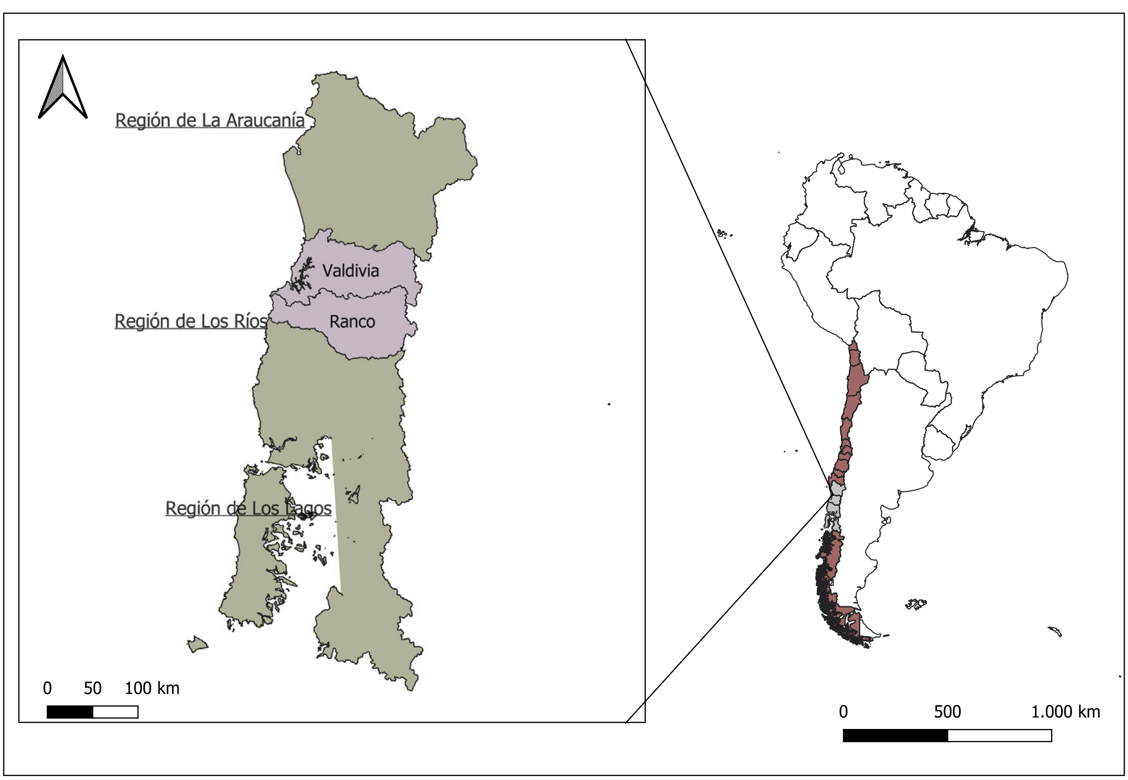

Fig. 1. Study area. Geographical location of Los Rios (with their two provinces (Valdivia and Ranco), de La Araucanía and Los Lagos regions, Chile.

Class attribute:
- *Dairy* (19%).
- *Beef* (fattening and breeders) (66%).
- *Mixed*: correspond to dairy herds that also breed male calves for sale (13%).
- *Others*: correspond to holdings that declare to have bovine animals, but their primary income is not from dairy or beef production (2%).
- *Markets:* (0.2%).
- Exhibition and sports centers (Ex/Sport) (0.2%).

Size Attribute: Holding size was defined using information about animals' existence per herd, declared to the National Animal Services in the "Animal Existence Formulary", which is reported annually to the authorities. From this individual document, farm size was derived and subsequently added to the movement database:

-*Small Herds*: Herds containing between 1 and 100 animals (10%).
-*Medium Herds*: Herds containing between 101 and 300 animals (14%).
-*Large Herds*: Herds containing 301 or more animals (76%).
-*Market/Exp*: This category was created to reference markets and sports/exhibition centers that do not have stable animal existence over time (0.04%). It is essential to mention that only 3 of the 34 markets in our database are in the Los Rios Region.

Location Attribute: Los Rios Region is divided into two provinces named Ranco and Valdivia; those provinces were used to categorize the herds depending on their location. Holdings that belong to other regions were categorized as "Others" because we only were interested in the study Region's impact and not their interaction. As a result, 15% and 14% of the premises belong to Ranco and Valdivia provinces, respectively; meanwhile, 72% of the herds belong to other Regions.

2.3. Data analysis

We performed a descriptive analysis of the movement general characteristics by herd size, class, and location. Then, SNA was used to explore and characterize the contact structure among cattle herds in Los Rios Region. We estimated network and farm level metrics for a Region-broad network, which we called Whole network (WN) and a within-region network that we called Los Rios-only network (LR-oN) disaggregated by season networks were directed. Only the number of outgoing and incoming movements was considered; we do not consider the number of animals moved in each shipment. We disaggregated the network by season, looking for management practices connected to pasture availability, such as an increase in movements during autumn to spend winter without an excess of animals, because production systems in southern Chile rely mostly on extensive grazing. The season's starting and ending were specified as follows:

-Spring: From September 23rd to December 20th.
-Summer: From December 21st to March 20th.
-Autumn: From March 21st to June 20th.
-Winter: From June 21st to September 22nd.

Network cohesion and farm centrality metrics were estimated for a whole network (WN) that includes all nodes, and for a within-Los Rios Region network (LR-oN), we included only within-region movements. Movements from Los Rios Region farms to farms outside Los Rios Region were not considered unless the movement has as a target a holding that sent animals to Los Rios Region. The following centrality and cohesion metrics were estimated.

2.3.1. Centrality measures

In-degree: Number of incoming movements of a specific destination node (holding) in a given time. This measure is potentially directly correlated with the probability introduction of infectious agents (Wasserman and Faust, 1994).

Out-degree: Number of outgoing movements from a specific origin node (holding). This measure is potentially directly correlated with infectious agents' spread (Wasserman and Faust, 1994).

Degree Distribution Fitting: Several authors report that their studied networks have a degree distribution that follows a power-law distribution and scale-free features (Aznar et al., 2011; Brown et al., 2019; Natale et al., 2009; Tinsley et al., 2012; VanderWaal et al., 2016). Scale-free networks, on the other hand, are said to be uncommon in real-world networks. Some authors emphasize the structural diversity of real-world networks and argue that stronger theories are needed to explain these patterns (Broido and Clauset, 2019; Clauset et al., 2009). The cumulative degree distribution was tested for the best model function fitting an empirical pattern to address this characteristic and assess structural properties of the network. The theoretical distribution functions tested were power-law distribution, exponential distribution, and discrete version of a generalized beta distribution (DGBD). The power law distribution was tested by plotting a log-log graph of the degree distribution and then fitting a linear slope, additional to this, the function "fit_power_law" from "igraph" package, that fits a power-law distribution to a data set and test the hypothesis that the original data could have been drawn from the fitted power-law distribution, small p-values smaller than0.05 for a Kolmogorov-Smirnof (KS.p) indicate that the test rejected the hypothesis (Clauset et al., 2009). The DGBD has the form:

$$f(r) = A(N+1-r)^b / r^a$$

where r is the rank value of the node degrees, N its maximum value, A is a normalization constant and (a, b) two fitting exponents. The exponent a is related to the "left to right" tail and the exponent b is related to the "right to left" tail of the data; hence, different values of a and b produce different shapes of the curve. If $a < b$, the curve shows a smooth exponential decay because the frequencies of occurrence are similar across ranks. If $a > b$, the curve shows a strong exponential decay because the left tail of the curve is significantly larger than the right tail. A log-log plot for the frequency in decreasing order was built, and the DGBD was fitted with a and b coefficients and R^2 (Martínez-Mekler et al., 2009; Lopez et al., 2018). The rank exponential distribution it is defined as:

$$f(r) = -\frac{1}{\mu}\ln\left(\frac{r}{N}\right)$$

A log-log plot for the frequency in decreasing order was built, and an exponential slope was fitted with μ parameter and R^2 (Martínez-Mekler et al., 2009; Lopez et al., 2018). Best model was selected according to Bayesian Information Criterion and R^2 values.

Betweenness: The frequency by which a node lies between pairs of other nodes in the network, corresponding to the number of shortest paths connecting them. The high betweenness nodes connect different groups, and because of this, they can play an essential role in the spread of infectious agents (Freeman, 1978).

Eigenvector centrality: Measures the influence of a node over the network, assigns a relative score to every node under the principle that links from important nodes (measured by degree centrality) are worth more than links from unimportant nodes. A node with a few links could have high eigenvector centrality scores if these links were to very well-connected nodes. Eigenvector centrality measures nodes importance by considering the importance of the neighbors (Golbeck, 2013).

Correlation between network metrics was undertaken with the Spearman correlation coefficient (ρ).

2.3.2. Cohesion measures

Density: Proportion of actives links between nodes over all possible links between all pairs of nodes (Wasserman and Faust, 1994). No isolated nodes were considered in overall networks because only nodes with registered movement during the study period were obtained. On the other hand, on disaggregated networks, isolates nodes were considered.

Diameter: The longest shortest path between any pair of livestock operations in the network (Wasserman and Faust, 1994).

Average shortest path length: Mean number of edges that must be traversed to connect two nodes. The temporal sequence of edges is ignored (Wasserman and Faust, 1994). Since we are dealing with a direct network, directionality was accounted for this metric estimation.

Reciprocity: Proportion of edges where an edge in the opposite direction also exists (Wasserman and Faust, 1994).

Assortativity coefficient (AC): It is the preference of the network's nodes to attach to others based on scalar properties or categorical attributes of the nodes. According to node degree (and other scalar properties), AC is operationalized as a correlation (r) between pairs of linked nodes; r lies between − 1 and 1. When $r = 1$, the network is said to have perfect assortative mixing patterns; when $r = 0$, the network is non-assortative, while at $r = -1$, the network is entirely disassortative (Newman, 2003). For categorical characteristics (herd size, herd class and herd location), the assortativity coefficient r will be estimated by comparing the proportion of links connecting nodes with the same attribute value, or type, relative to the proportion expected if the edges in the network were randomly rewired (Peel et al., 2018), the interpretation is identical as it is for AC in scalar properties**.**

2.3.3. *Measures accounting temporal sequence*

The *outgoing contact chain* or accessible world assess the number of nodes in contact with each node through animal movements leaving the node. The sequence of the movements is considered and includes direct and indirect movements. The *ingoing contact chain* measures all direct and indirect contacts through movements onto a holding; the sequence by which the movements occur is also considered (Nöremark et al., 2011). Contact chain measures were estimated for WN and LR-oN, followed by a re-estimation for both networks removing markets to evaluate the effect on the contact chain of those holdings. To assess possible associations between ingoing and outgoing contact chain and features like herd class, herd location and presence of markets alongside contact chain, a GLM with binomial distribution over permuted data was used. First, a dichotomization of response variables was undertaken. For this, the approach proposed by Nöremark (2011) was followed where contact chain measures were categorized as high and low contact chain using as cut off the 90th percentile based on data. Hence, over 90th percentile value for contact chain measures was set to 1 as "high contact chain values", and the rest set to 0 as "low contact chain values". Secondly, to account for contact chain data non-independence, a node label-swap permutation process was undertaken (Croft et al., 2011; Weiss et al., 2021), and later the GLM process over the permuted data was executed. Both processes were performed using the R package Animal Network Toolkit software (ANTs) (Sosa et al., 2020). The *ingoing* and *outgoing contact chains* were analyzed individually, and the evaluated variables were holding class, location, holding size and contact with market (CWM). CWM was set as a dichotomic variable in which 1 represents that the holding connects with a market in some part of their ingoing or outgoing contact chain, and 0 represents that the holding does not connect with markets during the study period. All statistical analyses were performed using the packages “igraph” and “EpiContactTrace” (Csardi and Nepusz, 2005; Nöremark and Widgren, 2014) from R (V.3.5.3) (R Core Team, 2019).

3. Results

3.1. *Descriptive statistics*

For all 2016–17 data from all nodes present in the whole network, 74% (17.397/17.219) were from outer regions, and they were involved with the Los Rios Region by sending animal shipments to it. Table 1 shows that the largest proportion of movements occurs within provinces (55% from Ranco province and 76% from Valdivia province). However, we need to remember that “Others” includes all the provinces across Chilean territory that sent animals to the Los Rios Region. Inside this Region, movement between provinces occurs mainly from Ranco to Valdivia because two of the three markets of the Region are in Valdivia province. Holdings from location “Others” sent slightly more shipments to Ranco province presumably because this province is near the Los Lagos Region, which is the most critical Region in the cattle business trade.

Table 1
Matrix of the frequency of cattle movements between provinces, for the whole network, during 2016–2017, in Los Ríos Region, Chile. In brackets the number of involved herds (origin and destination) for each movement is specified.

Origin (Province)	Destination (Province)			
	Ranco	Valdivia	Others	Total
Ranco	16.124 (1.955)	7.404 (957)	5.910 (1.088)	29.438 (2.020)
Valdivia	1.576 (458)	21.454 (1.942)	5.056 (841)	28.086 (1.967)
Others	5.428 (1.031)	3.590 (891)	104.247 (12.288)	113.265 (12.328)
Total	23.128 (1.695)	32.448 (1.346)	115.213 (12.328)	170.789

The most frequent destination holding for all categories were livestock markets and the most frequent destination within this class was beef herds. Beef herds were the category with most outgoing movement followed by dairy herds; the movements between herds of the same class were the second most frequent movement type (Table 2).

For all herd sizes, the most frequent destination of shipments were livestock markets; small herds present the higher number of outgoing movements followed by large herds as a whole category, outgoing movements from Markets were destinated to large and small herds most likely for breeding and fattening male calves (Table 3).

3.2. *Network analysis*

Table 4 shows the metrics for the WN and LR-oN networks. The networks showed density values of 0.05 and 0.015 respectively, an average shortest path length of 4.6 and 4.8 respectively, a diameter of 15 and 17 respectively, the reciprocity is similar for both networks (0.16 and 0.19 respectively). At node level, markets were dominant nodes, resembled in their high values for all node's metrics (Table 5).

This characteristic suggests that they could be determinant for disease spread by having more incoming and outgoing movements (degree), forming bridges between nodes (betweenness) and by being connected to other very well-connected nodes (eigenvector centrality) (Table 5).

Another evaluated aspect was the node's attachment preference with other nodes that are similar in specific attributes (Table 5). Size and Province were the attributes that featured moderate to a large level of assortativity, meaning that there is a tendency to contact between herds of similar size and between nodes that belong to the same Province. According to herd class, the network showed to be disassortative. The AC by node degree shows that a preference to attach between nodes of a similar degree does not exist as well. A low correlation between indegree and outdegree was observed ($p < 0.05$, $\rho = 0.17$, $\rho = 0.11$), moderate correlation between outdegree and betweenness ($p < 0.05$, $\rho = 0.36$, $\rho = 0.47$), and high correlation between in-degree and betweenness ($p < 0.05$, $\rho = 0.77$, $\rho = 0.57$) for WN and LR-oN respectively. The network metrics distribution was right skewed for both networks, where only a few holdings present many movements, and most holdings have a small number of connections (Fig. 2). The degree distribution for WN and LR-oN best fit with a DGBD distribution which was reflected in lower BIC values and higher R^2 in comparison with power law and exponential distributions (Figs. 3 and 4).

Table 4 also display the metrics values for disaggregated networks by year and season for both networks, where most of the metrics do not evidence significant changes in trough time. Density for WN and LR-oN networks across the two-year study remains extremely low, on average a node can contact other nodes between 4.06 and 5.10 paths in the WN

Table 2
Matrix of the frequency of cattle movements between herds according to herd classes. For the whole network. During 2016–2017 in the Los Ríos Region. Chile. In brackets the number of involved herds (origin and destination) for each movement is specified.

Origin (Herd-class)	Destination (Herd-class)						
	Beef	Dairy	Mixed	Others	Market	Export/Sport	Total
Beef	6.070 (2.134)	1.919 (830)	1.562(570)	618 (291)	70.319(9.689)	65 (37)	80.553
Dairy	6.427 (1.776)	9.844 (935)	2.881(682)	679 (191)	22.281 (2763)	24 (22)	42.136
Mixed	3.800 (1.043)	2.557 (540)	1.189(335)	499 (119)	14.371 (1.957)	19 (17)	22.435
Others	119 (104)	179 (60)	61 (30)	369 (20)	2.842 (356)	4 (2)	3.574
Market	16.465 (1.084)	2.154 (252)	2.060(211)	1.100 (93)	199 (22)	1 (2)	21.979
Export	68 (31)	15 (14)	10 (9)	–	19 (15)	–	112
Total	32.949	16.668	7.763	3.265	110.031	113	170.789

Table 3
Matrix of the frequency of cattle movements between Markets/Export centers. Herds and percentages of them. By herd size. For the whole network. During 2016–2017. In the Los Ríos Region. Chile.

Origin	**Destination**				
	Large	**Medium**	**Small**	**Market/ Ex.**	**Total**
Large	16.621 (1.082)	4.986 (980)	6.213 (1.691)	19.754 (1.367)	47.574 (2.412)
Medium	4.166 (969)	1.609 (538)	1.007 (626)	22.115 (2.149)	28.897 (1.081)
Small	1.218 (945)	814 (642)	2.139 (1.712)	68.037 (11.208)	72.208 (1.081)
Markets/ Exp	7.744 (326)	5.572 (380)	8.553 (949)	241 (33)	22.110 (1.578)
Total	29.749	12.981	17.912	110.147	170.789

network and between 2.3 and 3.5 paths for the LR-oN network (ASPL). Diameter was between 9 and 13 for the WN network and 7–12 for LR-oN network. Isolated nodes were considered for disaggregated network construction, it is worth to mention that in disaggregated networks between 33% and 46% of the nodes are responsible for the observed edges in WN and between 23% and 43% for LR-oN. As it was found for the WN and LR-oN networks, in disaggregated networks, nodes tend to connect with nodes from the same location and size, and no tendency to contact with herds of the same class or similar degree was observed in the study period. In Table 5, the same pattern of markets dominance observed in both overall networks are observed for disaggregated networks, however, for the LR-oN network the top 3 nodes of every node metrics are not always "markets", most likely because in this region exists only three markets and they are located in provinces that are close to neighbor regions, hence, a considerable amount of trade from markets in Los Rios Region to herds outside this region is not captured by the network.

3.3. Removing markets from networks

To further explore cattle networks, we removed markets and their connections to assess if they influence some underlying patterns or overlap characteristics from some nodes. In the overall static networks, the connectivity tends to drop, this is observed by an increase in the average shortest path length and diameter, and extremely low density on both overall networks (Table 6). Assortativity follows the same pattern as overall static networks, however, herd class assortativity for both networks changed from a disassortative to a moderate assortative network type, especially for the WN network (from −0.52 to 0.19) (Table 6). When networks without markets are disaggregated by season, connectivity tends to drop reducing even more density values due to rising isolates nodes, maintaining stable values for these metrics across the two-year study period. However, e ASPL and diameter values that account for a decrease in connectivity in seasonal networks were not observed.

Fig. 5 depicts the impact of eliminating markets from node metrics over time. Dairy and beef herds have the most nodes over the 90th percentile for all metrics; dairy herds are the most dominating nodes for all metrics; however, beef herds dominate in some seasons for eigenvector and in-degree centrality for both networks.

A strong positive correlation was found between indegree and betweenness ($p < 0.05$, $\rho = 0.59$), and betweenness and outdegree ($p < 0.05$. $\rho = 0.51$), no correlation for in-degree and outdegree ($p < 0.05$, $\rho = -0.058$) for the WN without markets was found. Meanwhile, for the LR-oN network excluding markets, the correlation for betweenness and indegree, betweenness and outdegree were strong and positive ($p < 0.05$, $\rho = 0.43$ and $\rho = 0.62$ respectively), but, for indegree and outdegree there was no correlation ($p < 0.05$, $\rho = -0.02$).

3.4. Temporal metrics

Descriptive measures in Table 7 shows that contact chains for WN and LR-oN networks are susceptible to the market's influence;

Table 4
Cattle movements network metrics for the Whole (WN) and Los Rios-only (LR-oN) networks during 2016–2017. In the Los Ríos Region. Chile.

Network	Metric	Total	Summer 2016	Autumn 2016	Winter 2016	Spring 2016	Summer 2017	Autumn 2017	Winter 2017	Spring 2017
WN	Nodes	17.219	17.219	17.219	17.219	17.219	17.219	17.219	17.219	17.219
	Isolates prop.		0.66	0.62	0.63	0.61	0.58	0.53	0.65	0.59
	Edges	170.789	15.614	19.965	21.045	20.743	22.314	26.075	19.634	23.849
	Density (%)	0.05	0.0052	0.006	0.007	0.006	0.007	0.008	0.006	0.008
	ASPL	4.6	5.1	4.6	4.06	4.75	4.08	4.08	4.3	4.1
	Diameter	15	13	18	9	14	12	11	13	13
	Reciprocity	0.16	0.09	0.09	0.12	0.11	0.12	0.12	0.13	0.13
LR-oN	Nodes	4.849	4.849	4.849	4.849	4.849	4.849	4.849	4.849	4.849
	Isolates prop		0.74	0.72	0.70	0.63	0.62	0.56	0.66	0.57
	Edges	46.558	3.409	4.144	5.105	5.490	6.125	7.866	5.952	8.024
	Density (%)	0.015	0.01	0.017	0.021	0.023	0.026	0.03	0.025	0.03
	ASPL	4.8	2.7	2.3	2.9	2.7	3.5	3.4	2.96	3.3
	Diameter	17	8	9	8	7	12	10	11	10
	Reciprocity	0.19	0.10	0.09	0.14	0.11	0.12	0.13	0.16	0.15

ASPL= Average shortest path length; Isolates prop.= Proportion of isolates nodes (nodes with degree of zero).

Table 5
Dominant holdings type for node centrality metrics for the Whole (WN) and Los Rios-only (LR-oN) networks, and node assortativity values by size, activity, location and degree. Using cattle movements during 2016–2017. In the Los Ríos Region, Chile.

Network	Metric	Total	Summer16	Autumn16	Winter16	Spring16	Summer17	Autumn17	Winter17	Spring17
WN	Betweenness	Market	Market	Market	Market	Market	Market	Market	Market	Market
		Market	Market	Market	Market	Market	Market	Market	Market	Market
		Market	Market	Market	Market	Market	Market	Market	Mixed	Market
	Eigenvector Centrality	Market	Market	Market	Market	Market	Market	Market	Market	Market
	Total degree	Market	Market	Market	Market	Market	Market	Market	Market	Market
	In-degree	Market	Market	Market	Market	Market	Market	Market	Market	Market
	Out-degree	Market	Market	Market	Market	Market	Market	Market	Market	Market
	AC									
	Size	0.28	0.31	0.31	0.29	0.22	0.29	0.33	0.28	0.25
	Class	-0.52	-0.51	-0.46	-0.51	-0.51	-0.57	-0.54	-0.53	-0.52
	Province	0.73	0.74	0.71	0.72	0.75	0.74	0.72	0.71	0.75
	Node degree	-0.31	-0.2	-0.27	-0.31	-0.3	-0.37	-0.32	-0.34	-0.32
LR-oN	Betweenness	Market	Market	Market	Market	Market	Market	Market	Market	Market
		Market	Market	Market	Market	Market	Market	Market	Market	Market
		Mixed	Market	Market	Beef	Market	Beef	Beef	Market	Market
	Eigenvector Centrality	Market	Market	Market	Market	Market	Market	Market	Market	Market
	Total degree	Market	Market	Market	Market	Market	Market	Market	Market	Market
	In-degree	Market	Market	Market	Market	Market	Market	Market	Market	Market
	Out-degree	Market	Market	Market	Market	Market	Market	Market	Market	Market
	AC									
	Size	0.32	0.41	0.42	0.31	0.23	0.33	0.38	0.29	0.23
	Class	-0.35	-0.33	-0.24	-0.3	-0.32	-0.39	-0.39	-0.39	-0.39
	Province	0.63	0.57	0.51	0.55	0.56	0.62	0.63	0.60	0.61
	Node degree	-0.3	-0.29	-0.25	-0.32	-0.32	-0.36	-0.38	-0.33	-0.38

AC= Assortativity coefficient.

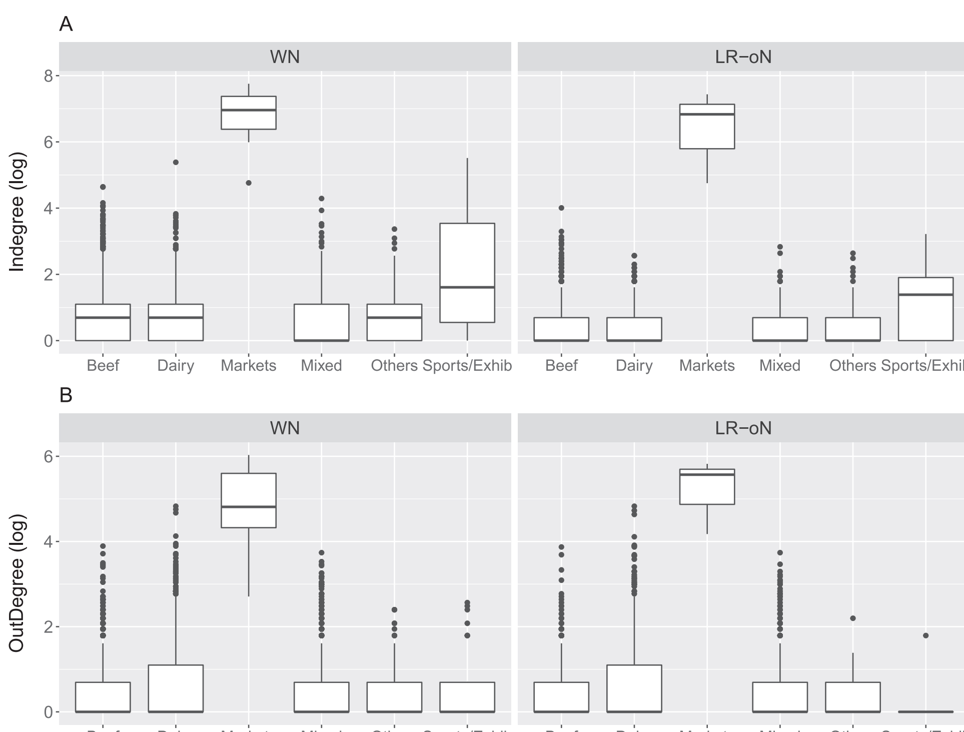

Fig. 2. In-degree (A) and out-degree (B) for the Whole (WN) and Los Rios-only (LR-oN) networks by holding class. Using cattle movements during 2016–2017, in the Los Ríos Region, Chile.

remarkable reductions in contact chain measures values are observed for both networks when markets and their connections are removed. The WN and LR-oN networks show an absence of linear relationship and low negatives values of Spearman coefficients between *ingoing* and *outgoing contact chain* (−0.09 and −0.11, respectively). Markets removal caused a variation in the Spearman coefficient to − 0.29 and − 0.22 for WN and LR-oN respectively, showing that when markets are removed a moderate inverse relationship arises between the ranked values of the *outgoing contact chain* and *ingoing contact chain.*

Table 8 shows the results of the GLM performed to assess possible associations between node characteristics and *infection chain* measures for the LR-oN network. Node class and location were associated ($p < 0.05$) with both higher *ingoing* and *outgoing contact chain* measures, where belonging to dairy or mixed class reduces the odds of having high values of *ingoing contact chain* but increases the odds of having high values of *outgoing contact chain* measures compared to beef herds.

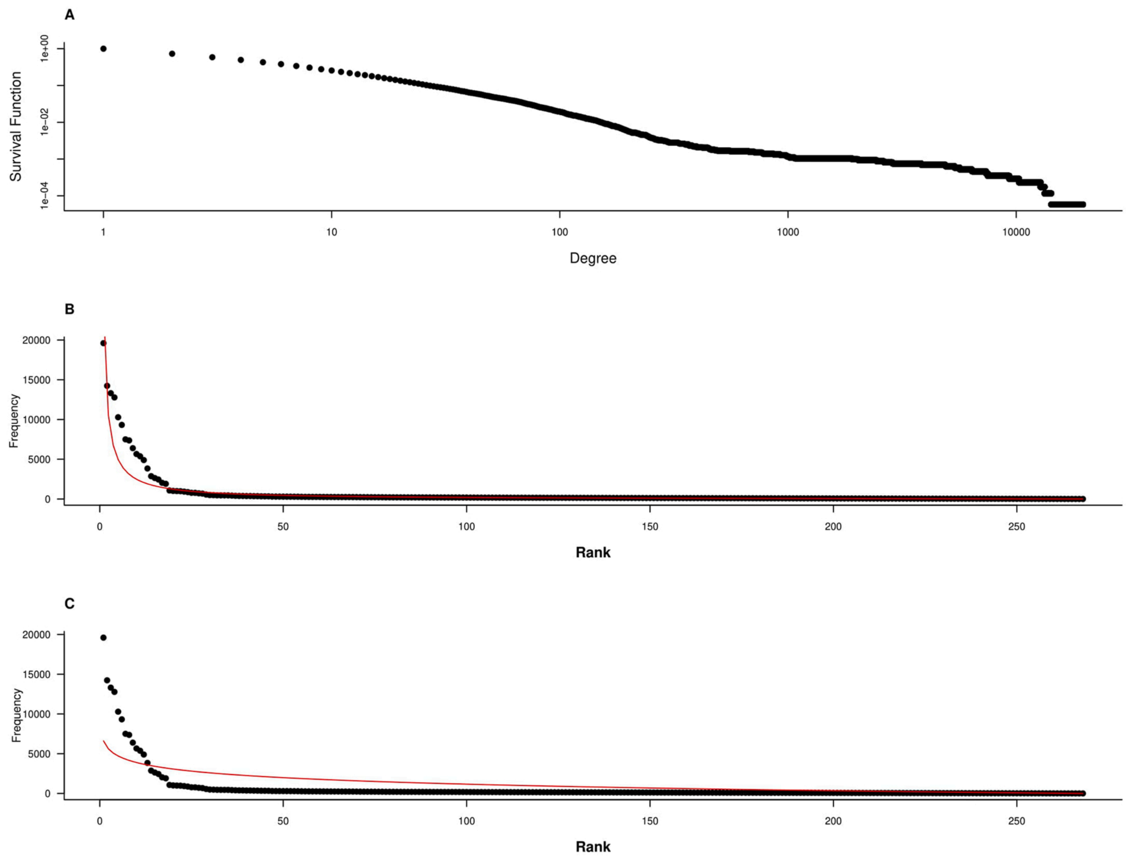

Fig. 3. Degree Distribution fit for whole network (WN). (A) Survival function for degree distribution, power law fit $R^2 = 0.67$, KS.p < 0.05. (B) Rank order of the degree distribution for DBBD fit $R^2 = 0.96$, BIC=^{2}517, (C) Exponential distribution fit $R^2 = 0.5$, BIC= 4003.

Markets class has a significant association only for the *ingoing contact chain* increasing the odds of having high *ingoing contact chain* values considerably. For both measures the location was significant but belonging to Valdivia province decreases the odds of a high *ingoing contact chain* and increases the odds of a high *outgoing contact chain*, suggesting that herds in this region represent more risk of spreading a disease than to be infected. If markets were anywhere on a herd's contact chain was significant for *ingoing infection chain* increasing the odds of high values of this measure, therefore, suggesting that markets can be an important source of infection to herds.

4. Discussion

The contact structure of cattle movements in southern Chile, emphasizing the Los Rios Region, is characterized by the fact that most of the farms involved in cattle trade with Los Rios Region belong to the two nearest regions; de La Araucanía to the north and Los Lagos Region to the south, both regions are important in cattle farming (breed and dairy production). However, it is complex to assess the impact of this relationship because most of the connections do not correspond to direct connections from herds outside regions to holdings within the Los Rios Region. Therefore, if an outbreak originated outside Los Rios Region, the pathogen's spread to the Los Rios Region can be slow and difficult for surveillance. On the other hand, for scenarios related to pathogens of fast spread (for instance FMD) a direct connection between these regions appears less likely.

The presence of livestock markets highly influences the movement flow between provinces in the Los Rios Region; two out of three markets of the region are in Valdivia province, which explains the high proportion of movements from Ranco to Valdivia even though Ranco province has the higher number of holdings of the region. The markets presence also explains the movements within Valdivia province, where small herds are the holding class that presented the highest number of outward shipments; their most frequent destination were livestock markets suggesting that markets are the primary commercialization channel for this group of farmers. Although they usually sell a small number of animals, it is more convenient for them to commercialize through auction markets instead of dealing directly with slaughterhouses, therefore, we need to consider different scenarios; if an epidemic starts on small herds the pathogen can be rapidly spread across the network due to markets influence; however, if the influence of highly connected nodes was absent, likely, the effect of small herds will be more at local spread level being more difficult for an epidemic to spread among a network, but the infection can be stored in a minor population acting as a reservoir. Thus, small herds movement features need to be further explored to assess in more detail for example if special considerations regarding control strategies need to be evaluated for this herd class, such as facilitating direct commercialization with slaughterhouses or promoting the increase of a specific disease-free status that ensures safe trade.

As in many other studies that characterize cattle movement, a small proportion of nodes are responsible for most movements, showing right-skewed degree distribution. Some studies reported degree distribution following a power-law distribution and scale-free properties of their studied networks (Aznar et al., 2011; Brown et al., 2019; Natale et al., 2009; Tinsley et al., 2012; VanderWaal et al., 2016) in comparison with the present study in which degree metrics fits best with a DGBD distribution.

Assortativity levels by size and province can be explained by the fact that the second-largest destination of animal shipment were nodes of the same size (being markets the most frequent destination for every holding) (Table 3). Meanwhile, movements within the same province are mainly driven by markets in both provinces, and also exhibit attachment

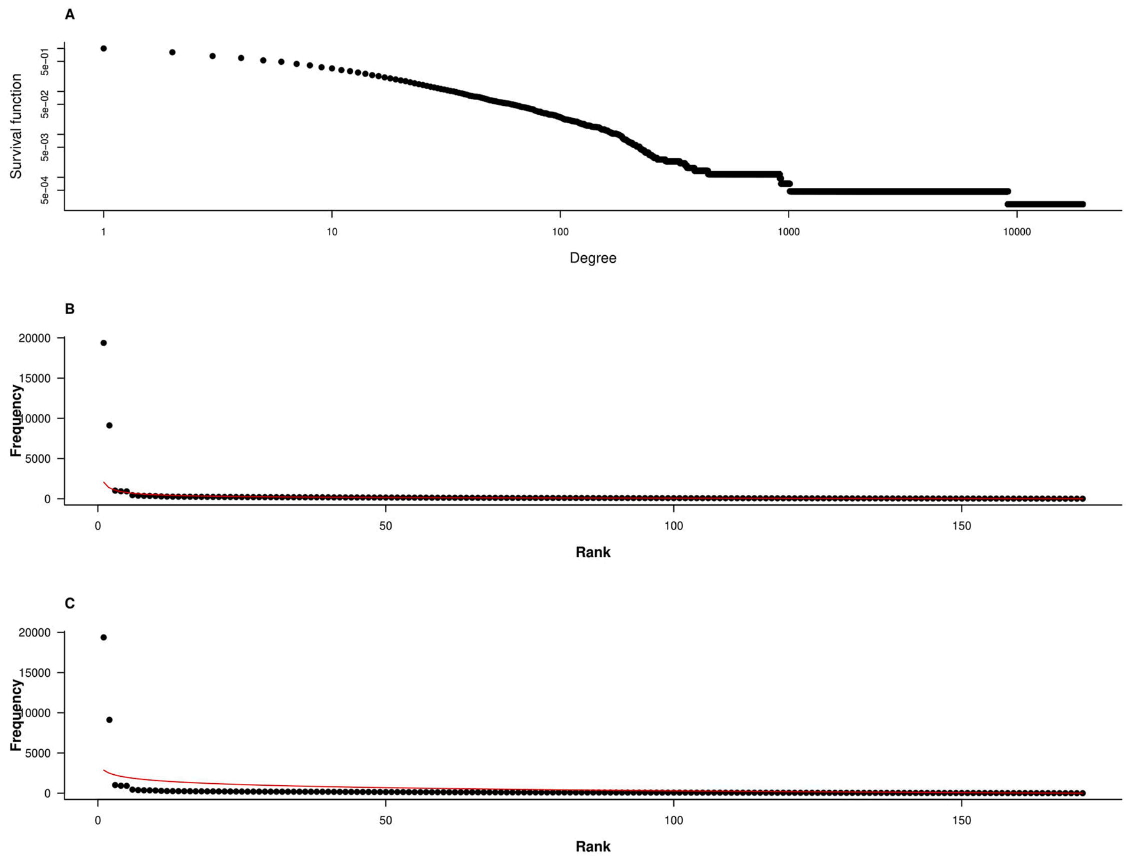

Fig. 4. Degree Distribution fit for los Rios only network (LR-oN). (A) Survival function for degree distribution, power law fit $R^2 = 0.75$, KSp< 0.05, (B) Rank order of the degree distribution for DBBD fit, $R^2 = 0.95$, BIC=^{2}515, (C) Exponential distribution fit $R^2 = 0.21$, BIC=^{2}500.

Table 6
Network metrics, Node assortativity measures and network disaggregation by season for the Whole (WN) and Los Rios-only (LR-oN) networks without markets. Using cattle movements during 2016–2017. In the Los Ríos Region. Chile.

Network	Metrics	Total	Summer16	Autumn16	Winter16	Spring16	Summer17	Autumn17	Winter17	Spring2017
WN	Nodes	17.219	17.219	17.219	17.219	17.219	17.219	17.219	17.219	17.219
	Isolates prop.		0.66	0.62	0.63	0.61	0.58	0.53	0.65	0.59
	Edges	38.978	3.056	4.434	5.219	4.940	4.249	5.285	5.396	5.836
	Density (%)	0.01	0.0001	0.0014	0.0017	0.0016	0.0014	0.0017	0.0018	0.0019
	Reciprocity	0.25	0.18	0.15	0.20	0.16	0.16	0.18	0.19	0.15
	ASPL	10	2	2.1	2.1	2.4	2.2	2.4	2.3	2.7
	Diameter	23	9	7	8	7	9	9	8	13
	AC									
	Size	0.23	0.15	0.19	0.19	0.17	0.34	0.34	0.29	0.15
	Province	0.71	0.74	0.6	0.67	0.68	0.78	0.7	0.68	0.77
	Class	0.19	0.02	0.04	-0.06	0.29	0.27	0.18	0.12	0.31
	Node degree	0.12	-0.16	0.74	-0.04	0.76	0.76	0.12	0.34	0.33
LR-oN	Nodes	4.849	4.849	4.849	4.849	4.849	4.849	4.849	4.849	4.849
	Isolates prop.		0.74	0.72	0.70	0.63	0.62	0.56	0.66	0.57
	Edges	17.162	1.292	1.685	2.396	2.114	1.926	2.319	2.421	2.789
	Density (%)	0.07	0.005	0.007	0.01	0.01	0.008	0.009	0.01	0.01
	Reciprocity	0.32	0.23	0.20	0.26	0.21	0.18	0.21	0.24	0.17
	ASPL	9.5	1.4	1.6	1.6	1.6	1.9	1.8	2.1	2.3
	Diameter	25	5	6	5	6	8	6	6	9
	AC									
	Size	0.2	0.23	0.26	0.16	0.12	0.24	0.34	0.21	0.1
	Province	0.7	0.69	0.65	0.76	0.76	0.67	0.65	0.73	0.69
	Class	0.008	-0.013	0.04	-0.03	-0.04	-0.13	0.1	-0.04	0.12
	Node degree	0.07	0.6	0.33	0.35	0.18	0.24	0.15	0.19	0.08

AC= Assortativity coefficient ASPL= Average shortest path length; Isolates prop.= Proportion of isolates nodes (nodes with degree of zero).

preference within the same province as well.

The Whole and Los Rios-only networks were found to be well connected, and this feature is consistent over seasons for the two years study period with small average shortest path lengths and small diameters in comparison to other studies (VanderWaal et al., 2016), also extremely low density and moderate reciprocity are among the main characteristics. This connectivity seems to be mainly caused by the markets, they showed extremely high values (data not shown) of node metrics

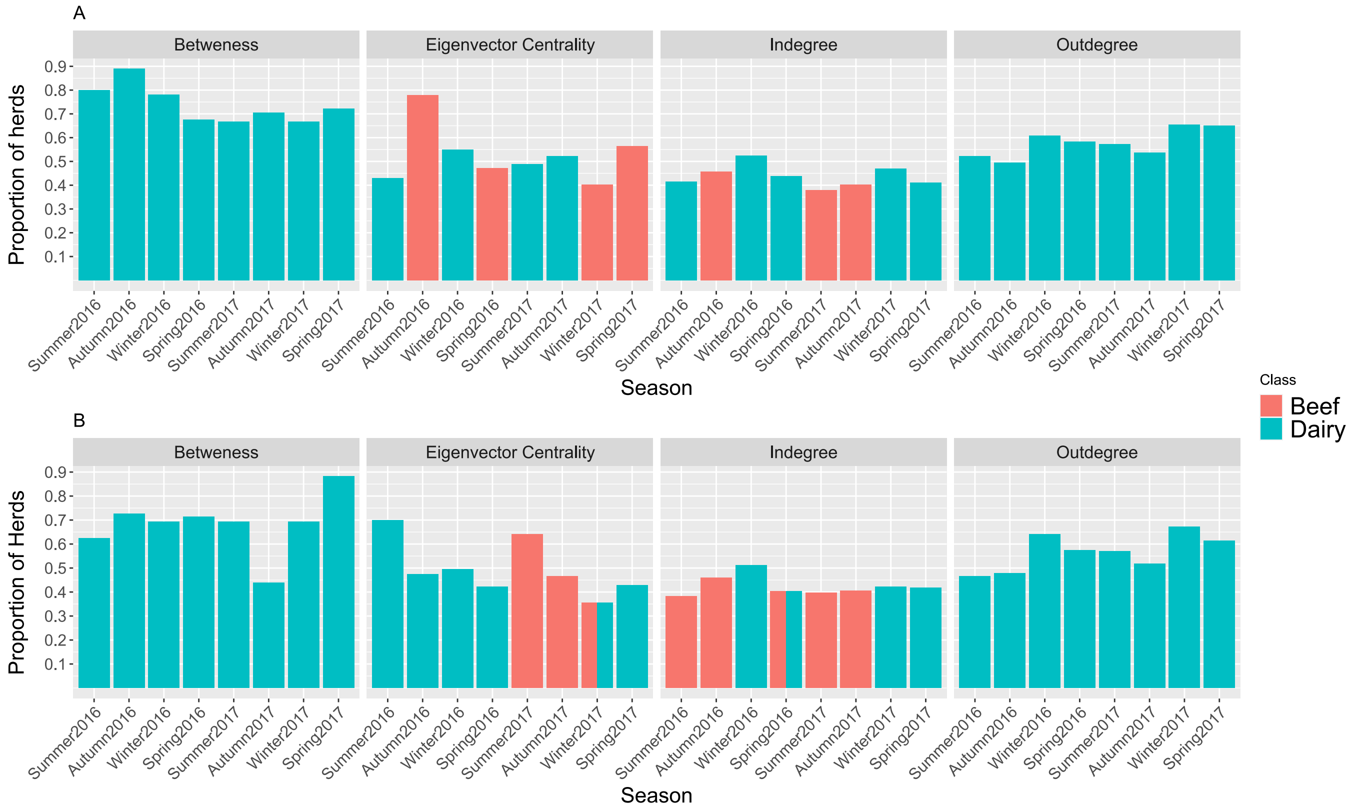

Fig. 5. Nodes classes with more herds in the 90th percentile for node metrics for the Whole (WN) (A) and Los Rios-only (LR-oN) (B) networks after removal of markets and their connections, using cattle movements during 2016–2017, in the Los Ríos Region. Chile.

Table 7
Descriptive statistics for contact chain measures for the Whole (WN) and Los Rios-only (LR-oN), and the networks after removing all movements to markets (wo. Markets). Using cattle movements during 2016–2017, in the Los Ríos Region. Chile.

	In-going Contact Chain			Out-going Contact Chain		
Networks	Median	Mean	Range	Median	Mean	Range
Whole	0	1.630	0 – 16.086	1.940	1.632	0 – 2.241
Whole wo. Markets	1	14	0 – 1.201	1	14	0–562
Los Rios	1	450	0 – 3.006	625	450	0 – 949
Los Rios wo. Markets	2	5	0 – 284	0	6	0 – 219

compared to other nodes with high values for the same measures, suggesting that markets can serve as bridges shortening pathways and increasing connectivity in the networks. Similar results were reported by (Brown et al., 2019), suggesting that access to nodes was easy due to small average shortest path length values for all networks. For pathogen transmission in southern Chile, markets can play a crucial role, not only connecting nodes that in other circumstances will not be reachable but also can be responsible for how fast a pathogen can spread between herds due to their high number of incoming and outgoing connections.

This dominance of markets in centrality measures suggests that they can have a significant role as pathogen spreaders and be targeted for control and surveillance measures. In this sense, Marquetoux et al. (2016) indicate that network fragmentation can be achieved by removing central nodes that serve as bridges between them because they connect otherwise non-connected nodes or clusters, decreasing the probability of large epidemics. In addition, Natale et al. (2009) suggest that centrality measures can characterize holdings assessing the potential to cause epidemics, showing that when nodes with high eigenvector centrality values the seed for an infection a strong correlation with the extent of the epidemics appears.

Ingoing and outgoing movements present a low correlation for both WN and LR-oN networks respectively ($p < 0.05$, $\rho = 0.17$, $\rho = 0.11$), suggesting that in southern Chile a few herds can have a high potential of getting infected and being able to spread the pathogen to others. The possible explanation is that most of the herds are primarily buyers or sellers, e.g, most fattening herds have a high in degree, however their outdegree is low because they usually sell a few times in the year. And cow-calf herds usually have low indegree, however, they have a high outdegree because the main economic activity is to sell the calves that they produce to other holdings to finish the fattening process or eventually to markets for intermediation.

In the Whole and Los Rios-only networks, nodes with higher indegree and outdegree are markets, Exhibition/Sport centers, and herds that we suspect are cattle dealers (in the official National Service System they are enrolled as generic beef herds). However, it is likely that the importance of Exhibition/Sport centers is only over a network subset and not for the complete network; this can be explained because the indegree and outdegree values are significantly smaller in comparison to markets and because Exhibition/Sport centers connect preferably with beef herds in terms of inwards and outwards movement. Notably, the correlation between degree measures and betweenness centrality is solid and positive, showing that most influential nodes are not only responsible for controlling the flow of animals transferred to other units (and the potential risk of spreading a pathogen for example), but they are also

Table 8
Results from the generalized linear model. Assessing between ingoing contact chain and outgoing contact chain with nodes characteristics; for Los Rios-only (LR-oN) network. Using cattle movements during 2016–2017. In the Los Ríos Region, Chile.

Category		OR	95% CI
Ingoing contact chain			
(Intercept)		0.10	0.08–0.13
Herd Class			
	Beef	Ref.	
	*Dairy**	0.54	0.41–0.70
	*Mixed**	0.61	0.45–0.83
	Others†	1.50	0.97–2.25
Market*		15.92	1.49–347.21
	Sports/Exhibition	0.80	0.04–4.17
Location (Province)			
	Ranco	Ref.	
	Valdivia*	0.57	0.45–0.71
Market in contact chain:			
	No	Ref.	
	Yes*	1.76	1.38–2.27
Outgoing contact chain			
(Intercept)		0.088	0.074–0.104
Herd Class			
	Beef	Ref.	
	Dairy*	2.277	1.84–2.815
	Mixed*	1.452	1.101–1.89
	Others	0.836	0.444–1.443
Market		199,166	0-NA
	Sports/Exhibition	0.000	NA-99.1
Location Province			
	Ranco	Ref.	
	Valdivia*	1.333	1.098–1.616

* $P < 0.05$.
† $P < 0.1$.

more likely to introduce animals (and become infected and/or spread/ maintain the circulation of a pathogen in the population). When markets are removed from the networks, the spearman correlation coefficients tendencies are similar; however, for in-degree and outdegree the coefficient is low and negative ($p < 0.05$, $\rho = -0.058$, $\rho = -0.02$) for the WN without markets and LR-oN without markets respectively. These correlations show that other less dominant nodes can play a similar role even though highly dominant nodes were removed, pointing out that the network's underlying features must be explored. Correlation between degree measures has been widely reported, however, results are not always in agreement (Dutta et al., 2014; VanderWaal et al., 2016; Volkova et al., 2010), mainly because of the differences in the production chain activities and production systems that have specific features for every country.

Removal of markets caused an apparent decrease in connectivity, resembled by an increase in average shortest path length and diameter, and density remaining extremely low for WN and LR-oN networks (Table 6). Diameter and density maintain stable in WN and LR-oN disaggregated by seasons as it was for the overall networks, but density decreases when networks are disaggregated, this is caused by the increase in isolated nodes causes by markets removal. Average shortest path length did not account for a connectivity decrease in disaggregated by season network, possibly given by direct trade among herds, which is the second-largest commercialization channel for herds in southern Chile (INE, 2015). When markets are removed, networks metrics values are also in concordance with (VanderWaal et al., 2016) who found similar results in the Uruguay cattle trade network where markets are not included.

Only direct contacts between farms remain in the absence of markets, and dairy herds take the place of markets as dominant nodes (Fig. 5). The fact that disaggregated networks did not account for a decrease in connectivity when compared to static overall WN and LR-oN without markets suggests that large static networks can mask connectivity features that arise in disaggregated networks. It could be due to the fact that connections develop and disappear over time, as well as the impact of new dominating nodes. We must also remember that in the real world, control measures such as market movement restrictions or standstill periods might result in a rewiring phenomenon, affecting connectivity and metric values (Robinson et al., 2007). As a result, networks must be thoroughly examined in order to completely comprehend the potential role of importance in apparent nodes in large networks over time.

As shown in Table 7, temporal metrics are also extremely sensitive to the effect of the market's removal. The reduction in temporal metrics values is not only a consequence of the absence of market's ingoing or outgoing movements but also because indirect contacts through markets were removed as well. Meaning that the *ingoing* and *outgoing contact chains* of a given herd significantly depends on if in anywhere on the contact chain markets are present (as direct or indirect contact). The values for yearly contact chain measures are similar to reported values by (Nöremark et al., 2011); however, ranges are quite different, especially for maximum *ingoing contact chain* that can reach 93% and 71% of the nodes present in WN and LR-oN. The exceptionally high values can be explained by the contact with markets for animal purchase which causes a high number of indirect contacts for the target herd.

The low median values for the ingoing contact chain (Table 7) are explained because most herds have few ingoing movements, not introducing animals frequently. On the other hand, when herds purchase animals from markets, the *ingoing contact chain* increases enormously (reflected in the maximum value of the range) because of the high number of incoming connections of the markets and the contact chain's indirect contacts as well. In this sense, connecting with markets increases the potential risk of introducing infected animals, since markets tend to receive animals from many herds. In contrast, the *outgoing contact chain* median is high because herds tend to sell more frequently than buy animals, and because of the influence of markets that can increase *outgoing contact chain*, presumably due to fattening herds purchase of male calves. The *outgoing contact chain* range maximum value is considerably less than the *ingoing contact chain* because most of the movements from markets are directly to slaughterhouses (not considered in this research) and secondly to fattening herds as mentioned earlier. The absence of markets causes that *ingoing* and *outgoing contact chain* values decreases due to between herds direct trade effect predominance, suggesting that markets favor pathogens dissemination by adding dynamism to the infection chain. In LR-oN some nodes do not present any outgoing movements once markets are removed from contact chain; this is because there are herds that sell only to markets (especially small herds), hence, they act as dead ends because network re-wiring after nodes removal is not considered. However, it is critical to remember that while evaluating these measures, the speed with which a pathogen might spread within a farm must be taken into account. Because a pathogen with a short infectious duration in a sparse network is unlikely to propagate before extinction, this is the case. One with a lengthy infectious period in the same network, on the other hand, is more likely to establish and spread widely (Fielding et al., 2019).

A positive and strong correlation was found for degree and contact chain measures indicating that herds with high indegree or outdegree also are the ones with the highest contact chain.

The associations between nodes characteristics and high contact chain measures (Table 8) are characterized by a reduction in the odds for dairy and mixed herds to have high values of contact chains measures and an increase in odds to have high values of *ingoing contact chain* for markets. Dairy and mixed herds are less likely to have high values of *ingoing contact chain* than beef herds and are more likely to have high values of *outgoing contact chain*. Usually, Dairy and mixed herds show a minor purchases frequency and most of the time they buy to other herds of the same class, because they rely especially on breeding their reposition animals. On the contrary, dairy and mixed herd sells young and old animals to fattening herds and markets, which are more connected, explaining the high value for *outgoing contact chain*. Markets were only associated with high values of *ingoing contact chain*, the high purchase frequency of markets can explain it; on the contrary markets move animals directly to slaughterhouses and less frequent to other herds, which cause that no significant association with *outgoing contact chain* was observed for them. However, herds that purchase animals from markets are more likely to show higher values of *ingoing contact chain* because of indirect contacts of herds with markets. Hence, surveillance or at least biosecurity measures prior to the introduction of animals purchased in markets is recommended due to the infectious potential given by the direct and indirect contacts of markets with herds with unknown or potential infected status.

Herds located in Valdivia province are less likely to have a high *ingoing contact chain* than those located in Ranco province. It is unclear what could be the reason for this given that both provinces are very well balanced in terms of number and type of herds. However, according to the 2015 National Livestock Survey (INE, 2015), in Valdivia providence breeding cattle is significantly larger than in the Ranco province, Hence, these herds tend to buy fewer cattle because they self-replace their stocks.

Our analysis has two potential limitations; First, we used a static network to represent a dynamic system in that all movements within a specified period are merged and the temporal order is lost. However, static networks are extensively used to explore contact structures, and epidemiological models of between-farm transmission, providing a good metric of epidemic size (Vernon and Keeling, 2009) though they may over-represent the network's connectivity, which can be quantified from data (Lentz et al., 2016). Second, it was challenging to identify nodes that act as cattle dealers and differentiate between fattening and breeding herds because all of those nodes are registered as generic beef herds in the official database. Third, weighting links and a lack of knowledge about the animals' residency period can be useful in determining the strength of relationships that may be significant for pathogen spread.

This study is the first cattle movement description in the country. And to our knowledge. Are only published two other descriptions of cattle movements in South America (Aznar et al., 2011; VanderWaal et al., 2016).

5. Conclusions

Cattle's contact structure in southern Chile shows aspects that need to be considered for disease transmission and control measures. Presence of a few highly connected central nodes and average short paths between herds increase the potential connectivity, essential for pathogen dissemination. Live animals auction markets have a significant effect on masking underlying networks characteristics and variation in some metrics that are important for assessing the risk for pathogen spread. For southern Chile conditions, markets can be good candidates for targeted surveillance due to their likely role of causing "super-spreading events". Also, the results showed that it is not always enough to set up control strategies over specific nodes (e.g., markets only) without a deeper exploration of the characteristics of the underlying network. These features can be critical, especially in the last phases of control and eradication strategies, because they can maintain infectious agents in the area.

This information will enhance our understanding of the epidemiology of many endemic infectious diseases, and it will be helpful to implement a future Bovine Viral Diarrhea Virus (BVDV) pilot control program in the area for example. Exploring the connections between Provinces within the Los Rios Region can provide insights for compartmentalization or zoning strategies.

Declarations of interest

None.

Competing Interests

The authors declares not to have any conflict of interest.

Acknowledgments

This work was funded by the National Agency for Research and Development (ANID) / Scholarship Program / DOCTORADO BECAS CHILE/2017 – 21151227. All data was provided by Animal Health Service (Servicio Agricola y Ganadero. SAG).

Data Statement

Because the Animal Health Service in confidentiality provided the data. Stakeholders were assured that raw data would remain confidential and would not be shared due to the sensitive nature of the information in this study.

References

Alocilla, O.A., Monti, G., 2022. Bovine Viral Diarrhea Virus within and herd prevalence on pasture-based dairy systems, in southern Chile dairy farms. Prev. Vet. Med. 198, 105533.
Aznar, M.N., Stevenson, M.A., Zarich, L., León, E.A., 2011. Analysis of cattle movements in Argentina, 2005. Prev. Vet. Med. 98, 119–127.
Broido, A.D., Clauset, A., 2019. Scale-free networks are rare. Nat. Commun. 10, 1017-1017.
Brown, E., Marshall, A.H., Mitchell, H.J., Byrne, A.W., 2019. Cattle movements in Northern Ireland form a robust network: implications for disease management. Prev. Vet. Med 170, 104740.
Caporale, V., A, G., Francesco C, Di, Calistri, P., 2001. Importance of the traceability of animals and animal products in epidemiology. Rev. Sci. Et. Tech. (Int. Off. Epizoot.) 20 (2), 372–378.
Clauset, A., Shalizi, C.R., Newman, M.E.J., 2009. Power-law distributions in empirical data. SIAM Rev. 51, 661–703.
Croft, D., Madden, J., Franks, D., James, R., 2011. Hypothesis testing in animal social networks. Trends Ecol. Evol. 26, 502–507.
Csardi, G., Nepusz, T., 2005. The igraph software package for complex network research. Inter. Complex Syst. 1695.
Christley, R., E. Robinson, S., Lysons, R., French, N, 2005, Network Analysis of Cattle Movements in Great Britain. Proceedings of a meeting held at Nairn, Inverness, Scotland.
Dubé, C., Ribble, C., Kelton, D., McNab, B., 2009. A review of network analysis terminology and its application to foot-and-mouth disease modelling and policy development. Transbound. Emerg. Dis. 56, 73–85.
Dubé, C., Ribble, C.S., Kelton, D., McNab, B., 2011. Inroduction to network analysis and its implications for animal disease modelling. Rev. Sci. Et. Tech. -Off. Int. Des. Epizoot. 30, 425–436.
Dutta, B.L., Ezanno, P., Vergu, E., 2014. Characteristics of the spatio-temporal network of cattle movements in France over a 5-year period. Prev. Vet. Med. 117, 79–94.
Fielding, H.R., McKinley, T.J., Silk, M.J., Delahay, R.J., McDonald, R.A., 2019. Contact chains of cattle farms in Great Britain. Royal Society Open Science 6, 180719.
Freeman, L.C., 1978. Centrality in social networks conceptual clarification. Soc. Netw. 1, 215–239.
Frössling, Jenny, et al., 2012. "Application of network analysis parameters in risk-based surveillance-examples based on cattle trade data and bovine infections in Sweden.". Prev. Vet. Med. 105. 3 202–208.
Gates, M.C., Woolhouse, M.E.J., 2015. Controlling infectious disease through the targeted manipulation of contact network structure. Epidemics 12, 11–19.
Golbeck, J., 2013, Chapter 3 – Network Structure and Measures, In: Analyzing the Social Web. Morgan Kaufmann, Boston, pp. 25–44.
INE, 2007, VII Censo Nacional Agropecuario y Forestal. Restulados preliminares 2006–2007. INE. Instituto Nacional de Estadisticas.
INE, 2015, Encuesa de Ganado Bovino 2015. Insituto Nacional de Estadisticas.
Lentz, H.H.K., Koher, A., Hövel, P., Gethmann, J., Sauter-Louis, C., Selhorst, T., Conraths, F.J., 2016. Disease spread through animal movements: a static and temporal network analysis of pig trade in Germany. PLOS ONE 11, e0155196.
Lopez, D.N., Camus, P.A., Valdivia, N., Estay, S.A., 2018. Food webs over time: evaluating structural differences and variability of degree distributions in food webs. Ecosphere 9 (12), e02539. https://doi.org/10.1002/ecs2.2539.
Marquetoux, N., Stevenson, M.A., Wilson, P., Ridler, A., Heuer, C., 2016. Using social network analysis to inform disease control interventions. Prev. Vet. Med. 126, 94–104.
Martínez-Mekler, G., Martínez, R.A., del Río, M.B., Mansilla, R., Miramontes, P., Cocho, G., 2009. Universality of Rank-Ordering Distributions in the Arts and Sciences. PLOS ONE 4 (3), e4791. https://doi.org/10.1371/journal.pone.0004791.
Natale, F., Giovannini, A., Savini, L., Palma, D., Possenti, L., Fiore, G., Calistri, P., 2009. Network analysis of Italian cattle trade patterns and evaluation of risks for potential disease spread. Prev. Vet. Med 92, 341–350.
Newman, M.E.J., 2003. Mixing patterns in networks. Phys. Rev. E 67, 026126.

Nöremark, M., Håkansson, N., Lewerin, S.S., Lindberg, A., Jonsson, A., 2011. Network analysis of cattle and pig movements in Sweden: measures relevant for disease control and risk based surveillance. Prev. Vet. Med 99, 78–90.
Nöremark, M., Widgren, S., 2014. EpiContactTrace: an R-package for contact tracing during livestock disease outbreaks and for risk-based surveillance. BMC Vet. Res 10, 71-71.
Peel, L., Delvenne, J.C., Lambiotte, R., 2018. Multiscale mixing patterns in networks. Proc. Natl. Acad. Sci. 115, 4057.
R. Core Team, 2019, R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria.
Sosa, S., Puga-Gonzalez, I., Hu, F., Pansanel, J., Xie, X., Sueur, C., 2020. A multilevel statistical toolkit to study animal social networks: the Animal Network Toolkit Software (ANTs) R package. Sci. Rep1 0, 12507.
Tinsley, M., Lewis, F.I., Brulisauer, F., 2012. Network modeling of BVD transmission. Vet. Res 43, 11.
VanderWaal, K.L., Picasso, C., Enns, E.A., Craft, M.E., Alvarez, J., Fernandez, F., Gil, A., Perez, A., Wells, S., 2016. Network analysis of cattle movements in Uruguay: Quantifying heterogeneity for risk-based disease surveillance and control. Prev. Vet. Med 123, 12–22.
Verdugo, C., 2004, Caracterización del flujo de ganado bovino en Chile. Ministerio de Agricultura.
Vernon, M.C., Keeling, M.J., 2009. Representing the UK's cattle herd as static and dynamic networks. Proc. Biol. Sci. 7 276 (1656), 469–476.
Volkova, V.V., Howey, R., Savill, N.J., Woolhouse, M.E.J., 2010. Potential for transmission of infections in networks of cattle farms. Epidemics 2, 116–122.
Wasserman, S., Faust, K., 1994. Social Network Analysis: Methods and Applications. Cambridge University Press,, Cambridge.
Weiss, M.N., Franks, D.W., Brent, L.J.N., Ellis, S., Silk, M.J., Croft, D.P., 2021. Common datastream permutations of animal social network data are not appropriate for hypothesis testing using regression models. Methods Ecol. Evol. 12, 255–265.
Widgren, S., Engblom, S., Bauer, P., Frössling, J., Emanuelson, U., Lindberg, A., 2016. Data-driven network modelling of disease transmission using complete population movement data: spread of VTEC O157 in Swedish cattle. Vet. Res. 47, 81.