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Sheep Movement Networks in Three Chinese Regions and the Implications of Network Properties for the Spread of Brucellosis*

中国三个不同地区的活羊调运网络及其布鲁氏菌病传播风险

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Abstract:【Objective】To reveal the sheep movement networks in different regions,compare the risk of brucellosis outbreak,and find out the keys for its prevention and control.**【Methods】**We constructed a social network of sheep transportation in three different regions of Inner Mongolia and conducted social network analysis,using Uninet6.0 to draw network diagrams and calculate relevant network measures.**【Results】**The agricultural network we constructed was reticular,whereas the pastoral region network presented "snowflake-like" structures. The agricultural-pastoral network had characteristics of both the agricultural and pastoral networks. The "small-world" properties of the agricultural and agricultural-pastoral network indicated a higher risk of brucellosis outbreak. The majority of the influential nodes in the agricultural network were farmers,whereas the influential nodes in the pastoral and agricultural-pastoral networks were mostly sheep traders.**【Conclusion】**The sheep-movement networks of agricultural and agricultural-pastoral region have higher risk of brucellosis outbreak. The combination of social network analysis and animal transportation tracking system can better serve as a support for the prevention and control of brucellosis. Freezing live sheep circulation activities at key nodes during an outbreak can effectively control the epidemic.

Key words: brucellosis,network analysis,sheep movement,disease spread,outbreak

摘要:【目的】揭示不同地区的活羊调运网络结构,对比其布鲁氏菌病疫情暴发风险大小,并找出其防控关键点。

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【方法】构建内蒙古3个不同地区的活羊调运社会网络并进行社会网络分析，采用 Uninet6.0 绘制网络关系图及计算相关的网络测度。【结果】农区活羊调运网络为网状结构，而牧区活羊调运网络呈现许多"雪花状"结构，半农半牧区的活羊调运网络则兼具农区和牧区的网络特征；农区和半农半牧区的活羊调运网络表现出"小世界"的特征；农区传播力较强的节点大多为养殖户，而贩运经纪人在牧区和半农半牧区网络中具有重要的传播影响力。【结论】农区和半农半牧区的布鲁氏菌病暴发风险较高；社会网络分析与动物调运追踪系统结合能更好地作为布鲁氏菌病防控的支撑，在疫情暴发时冻结关键节点的活羊流通活动能够有效控制疫情。
关键词：布鲁氏菌病　网络分析　活羊调运　疾病传播　暴发

中图分类号：R183，O175　　**文献标识码**：A　　**文章编号**：1005-9164(2018)03-0304-09

0 Introduction

Brucellosis, which occurs in more than 100 countries, is the most common zoonotic disease worldwide[1-2]. Although the mortality of brucellosis is low, brucellosis remains a significant issue worldwide and substantially affects the economy and human health[3]. Transmission of brucellosis between humans is rare. Individuals mainly obtain the disease from livestock, such as sheep, therefore, controlling human brucellosis requires the control of animal brucellosis[4]. Contacts between locations during sheep movements determine the global spread of brucellosis. Sheep movements between locations can be considered a network in which the locations are represented as nodes and the movements are defined as edges or relationships. Therefore, the brucellosis transmission network occurs within the sheep-movement network[5], and data from the sheep-movement network are valuable for understanding the epidemiological characteristics of brucellosis. Thus, various sheep-movement networks contribute to the different risk levels for brucellosis outbreaks in different regions[6].

Because livestock movement data are valuable in the prevention and control of zoonotic diseases, many countries have established livestock movement databases or animal-trace-bank systems. A promising approach to analyzing livestock movement network data is social network analysis (SNA)[7]. SNA has been used widely in human epidemiology as a tool to research infectious diseases such as SARS[8], AIDS[9-10] and tuberculosis[11], but it has only recently been applied in preventive veterinary care. Many countries, including England, Spain, Italy, Denmark, Sweden, and France, have applied SNA to the analysis of livestock movement data. Bigras-Poulin characterized the trade patterns of the Danish cattle and swine industries and evaluated the potential risk for disease spread with SNA[12-13]. Using SNA techniques, Natale described the global structure of the Italian cattle industry and the relationships between locations relative to the potential implications of the transmission of cattle diseases[14]. Rautureau proposed a method based on the analysis of specific subnetworks to assess network vulnerability in the spread of infectious diseases and to determine an efficient method for developing emergency control strategies[15]. In general, SNA offers benefits for characterizing the pattern of livestock movements, exploring the risk of potential disease spread, analyzing the effects of livestock movement network structures in the spread of diseases and providing a method for identifying high-risk individuals or groups for the introduction or spread of zoonotic diseases in preventive veterinary medicine.

This paper describes the sheep-movement networks of various regions in Inner Mongolia of China. Several statistical network metrics were estimated, representing the network properties and vulnerability to the spread of brucellosis. The risk of brucellosis outbreak in different regions was then calculated based on related SNA indicators and the high-risk nodes and key points of brucellosis prevention in each network were also explored.

1 Materials and Methods

1.1 Profile of sheep Farming system in Xingan Alliance

The sheep farming system profile in the Xingan Alliance Inner Mongolia is one of several provinces in China with a particularly high incidence of brucellosis. This study was conducted in the Xingan Alliance of Inner Mongolia. The Xingan Alliance is located in the northeastern region of Inner Mongolia. With rich pasture resources (3 000 acres) and a large carrying capacity (6.4 million sheep), the Xingan Alliance is becoming a major livestock production base of Inner Mongolia and China. Recently, the incidence of brucellosis in humans in the Xingan Alliance has increased, in part because of an increase in the number of herdsmen. The total number of brucellosis patients from 2001 to 2009 was 5 420. Sick sheep are the main infectious source of animal and human brucellosis in the Xingan Alliance.

For the sheep-movement relationships between locations along the sheep production chain in the Xingan Alliance, see Fig. 1. The sheep flow between herdsmen is a retailer network, whereas the network between herdsmen and live sheep traders is wholesale. There are considerable variations in the sheep farming system, sheep-movement patterns and the risk of brucellosis outbreak in different regions of the Xingan Alliance. One of the study objectives was to compare the risk of brucellosis outbreak in different regions based on a sheep-movement network analysis.

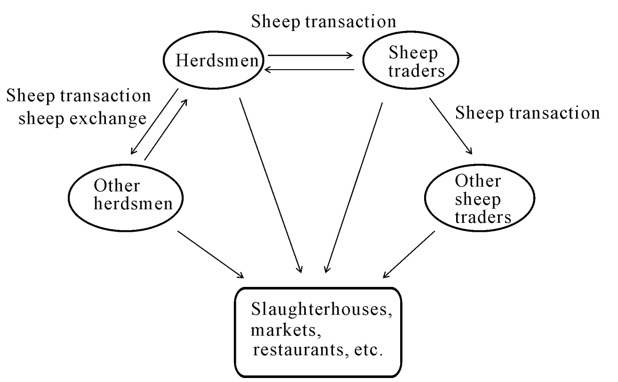


Fig. 1 The sheep-movement relationships between locations along the sheep production chain in the Xingan Alliance

1.2 Data

Expert-opinion elicitation panels were conducted in the initial stage of this study, including slaughterhouse managers and experts from animal health supervision agencies and from animal disease prevention and control agencies from the three regions of Inner Mongolia. The purpose of the informal discussion was to understand the history of the brucellosis epidemic, the related prevention and control strategies and the sheep flow pattern of Inner Mongolia.

A questionnaire was used as a survey tool in the second stage of the study. One hundred farms or herdsmen and 20 sheep traders completed the questionnaire, in each of the three regions of Inner Mongolia after stratified sampling. The following attributes for each premise were included in the questionnaire: the location type (farms, herdsmen or sheep traders) and a record of each sheep movement, including the date, number, origin and destination.

1.3 Network construction and analysis

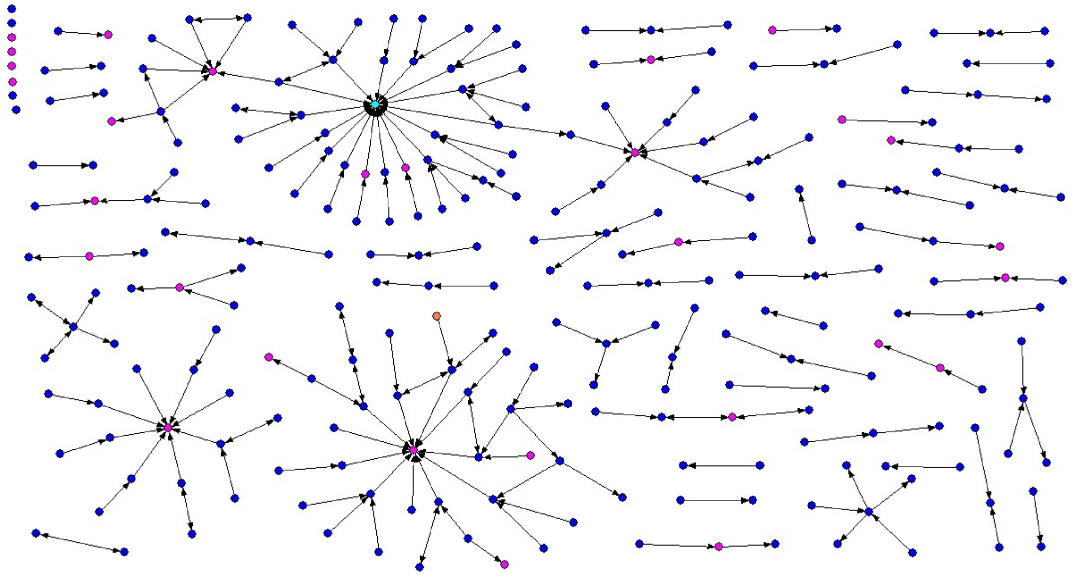
Based on the sheep-movement data we obtained from the questionnaire, we constructed sheep-movement matrices to construct directed sheep-movement networks of the three regions, in which each location was considered a node and each sheep movement represented an edge. Because a small number of sheep flowed into local consumption, we defined a node in each of the three networks to represent the local markets and restaurants.

The sheep-movement matrices were initially translated into maps of sheep-movement networks. For each network, the following network measures were calculated to investigate the network structure and vulnerability: density, the characteristic path length, diameter, centralization, clustering coefficient and components. For each node, the indegree, outdegree and betweenness were calculated to explore the influence of the node on the spread of brucellosis. The correlation between the indegree and outdegree was examined because a high correlation between these variables accelerates the spread of brucellosis.

2 Results

2.1 Maps of the three sheep-movement networks

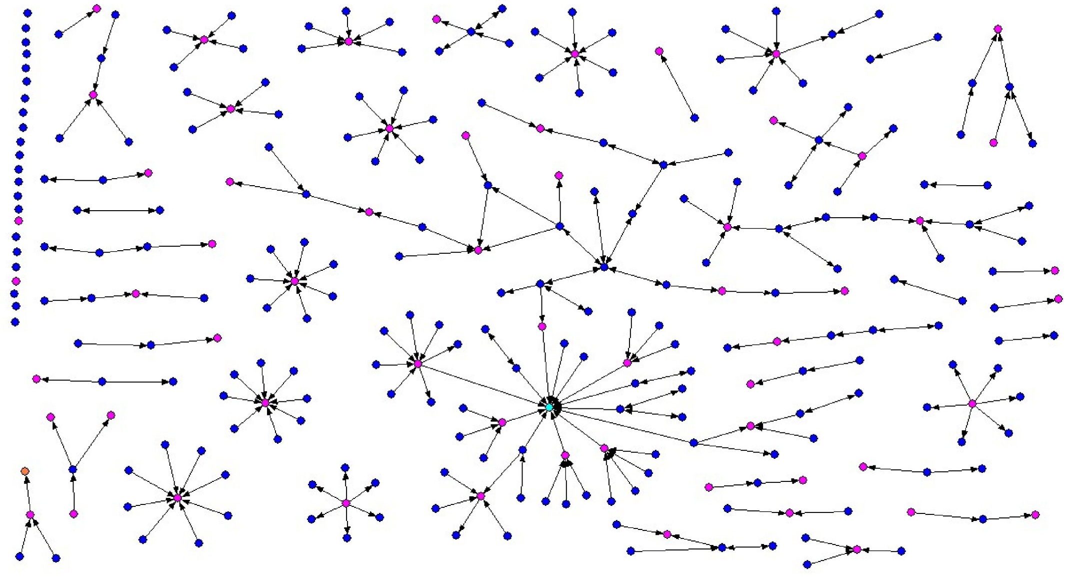
Fig. 2 shows that with three obvious hub nodes, the sheep-movement network of the agricultural region is reticular. Many nodes are scattered around the hub nodes and point inward. Additionally, the network map includes many small components of one to five nodes. The dark blue dots are prone to directly connecting to other dark blue dots, thus showing that the sheep transaction and exchange between farms is more frequent in this agricultural region. Generally, the sheep were moved several times before being dispatched to the slaughterhouse.



Dark blue dots represent farms, light blue dots represent slaughterhouses, red dots represent sheep traders, and orange dots represent markets or restaurants

Fig. 2 The sheep-movement network map for the agricultural region

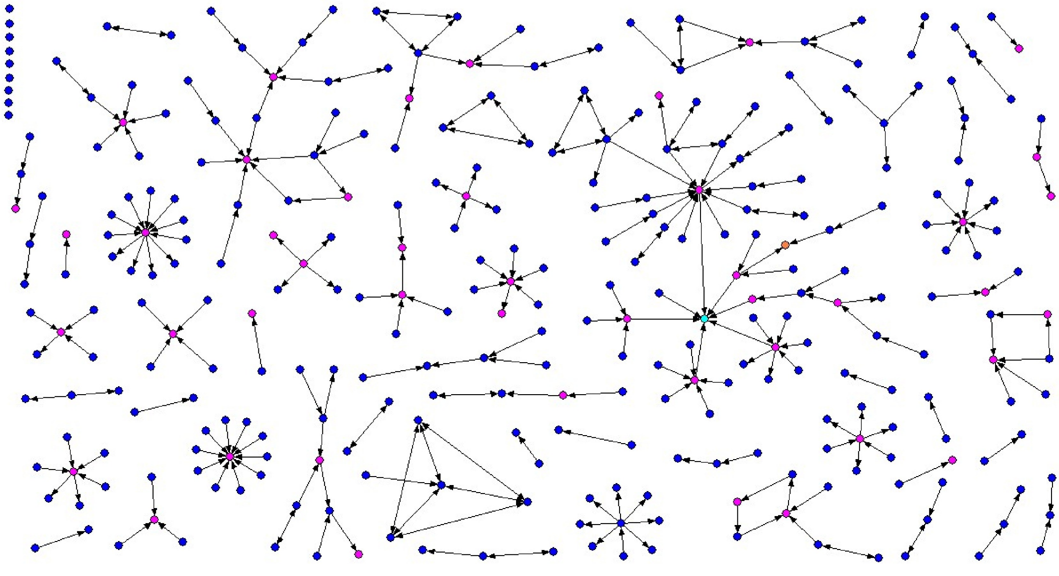
Fig. 3 shows the sheep-movement network of the pastoral region. This network consists of a huge cluster and several small components. More specifically, the network includes many "snowflake-like" structures with central red dots and surrounded by dark blue dots. Unlike the agricultural network, most of these dark blue dots connect to red dots rather than to other dark blue dots, thus demonstrating that in the pastoral region, there were few exchanges of sheep between herdsmen and few total sheep transactions. Most of the sheep were initially wholesaled to sheep traders and sent to market or to the slaughterhouse by the sheep traders. In this region, the sheep trader plays an intermediary role in the circulation of sheep.



Dark blue dots represent farms, light blue dots represent slaughterhouses, red dots represent sheep traders, and orange dots represent markets or restaurants

Fig. 3 The sheep-movement network map of the pastoral region

Fig. 4 shows that the agricultural-pastoral network has the characteristics of both agricultural and pastoral region networks. This region had many "snowflake-like" structures with red dots at the center, and there were also many blue nodes connected into small chain-like components. The farms and the pastures were relatively isolated. The sheep-circulation mode of the agricultural-pastoral farms was similar to that of the agricultural region, whereas that of the herdsmen of agricultural-pastoral region was similar to that of the pastoral region.



Dark blue dots represent farms, light blue dots represent slaughterhouses, red dots represent sheep traders, and orange dots represent markets or restaurants

Fig. 4 The sheep-movement network map of the agricultural-pastoral region

2.2 The comparison of the size of the three sheep-movement networks

Table 1 shows that there is no difference in the average geodesic distance or diameter of the three networks. The agricultural network contained fewer nodes and directed links and the pastoral network contained more isolated nodes in the three networks. The average geodesic distances of the three sheep-movement networks are 3.851, 4.905, 3.457, and the longest distance between any two nodes in the three networks is less than five.

Table 1 Descriptive statistics of network size

Region	Measures				
	Number of nodes	Number of isolated nodes	Number of directed links	Average geodesic distance	Diameter
Agricultural region	258	8	225	3.851	10
Pastoral region	284	23	242	4.905	13
Agricultural-pastoral region	308	9	290	3.457	9

Fig. 5 and Fig. 6 show that the frequency distributions of the outdegrees and indegrees of the three networks were highly similar. Node degree, particularly the indegree, showed heterogeneity. Most outdegrees were 1, followed by 0, whereas most indegrees were 0, followed by 1.

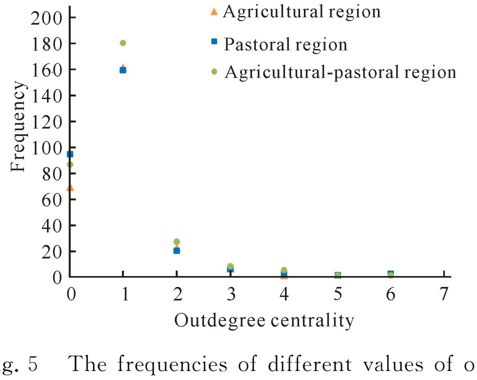


Fig. 5 The frequencies of different values of outdegree centrality

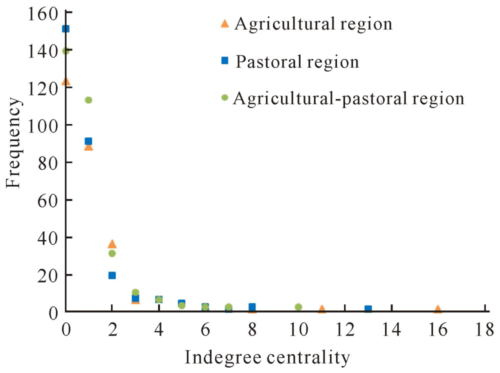


Fig. 6　The frequencies of different values of indegree centrality

2.3　A comparison of the risk of brucellosis outbreak of the three sheep-movement networks

Table 2, shows that the densities of the three sheep-movement networks were not high, thus indicating that the networks were all sparse. The clustering coefficients of the agricultural and agricultural-pastoral networks were both higher than that of the pastoral network. Table 1 shows that the average geodesic distances of the agricultural and agricultural-pastoral networks were smaller than that of the pastoral network, thus demonstrating the small-world characteristics of the agricultural and agricultural-pastoral networks. There were no large differences in most of the components, the size of the largest component or the average size of the components of the three networks.

Table 2　Descriptive statistics of network structure and vulnerability

Region	Measures				
	Density	Clustering coefficient	Number of components	Size of the largest component	Average size of the components
Agricultural region	0.003 4	0.062 0	58	61	4
Pastoral region	0.003 0	0.009 0	64	75	4
Agricultural-pastoral region	0.003 1	0.133 0	62	57	5

2.4　The influence of nodes in the spread of brucellosis

The nodes could be divided into four types based on the different degree of each node. The sending nodes exported sheep and were likely to spread brucellosis, whereas the receiving nodes imported sheep and were likely to be infected by brucellosis. The transfer nodes, which both export and import sheep, were undoubtedly high-risk nodes and are considered the main disseminators of brucellosis in the network. Table 3 summarizes the number and proportion of each node type. Table 3 shows that sending nodes formed the highest proportion of nodes in all three networks. The distributions of the different node types in the three networks were significantly different ($\chi^2 = 14.930$, $P = 0.021$). Specifically, the difference between the agricultural and agricultural-pastoral networks was not statistically significant, but the difference between the pastoral network and each of the other networks was statistically significant. Compared with the other networks, the pastoral network showed a higher proportion of isolated nodes and a smaller proportion of transfer nodes.

Betweenness centrality is mainly used to identify nodes that act as bridges in the network. Nodes with high betweenness nodes play an important role in the diffusion of brucellosis bacteria. Table 4 shows that the mean betweenness of nodes in the pastoral and agricultural-pastoral networks was high and the betweenness centralizations in both pastoral and agricultural-pastoral networks were higher than that of the agricultural network, thus showing strong centralization tendencies in the networks of both the pastoral and agricultural-pastoral regions.

Table 3　The numbers of different types of nodes (proportion (%))

Region	Types of nodes			
	Isolated nodes (Both the outdegree and indegree values are zero)	Sending nodes (Indegree is zero, outdegree is not)	Receiving nodes (Outdegree is zero, indegree is not)	Transfer nodes (Both out- and indegree are non-zero)
Agricultural region	8 (3.10)	115 (44.57)	61 (23.64)	74 (28.68)
Pastoral region	23 (8.10)	128 (45.07)	71 (25.00)	62 (21.83)
Agricultural-pastoral region	9 (2.92)	130 (42.21)	77 (25.00)	92 (29.87)

Table 4 Descriptive statistics of betweenness centrality

Region	Parameter				
	Mean	Median	Minimum	Maximum	Betweenness centrality (%)
Agricultural region	0.574	0	0	8	0.010
Pastoral region	1.574	0	0	112	0.140
Agricultural-pastoral region	1.136	0	0	57	0.060

Table 5 lists the ten nodes with the highest betweenness centrality in each of the three regional networks. The ten nodes with the highest betweenness centrality in the agricultural network were all farm nodes, whereas those in the pastoral and agricultural-pastoral networks contained some sheep-trader nodes. The descriptive statistics of network structure and vulnerability were recalculated using UCINET 6.0 after removing the ten nodes with the highest betweenness centrality in each of the three regional networks. The results are shown in table 6. (Lines with a white background show the initial values from table 2, and lines with a light gray background are the new values that were calculated after the removal of the nodes with the highest betweenness centrality nodes.) Apart from the clustering coefficient of the agricultural-pastoral network, there were distinct changes in the other measures after the removal of the nodes with the high betweenness centrality. There were significant decreases in the density of all three networks and in the clustering coefficients of the agricultural and pastoral networks. The total number of components in the three regional networks significantly increased, and the size of the largest component and average size of the components decreased. These changes indicate that the targeted removal of nodes based on betweenness centrality improved the properties of all three networks. Thus, the risk of brucellosis outbreak declined.

Table 5 Ten of the highest betweenness centrality nodes of the three networks

Ranking	Agricultural region		Pastoral region		Agricultural-pastoral region	
	Node label	Betweenness centrality	Node label	Betweenness centrality	Node label	Betweenness centrality
1	NY095	8	MY040	112	BJ38	57
2	NY017	7	MY035	46	BJ14	28
3	NY007	7	MY045	45	BY065	20
4	NY026	6	MY046	34	BJ25	12
5	NY088	6	MY071	27	BY069	12
6	NY068	6	MY032	27	BJ07	12
7	NY055	6	MJ43	20	BY080	11
8	NY012	6	MJ07	15	BY031	9
9	NY021	5	MY070	11	BY067	9
10	NY100	4	MJ31	10	BJ04	8

Notes: Nodes labeled NY, MY and BY represent farms or herdsmen in the agricultural, pastoral and agricultural-pastoral networks, respectively. Nodes labeled NJ, MJ and BJ represent sheep traders in the agricultural, pastoral and agricultural-pastoral networks, respectively

Table 6 Descriptive statistics of network structure and vulnerability

Region	Measures				
	Density	Clustering coefficient	Number of components	Size of the largest component	Average size of the components
Agricultural region	0.003 4	0.062 0	58	61	4
	0.003 0	0.045 0	77	41	3
Pastoral region	0.003 0	0.009 0	64	75	4
	0.002 8	0.000 0	79	40	3
Agricultural-pastoral region	0.003 1	0.133 0	62	57	5
	0.002 7	0.134 0	96	21	3

3 Discussion

Animal movements, which transfer both infected and non-infected animals, are considered the primary cause of the introduction and spread of infectious diseases[16]. Sheep-movement networks are extremely important for understanding the epidemic of brucellosis[17]. The results presented in this paper demonstrate that the structure of the sheep-movement network plays an important role in the introduction or spread of brucellosis. The heterogeneity of the different sheep-movement networks leads to different epidemics of brucellosis in different regions.

Trading of live sheep is a major cause of the long-distance diffusion of brucellosis. The topology of the sheep-movement network influences the size and speed of brucellosis diffusion. The outcomes of our study confirmed that the sheep-movement networks for both the agricultural and agricultural-pastoral regions had small-world properties. This result was also reported in other studies of livestock networks[18-19]. The presence of "hubs" and small-world properties accelerated the spread of brucellosis. The average distance between nodes in a sheep-movement network with small-world properties is small. That is, the sheep flow is much more frequent between herdsmen or farms in a sheep-movement network with small-world properties.

The sheep-movement network of the agricultural region categorized in this study was reticular, and the sheep flow chain contained many links. Before transfer to a slaughterhouse, the sheep were moved several times between farms or sheep traders. Many sheep in the agricultural region were consumed locally, producing a high risk of brucellosis outbreak. The sheep flow chain in the pastoral region had a stronger central tendency. Thus, the sheep traders acted in a transit role in nearly all of the sheep movements, and the herdsmen were relatively isolated. Most of the sheep were sold to sheep traders by herdsmen and then resold to other buyers by the sheep traders. Because few sheep in the pastoral region were exchanged between the local herdsmen, the risk of brucellosis outbreak in the pastoral region was relatively low. The sheep-movement network in the agricultural-pastoral region had characteristics of both the agricultural and pastoral networks. The results showed that the risk of brucellosis outbreak in the agricultural-pastoral region was high. Based on the respective characteristics of different sheep-movement networks, in the agricultural region, farms should be targeted in brucellosis prevention and control work. In the pastoral region, such work should emphasize the supervision and control of sheep traders, and in the agricultural-pastoral region, brucellosis control should focus on the management of farms/herdsmen and sheep traders.

The combination of social network analysis and animal movement data will better support brucellosis prevention and control work. One of the effective prevention measures against the introduction and spread of a new brucellosis infection in Inner Mongolia is sheep quarantine or movement restrictions based on the degree centrality. Highly connected nodes with high indegree and outdegree values were considered the super spreaders of brucellosis. These nodes were likely to become infected and to transmit brucellosis and should be emphasized in surveillance, prevention and control activities. The outcomes of our study confirm that the proportion of super-spreader-nodes in the pastoral region was smaller than in the other two regions, thus also reflecting the lower risk of brucellosis outbreak in the pastoral region.

However, the clustering subgroup and visual analyses for social network analysis technology based on sheep-movement records contributed to the estimation of the extent of the brucellosis epidemic and identified crucial nodes in the spread of brucellosis. With an outbreak of brucellosis, the capacity to rapidly identify the crucial, potential infection-spreading nodes is beneficial. Timely implementation of prevention measures for crucial high-risk nodes, such as restrictions on sheep movement may undoubtedly control the brucellosis epidemic. The targeted removal of nodes based on betweenness centrality improved the properties of all three networks, thus decreasing the risk of brucellosis outbreak.

The results reported in this paper represent the benefits of social network analysis technology for the prevention and control of brucellosis. Further research in this field should incorporate temporal dynamics and spatial dimensions into the sheep-movement network because patterns of sheep movement in different seasons may present different risks for brucellosis outbreaks.

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