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Research Article

Characterization of Domestic Ruminant Movement Patterns in a Transfrontier Region of North-Eastern KwaZulu-Natal, South Africa

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Introduction: Livestock movement patterns play a crucial role in animal and public health management, disease transmission and sustainable livestock farming. Understanding these patterns is vital for disease surveillance and preventing the spread of animal diseases.
Study Area: This study was conducted in the far north-eastern region of KwaZulu-Natal (KZN) province, South Africa, with Eswatini bordering to the west and Mozambique to the north. The study area is located at a wildlife–livestock interface and includes sections classified as a foot-and-mouth disease (FMD) control zone. Animal and animal product movements within, into and out of the area are restricted by state veterinary-issued movement permits.
Aims: The study aimed to quantitatively describe livestock movement characteristics within, into and out of the study area and identify potential hubs for disease transmission.
Study Design and Sampling Strategy: Data sources included official animal movement permit records (2015–2018) from the KZN Department of Agriculture and Rural Development, and the data are obtained via face-to-face interviews with livestock traders (August to November 2020). Traders' data were used to complement the interpretation of the permit dataset and to understand the livestock movement patterns, especially from the perspective of traders who operate from our study area. The permit data offered a detailed record of official livestock movements over multiple years, enabling us to identify the movement trends. In contrast, the face-to-face interviews provided real-time insights from traders regarding informal movement trends and disruptions not reflected in the permit data. The permit dataset was used to construct stratified animal movement networks by species using social network analysis (SNA), treating dip tanks (origins) and the destination locations (municipalities, districts or provinces) as two disjoint sets before being projected into a one-mode network. Bipartite-specific statistics were computed to compare the constructed networks.
Results: A total of 3598 movements between 2015 and 2018, representing 33,561 animals, were recorded from the permit datasets. Additional 74 movements representing 3296 animals occurred in the traders' dataset in 2020. Of the total number of animals moved, 64% were directed outside the study area. Overall, the network analysis highlighted distinct movement patterns for cattle and goats, with Ndlondlweni and Phelandaba dip tanks as the key nodes facilitating animal movements. These are both dip tanks with high centrality and highly connected hubs, with the potential for facilitating the transmission of diseases to the entire province and other places.
Conclusion: These findings contribute to a better understanding of livestock trade and animal movement dynamics for effective disease control and management. Two dip tanks emerged as high-frequency hubs for animal movements outside the study area, posing risks for disease transmission to the province and beyond. Intensifying surveillance in these areas is recommended to mitigate the spread of animal diseases. Veterinary authorities should enforce the use of animal movement permits by livestock traders for effective disease prevention and control.

Keywords: communal farmers; dip tank; livestock; livestock movement; livestock traders; movement permit; Rift Valley fever; social network analysis

1. Introduction

Livestock is one of the few tradable assets available to communal farmers worldwide and is used as an animal bank that is sold when money is needed. As the world population continues to increase, so does the demand for livestock meat and meat products, creating business opportunities for smallholder livestock farmers all over the world [1]. Transboundary animal diseases (TADs) have an adverse economic impact on the livelihoods of smallholder rural farmers in developing countries, necessitating effective prevention and control measures as part of the sustainable development [2, 3]. Livestock movement patterns of cattle, sheep and goats are crucial considerations for animal and public health management, disease transmission and sustainable livestock farming. Understanding animal movement patterns is vital to inform effective disease surveillance and prevent the spread of animal diseases from one location to another, especially TADs in Southern Africa such as foot-and-mouth disease (FMD), Rift Valley fever (RVF), peste des petits ruminants (PPR), African swine fever (ASF) or brucellosis. The spread of animal diseases via animal movement depends on parameters such as the presence of pathogens from the original areas, the presence of susceptible hosts at the destination areas, the biosecurity levels of the farms and the degree of contact between animals during transportation, especially in the subclinical phase of the disease when animals are shedding the pathogens [4].

The far north-eastern region of South Africa's KwaZulu-Natal (KZN) province, bordering Eswatini to the west and Mozambique to the north, is classified as a controlled zone for FMD. Animal movements in the specified area are restricted and necessitate permits from the state veterinary service, including the FMD protection zone in some parts of northern KZN. Farmers are required by the Animal Diseases Act of 1984 to obtain authorized veterinary permits to prevent health risks and maintain animal movement records [5–7]. However, this region is of particular interest due to reported illegal livestock movement across these borders [8], potentially resulting in the introduction and spread of TADs, especially trade-sensitive ones. Many livestock farmers take their animals once a month for sale at the community live animal auction market. Others sell theirs at the dip tanks and households to local traders, where animal movements are rarely recorded and reported to the state-employed animal health technicians (AHTs). Although livestock are taken to the dip tanks for tick control, local farmers commonly trade their animals at these dip tanks among themselves and with local traders. Most farmers move the species separately during herding and to the markets.

The area is also endemic for brucellosis [9–11], and endemic circulation of RVF virus has been reported [12]. The spread of TADs is connected to animal movement within and between farms and communities, making the livestock sector susceptible to new outbreaks due to its role in transmitting infectious diseases [13–15]. To avoid disease spread from infected areas to uninfected areas, it is crucial to monitor and analyse animal movement trends [16].

Social network analysis (SNA) is a tool that defines the relationship between different entities referred to as "nodes". A node can be an individual or group of animals, humans, locations or objects, either individually or in a group. It helps to understand the relationships between the movements that produce pathways for transmission of pathogens [17]. SNA can be used to describe patterns of animal movement, and it can identify areas at risk of new disease outbreaks by analysing animal movement data from disease-endemic areas [18, 19]. It identifies surveillance and intervention areas to prevent and control diseases that spread through animal movements [15, 16, 20]. SNA of animal movement has helped understand animal movement, disease surveillance, tracing, outbreak prediction, intervention planning and epidemiological linkages between provinces. The route and patterns of animal movement are essential for predicting the outcome of a disease outbreak and controlling its spread.

To understand the potential for north-eastern KZN to act as a hub for the spread of livestock diseases, particularly to other parts of South Africa, it is essential to understand the dynamics of livestock movement, including the network nodes and links. Distinguishing between the movement patterns of cattle and goats is useful for understanding the epidemiological dynamics of disease spread. It allows for more effective risk assessment, surveillance, control measures and overall public health and economic management strategies in both endemic and at-risk areas. This study aimed to quantitatively describe the characteristics and patterns of livestock movements within, into and out of the far north-eastern KZN region to identify hubs for livestock movements and the difference between the patterns of cattle and goat movements.

2. Materials and Methods

2.1. Study Area. This study was conducted in the far north-eastern part of KZN province, South Africa, in two local municipalities: Jozini (3442 km^2) and uMhlabuyalingana (3964 km^2) of the umKhanyakude District. Jozini is located in the north-western part of the district and uMhlabuyalingana in the north-eastern part; the area is bordered by Eswatini to the west and Mozambique to the north (Figure 1). It has a hot and humid tropical climate, with most rainfall falling in summer between December and March. The study area includes floodplains and pans, with two major rivers, Phongolo and Usuthu. The Usuthu River separates South Africa from Mozambique to the north of the Ndumo area.

Some of the study area is located at a wildlife–livestock interface, with Ndumo Game Reserve and Tembe Elephant Park in the study area (Figure 1). The predominant ethnic

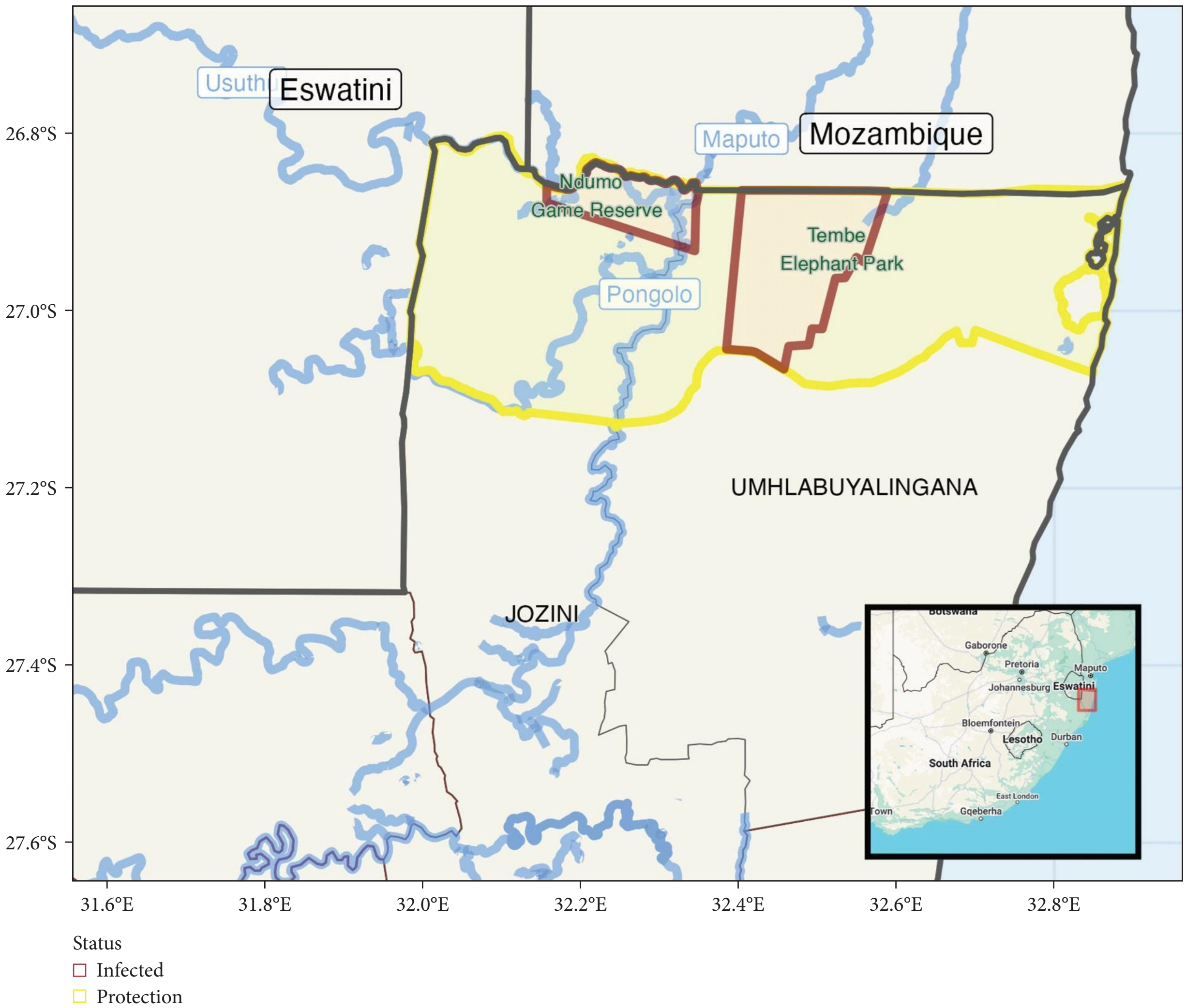


Figure 1: Map of uMkhanyakude district of the KwaZulu-Natal province of South Africa, showing the FMD-infected zone in red and FMD-protected zone in yellow. The map shows the major rivers (blue lines) and locations of the wildlife reserves in the area. Waterway data were downloaded from OpenStreetMap [21] to generate the map.

group within the study area is Zulu. Most farmers in the study area rely on livestock rearing on communal land, and relatively few practice crop farming [8]. Because some areas are classified as controlled zones for FMD (Figure 1), the unrestricted movement of animals and humans across the border could impact the spread of cross-border disease outbreaks, especially FMD [8]. Animal and animal product movements out of, into, within and through the area are restricted and require movement permits issued by the state veterinary service [6].

2.2. Study Design and Sampling Strategy. This study used two sources of data: the official animal movement permit records obtained from the KwaZulu-Natal Department of Agriculture and Rural Development (KZNDARD) from January 2015 to December 2018 and traders' data obtained via face-to-face interviews of livestock traders using a questionnaire between August and November 2020 (Supporting Information 4: Livestock traders' questionnaire). The traders' dataset was used to complement the official animal movement permit dataset. Because there is no precise record of the number of livestock traders in the study area, a snowball sampling method was employed to select livestock traders to participate in the survey, starting with traders identified by farmers during a concurrent study [8]. This lack of formal registration of traders posed a challenge to establishing an exact population size, which impacted our sampling approach. The traders were interviewed at their homes. The respondents were asked about animal movement, the number of animals bought and sold per month, the origin and destination of animals purchased and sold, respectively, and what they believed happened to the animals after being sold. In both data sources, the farmers and traders were asked to state the purpose of transporting the animals.

2.3. Ethical Considerations. Ethical clearance and research approval were obtained from the Research Ethics Committee of the Faculty of Veterinary Science, University of Pretoria (REC151-19). Approvals were also obtained from the Jozini chief state veterinarian of the KZNDARD and the local

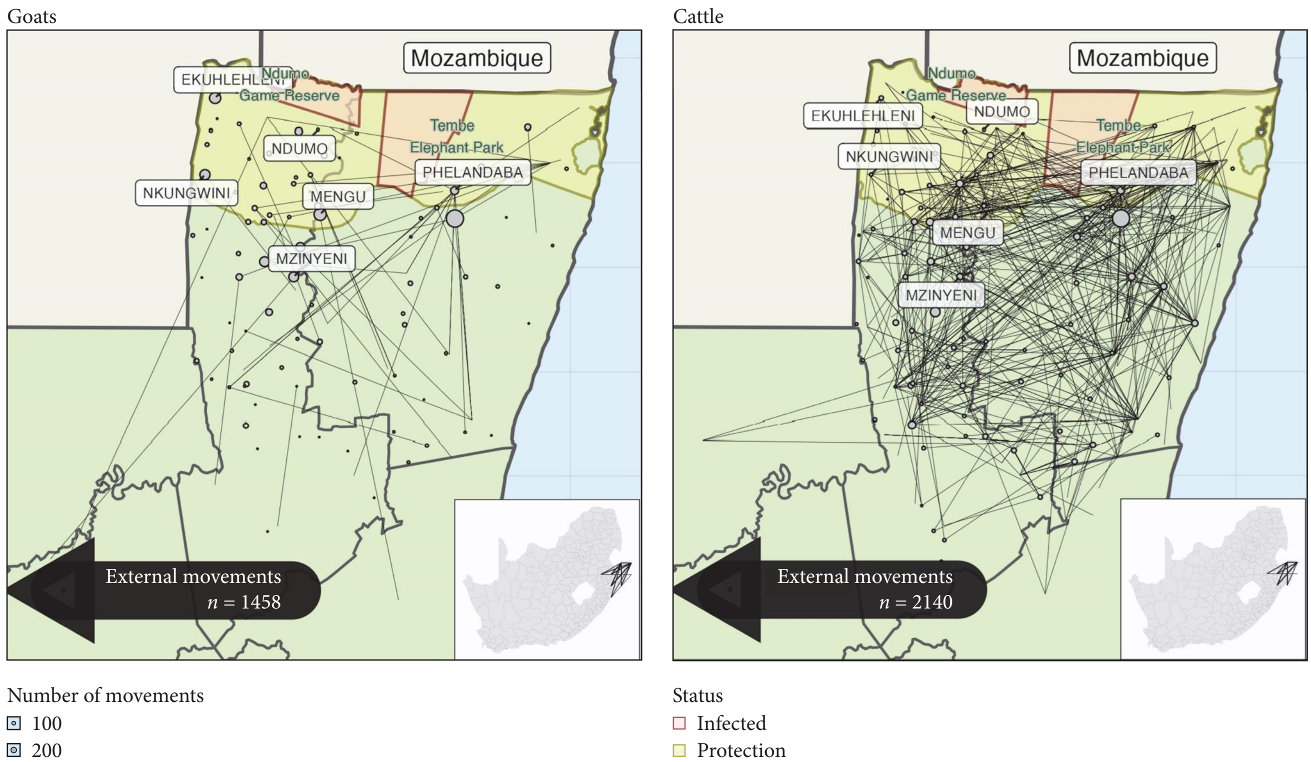


FIGURE 2: Map of the north-eastern KwaZulu-Natal province of South Africa, showing animal movement within the study area by species. Labels highlight the locations with the highest number of recorded movements. The yellow background shows the FMD-controlled zone, and the red background shows the FMD-infected zone.

izinkosi (kings or chiefs) before the project began. Informed consent was obtained from each respondent before they participated in the survey.

2.4. Data Collection. Retrospective animal movement surveillance data were obtained by capturing data from paper-based animal movement permits issued from 2015 to 2018 by the office of the Jozini State Veterinarian, KZNDARD, at Makhathini Research Station, Jozini. The movement permits contain the file number, place of issue, date of movement, species, number moved, origin and destination. These were captured into a Microsoft Excel spreadsheet and cleaned before exporting into RStudio for analysis and generation of all figures and maps [22]. Data from the traders' survey were collected using a hard copy questionnaire via face-to-face interviews between August and November 2020. The information collected included the date of animal movement, livestock market name, species of livestock, origin and destination, purpose of movement, price of the animals and method of transportation. The traders' survey questionnaire (Supporting Information 4) was first developed in English and translated into isiZulu for the interview of Zulu-speaking respondents. All responses from the two datasets were recorded in English before being captured into a Microsoft Excel spreadsheet. Coordinates of the dip tanks were obtained from KZNDARD or using Google Maps.

2.5. Network Analysis. Descriptive analysis was done to quantify the total number of animals moved within a specific period, species, sources and destination of the animals. Animal movements were defined as the shipment of at least one animal from one dip tank to another place. Movement within the study area was displayed by node links, with nodes representing the nearest dip tank locations. For locations outside the study area, nodes were defined as the closest dip tank or local municipality, district or province, depending on the available information. Edges represented the movement of animals between locations. Movements from or to places that could not be identified were excluded from the analysis.

The animal movement permit data obtained from KZNDARD were used to construct stratified animal movement networks by species (Figure 2). Due to the nature of the data collected, where origins and destinations were recorded at different spatial scales, we analysed the network as a bipartite network where the dip tanks (origins) and the destination locations (municipalities, districts and provinces) were defined as two disjoint sets. Bipartite networks, also known as two-mode networks, are a special type of graph in which the nodes can be categorized into two distinct sets (e.g. dip tank and municipalities, districts and/or provinces). It comprises nodes of two different kinds, with links connecting only the opposite nodes [23]; this type of network has been widely used in ecology and other areas in biological sciences, for example, to describe food webs, mutualistic networks and other interactions between species in an ecosystem (e.g. plants and pollinators) [24]. As opposed to one-mode networks (all nodes are the same in the network, e.g. dip tank to dip tank), which are often defined as $G = (N, E)$; typically, most networks are defined as consisting of one set of nodes that are similar to each other. The maximum one-mode network number of links that connect each node is the same number inside that node [25]. A bipartite network can be defined as $G = (U, V, E)$ where U and V represent the distinct node types connected by an edge E. The bipartite network can be further projected into two one-mode networks, $G_v = (U, E_v)$ and $G_u = (V, E_u)$, where the projected networks are composed of only one set of nodes and the edges represent indirect paths connected through shared connections of the complementary set of nodes [24].

For this analysis, we examined a bipartite network with two sets of nodes defined as the dip tanks and the destination locations. This provided insights into specific relationships among subsets of nodes. Then we projected the bipartite full network into two one-mode networks: one projection representing the indirect paths between the dip tanks and another projection for the indirect paths between the municipalities. Different global and local bipartite-specific network statistics were calculated to describe mathematically some of the observed network properties. Global statistics refer to statistics that aim to describe the whole network, while local statistics aim to describe individual nodes of the network. The bipartite-specific global statistics calculated for the stratified networks by species included network density (also known as connectance for bipartite graphs), weighted nestedness, compartment diversity, C-score and web asymmetry. The membership of the modules detected in each stratified network is presented in Supporting Information 1. Network density, or connectance, describes the proportion of links observed from all the possible pairs of nodes; they are a fraction of all possible links realized in a network [26]. Higher values suggest that many dip tanks have animal movements to different destinations, while low values suggest that movements are concentrated in specific destinations. Nestedness is a measure of structure in an ecological system; it describes how animals are spread out and how they connect with each other across locations, usually as bipartite networks. Nestedness describes patterns where interactions in the network are organized in a hierarchical manner; that is, a high nestedness value implies that certain dip tanks are more specialized and send animals to a subset of destination locations (municipalities, districts or provinces); others may be more generalized and send animals to a broader range of destination locations. Compartment diversity explains the distribution and diversity of interactions between compartments in the network (i.e. groups of nodes with shared interactions in the network). The C-score indicates how strong the compartmental structure in the network is, with higher values suggesting that the network presents well-defined compartments. Web asymmetry provides insights into the imbalances or directional differences in animal movements between dip tanks and destination locations. We also computed the network modularity to evaluate the clustering of nodes and identify groups of nodes, known as modules, that present higher interaction within modules than between modules [27]. The identification of modules can highlight distinctive communities with similar shipment patterns or shared characteristics. The membership of the modules detected in each stratified network is highlighted in Supporting Information Table 1.

Table 1: Descriptive statistics of the movement records and the number of movements by purpose recorded in the permit data.

	Permit data	
	Total number of movements (3611)	**Total number of animals moved (33,657)**
Cattle	2140 (59.3%)	11,287 (33.5%)
Goats	1458 (40.4%)	22,274 (66.2%)
Other[a]	13 (0.3%)	96 (0.3)
Purpose	**Shipments**	**Animals**
Drought	161 (4.6%)	1340 (4.08%)
Grazing	230 (6.6%)	1017 (3.1%)
Gift	2 (0.1%)	2 (0.01%)
Lobola	125 (3.6%)	490 (1.5%)
Sell	107 (3.1%)	1499 (4.6%)
Slaughter	298 (8.5%)	599 (1.8%)
Not stated	2573 (73.6%)	27,885 (84.9%)
Total	3496	32,832

[a]Others (Nyala, pig and sheep).

Other unipartite network local statistics computed included degree, edge weight and the number of neighbours. The degree represents the number of interactions a given node has, which, in the case of this directed network, can be incoming (indegree) or outgoing (outdegree) movements of animals. The edge weight represents the number of animals moved for each shipment. The neighbours in the network represent the different nodes to which a given node is connected, so the average number of neighbours indicates the network's diversity. Other commonly used network centrality measures, such as betweenness, were not used in this analysis due to the nature of bipartite networks. Instead of unipartite networks, which have two distinct sets of nodes, there are no shortest paths between nodes in the same set.

All the network analysis was done in R using the following libraries: *tidygraph* was used for network manipulation and calculating unipartite network centrality measures [28], *ggraph* [29] and *ggplot2* [30] were used for visualization, and *bipartite* [31] was used for the estimation of bipartite-specific centrality measures.

3. Results

3.1. Animal Movement Characteristics. A total of 3598 movements between 2015 and 2018, representing 33,561 animals, were recorded from the permit datasets. In this analysis, we focused on the movements of cattle and goats only, with cattle representing 58.7% and goats accounting for 41.3% of the total movements in permit datasets. Eight hundred twenty-five (2.5%) movements were excluded from the permit dataset because we could not identify their origin or destination names. The majority of the movements from the permit (68.2%) were from the study area to other places outside the study area. The most common purposes for these movements included slaughter (8.5%), grazing (6.6%),

Table 2: Descriptive statistics of the movement records and the number of movements by purpose recorded in the trader survey data.

Trader survey data		
Total number of movements (74)		Total number of animals moved (3296)
Cattle	16 (21.6%)	340 (10.3%)
Goats	58 (78.4%)	2956 (89.7%)
Other	0	0
Purpose	**Shipments**	**Animals**
Drought	0	0
Grazing	5 (6.8%)	166 (5.0%)
Gift	0	0
Lobola	3 (4.0%)	30 (0.9%)
Sell	50 (67.6%)	2447 (74.3%)
Slaughter	16 (21.6%)	653 (19.8%)
Not stated	0	0
Total	74	3296

drought (4.6%) and selling (3.1%). In the study area, the majority of livestock farmers (60.1%) raise cattle only, while 26.8% engage in mixed farming by keeping both cattle and goats. Additionally, 13.1% of farmers raise goats only (Table 1).

From the trader survey dataset, a total of 74 livestock movements events were reported by 11 livestock traders between August and November 2020 (Table 2). Each individual livestock trader contributed to at least two events of animal movement (Figure 3). Across these events, a cumulative total of 3296 livestock were moved, averaging 45 animals per movement event. Goats accounted for the majority of these movements, representing 78.4% of the total movements and 89.7% of the animals moved. In contrast, cattle movements were significantly lower, comprising only 21.6% of the movements and 10.3% of the animals moved. The most common purpose for these movements was selling, which accounted for 67.6% of the movements and 74.3% of the animals moved. This was followed by slaughter, representing 21.6% of the movements and 19.8% of the animals moved (Table 2). These findings indicate that the majority of livestock movements were driven by commercial purposes, particularly selling, with goats being the dominant species. There were no recorded movements for reasons such as drought or gifting, underscoring the commercial nature of the livestock trade (Table 2).

Descriptive statistics for the number of movements and animals for each species and data source are presented in Tables 1 and 2. The network of animal movement within the study area is presented in Figure 2 using locations that were successfully geocoded from the permit dataset. The number of movements through the year and the average number of animals per shipment are presented in Figure 4. The spatial distribution of the movements for each animal species and year is shown in Figure 3. Overall, the dataset showed that the dip tank origin that contributed to the highest number of animals moved was Ndlondlweni, with 1995 cattle and 4232 goats, accounting for 17.2% and 16.8%, respectively, of the total number of animals moved for the observation period. The average number of animals per movement was higher for goats (16.6) compared to cattle (5.4).

3.1.1. Permit Data. A total of 3598 animal movements (edges) with 107 unique origins (dip tanks) and 54 unique destinations (district, municipalities or province) were recorded between 2015 and 2018, 10.9% in 2015, 24.8% in 2016, 32.9% in 2017 and 31.1% in 2018. Only 31.8% of the movements were within the study area; the rest had destinations outside the study area. In the permit data, about 60% of movement records were for cattle and 40% for goats, although goats comprised about two-thirds of the total number of animals moved (Table 1).

According to the permit data, most farmers (73.6%) did not indicate the purpose of moving their animals. However, farmers who responded to this question indicated moving their animals for the purpose of slaughter (8.5%), followed by farming (6.6%), drought (4.6%) and lobola (bride price) payment (3.6%).

The characteristics of animal movement from permit data by year show similarity in the number of animals moved between 2017 (32.9%) and 2018 (31.2%); these years recorded the highest number of animals moved, followed by 2016 (24.9) and 2015 (11.0%). In 2015, most movements occurred between weeks 40 and 52 (October to December), reaching peaks around weeks 45–50 (mid-November and December) for cattle and goats. However, this was different in the movement pattern in 2016, where peak movement was recorded in week seven (February) for cattle, with the lowest observed movement in weeks 40–50. In 2017 and 2018, there was movement throughout the year, with peaks observed in weeks 10, 20, 40 and 50 for cattle and goats. The highest average number of animals moved per year for cattle and goats was reported in 2016 (Figure 4). The permit data showed that Ndlondlweni was the dip tank (origin) with the largest proportion of livestock shipped.

3.1.2. Trader Survey Data. A total of 74 animal movements were recorded from the trader survey dataset between August and November 2020 among 11 livestock traders from the far north-eastern KZN province. Only the movement of cattle and goats was reported for this period. Goats accounted for 58 (78.4%) and cattle for 16 (21.6%) movements. There were 3296 livestock moved, averaging 45 animals per movement. Most animal shipments were goats, totalling 2956 (89.7%) (Table 2). The trader survey data showed that Phelandaba dip tank shipped most goats to various areas (Figure 3).

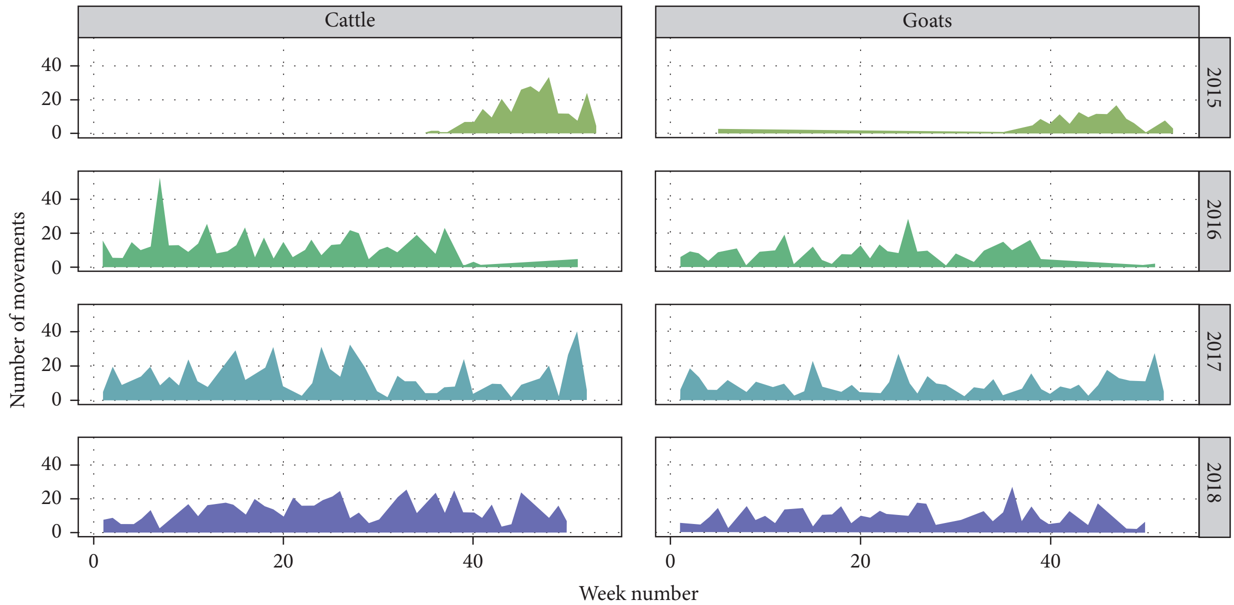
The main means of transportation reported was by vehicle (91.5%), followed by on foot (8.5%). The traders' data showed that the majority (66.2%) of the livestock shipped was for selling purposes, followed by slaughter (23.5%), grazing (6.8%) and trading for lobola payment (4.0%) (Table 2). None of the traders reported breeding livestock for sale; however, respondents indicated they bought from nearby villages and kept them for a short period before shipment to distant locations. The traders' data showed that goats were the animals that moved the most (Figure 3).

Figure 3: Distribution of the trader survey data movements. (a) shows the flow of the animal movements, where the first column represents each of the trader, the second column the origin and the third column the destination. The width of the lines between the columns represents the number of animals moved. (b) represents the locations of the dip tank origins from the trader survey data.

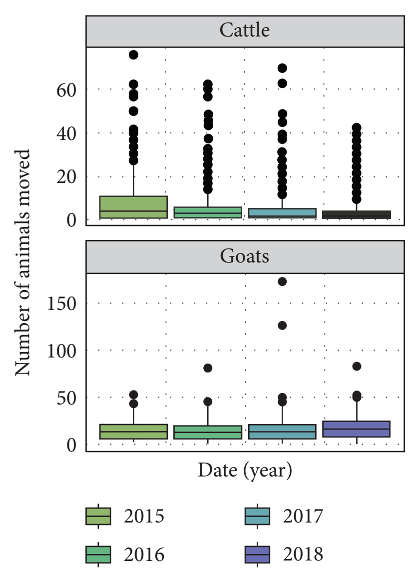
3.2. Network Analysis. Due to the low representation of movements for 2019 and for species other than cattle and goats, we restricted our analysis to cattle and goats for the years 2015, 2016, 2017 and 2018 (permit data). The overall network global statistics compared to the projected networks are presented in Figure 3. Figure 5 shows global and local statistics calculated for the one mode and projected networks. Despite the bipartite network having a larger number of nodes, the number of edges and the average number of neighbours were noticeably higher for the projected networks and the network density, with a larger difference in the dip tank projections (Figure 5a). The degree distribution for the one-mode networks spanned a range from 1 to more than 600, indicating a right-skewed distribution. However, upon projecting the network, the centrality degree distribution, particularly in the case of the dip tank projections, exhibited a left-skewed pattern (Figure 5b). The descriptive statistics of the one-mode and projected networks are shown in Supporting Information Table 3.

The permit data showed that the cattle network had 135 nodes with 529 edges compared to the goat network, with 123 nodes and 397 edges. The average number of neighbours was 83.3 for cattle and 48.4 for goats at the dip tanks (Table 3).

To evaluate potential subcommunities where the contacts within groups are stronger, we computed modules (groups of

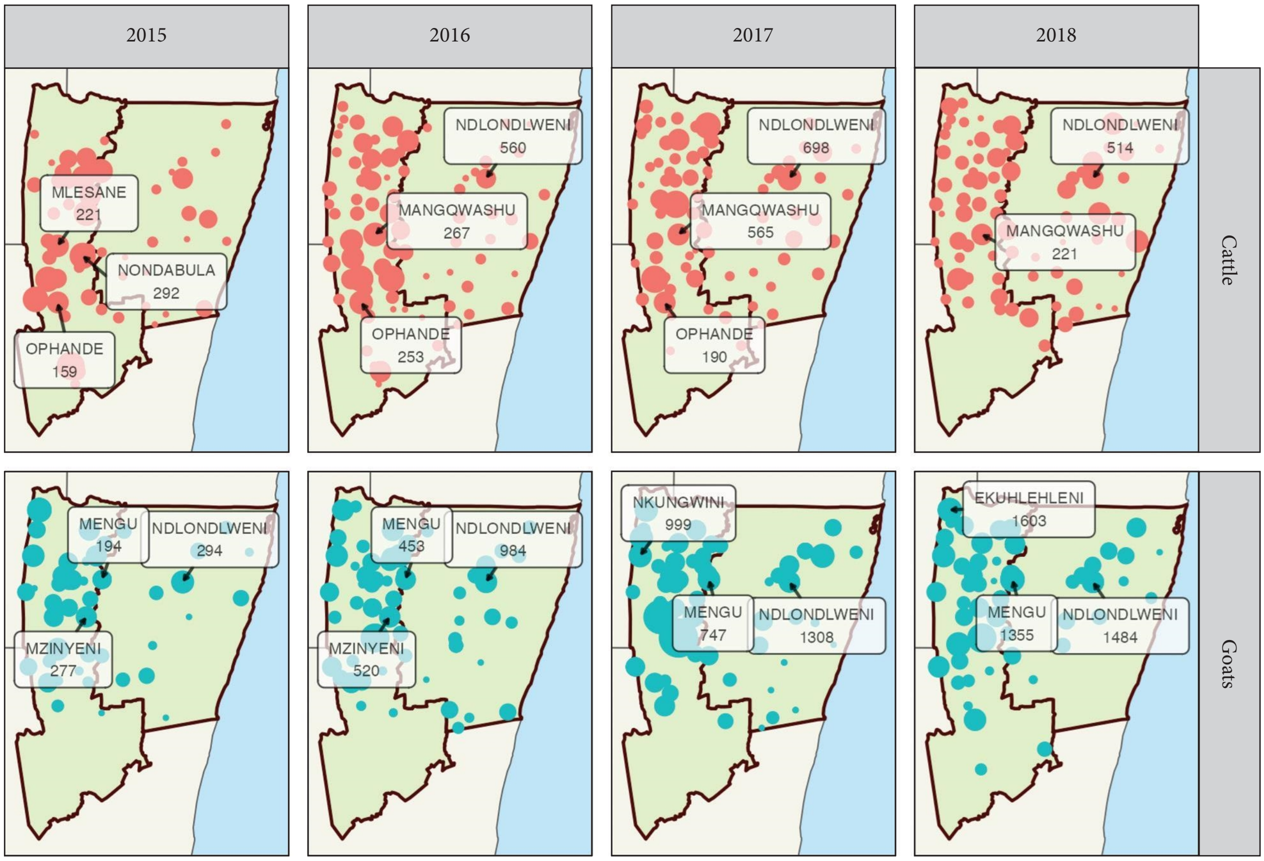


(a)



(b)

Figure 4: Continued.



(c)

FIGURE 4: Spatiotemporal distribution of the permit data movements during the period analysed, including the (a) number of movements by week, (b) distribution of the number of animals moved and (c) locations of the movements by dip tank (2015, 2016, 2017, and 2018).

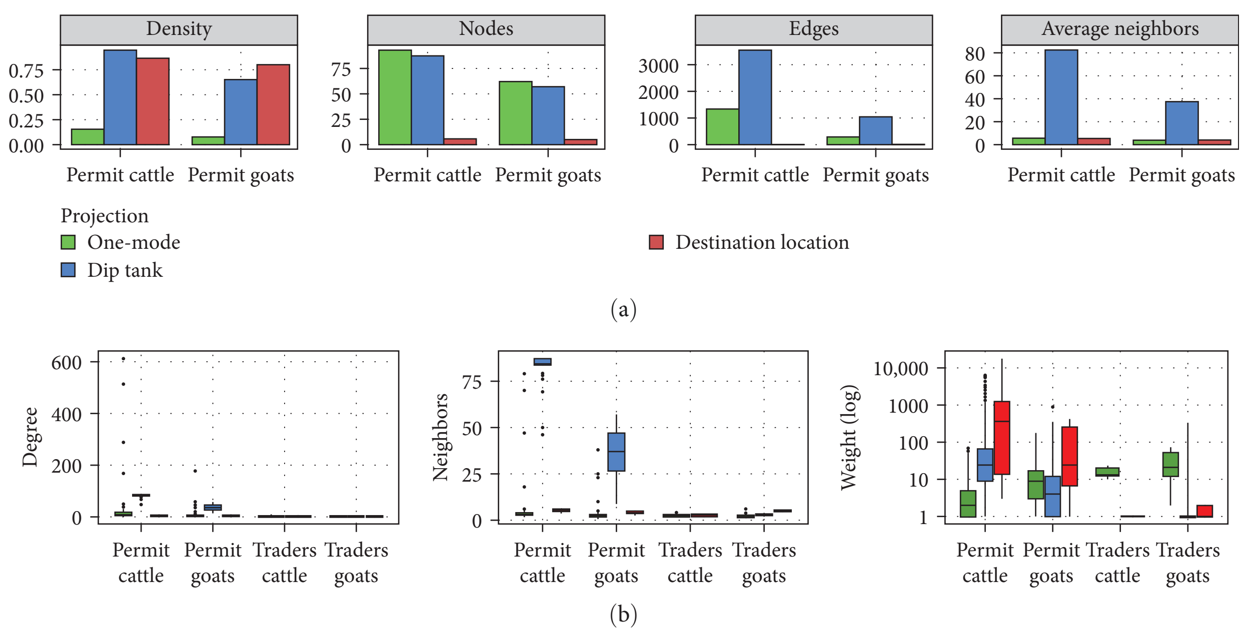


FIGURE 5: Global (a) and local (b) statistics for the one-mode and projected networks stratified by species from permit dataset. The fill represents the network projection, the x-axis represents the stratified network, and the y-axis represents the index value.

Table 3: Bipartite network indices for the stratified network by species.

Statistic	Permit	
	Cattle	Goats
Number of node municipality	43	41
Number of node dip tank	92	82
Mean number of shared partner municipality	2.15	1.94
Mean number of shared partner dip tank	2.32	1.29
Connectance	0.13	0.12
Web asymmetry	−0.36	−0.33
Cluster coefficient	0.04	0.06
Weighted nestedness	0.69	0.60
Cluster coefficient municipality	0.41	0.28
Cluster coefficient dip tank	0.19	0.22
C-score municipality	0.6	0.59
C-score dip tank	0.28	0.54
Modules detected	8	11
Proportion of within module movements	0.45	0.50

Note: For more detail on the definitions of these metrics, see Section 2.5 Methods and Supporting Information 2.

nodes) using a previously developed algorithm [32] weighted based on the total animals moved. Modules can be seen as groups of nodes in a community that are connected by numerous links; if modules are perfectly separated, with no interaction or link within a community, they are called compartments and should be seen as clearly separated groups of nodes [27]. Eight modules were identified for the cattle network and 11 for goats. The three largest modules detected for each network are presented in Figure 6.

Figure 6 illustrates cattle movements from permit data in the KZN province. Most cattle were transported to coastal areas such as Mtubatuba, eThekwini (Durban) and Mandeni. These coastal movements mainly originate from dip tank areas like Mangqwashu and Ezulwini, which supply coastal and inland regions. In contrast, inland movements come from dip tank areas like Mangqwashu and Nondabula.

Regarding goat movements recorded in the permit data, the majority of the movements were to the periurban inland areas such as Mandeni, Nqutu and Ladysmith. These movements originate from dip tank areas like Ndlondlweni and Mzinyeni.

Regarding traders' cattle movements, there was a difference between inland areas such as Ladysmith and Newcastle and coastal areas like Stanger and Manguzi. The periurban areas received cattle from dip tank areas like Ndlondlweni and Jozini, except for Ladysmith, which receives cattle from Phelandaba.

Traders' goat movements include inland areas like Eshowe and Nongoma and a few coastal areas like Empangeni and Durban. Dip tank areas such as Ndumo and Phelandaba contribute to movements in both inland and coastal regions. Nkandla is an exception, being a rural destination. Overall, both cattle and goat movements exhibit patterns of periurban focus in the inland areas, with specific dip tank areas such as Ndlondlweni, Phelandaba and Mangqwashu playing crucial roles.

4. Discussion

Our analysis sheds light on the movements of cattle and goats in the far north-eastern part of KZN province. We used SNA methods to better understand animal movement patterns in an international border area with the potential for illegal animal imports and the spread of transboundary diseases. Our study showed that animals were moved to both urban and rural areas up to several 100 km from the study area, highlighting the potential for long-distance spread of infectious diseases.

A total of 3598 movements between 2015 and 2018, representing 33,561 animals, were recorded from the permit datasets. The network analysis highlighted distinct movement patterns for cattle and goats, with Ndlondlweni and Phelandaba dip tanks as the key nodes facilitating animal movements. These are both dip tanks with high centrality and highly connected hubs, with the potential for facilitating the transmission of diseases to the entire province and other places.

Our traders' data analysis showed that livestock traders receive animals regularly and animals are kept for a very short period before being supplied to buyers. Animal movement involving traders can present higher risks of spreading infectious diseases by mixing multiple animals from different sources. As indicated in our study, animals are collected from many sources or villages to distribute to buyers in different locations. These activities have been proven to spread diseases quickly [17].

Traditionally, SNA has relied on using origin and destination nodes at the same level of resolution. However, the main limitation of the permit data used in the analysis of animal movement out of the study area is that the origins and destinations were collected at different levels of resolution (specifically, dip tanks moving to municipalities, districts and provinces). This limitation constrained our analysis and prevented us from utilizing community detection algorithms like *walktrap* or *infomap* [33]. To overcome this challenge, we analysed the data as a bipartite graph, which has not been previously explored in animal health research. By analysing the data as a bipartite graph, we were able to assess potential interactions between nodes that may not have been directly observed in the collected data.

This approach enabled us to identify distinct groups of nodes characterized by more within-group interactions. For instance, in the cattle network from the permit data, there was a noticeable increase in connectance, weighted nestedness and mean number of shared partners (Table 3). This indicates a greater reliance on specific nodes for indirect connections at the destination location, which can highlight nodes that have demand issues, trade restrictions due to infectious diseases or adverse weather conditions. Such issues could significantly impact farmers' economies and the supply/demand dynamics of animal protein and subproducts. In contrast, the

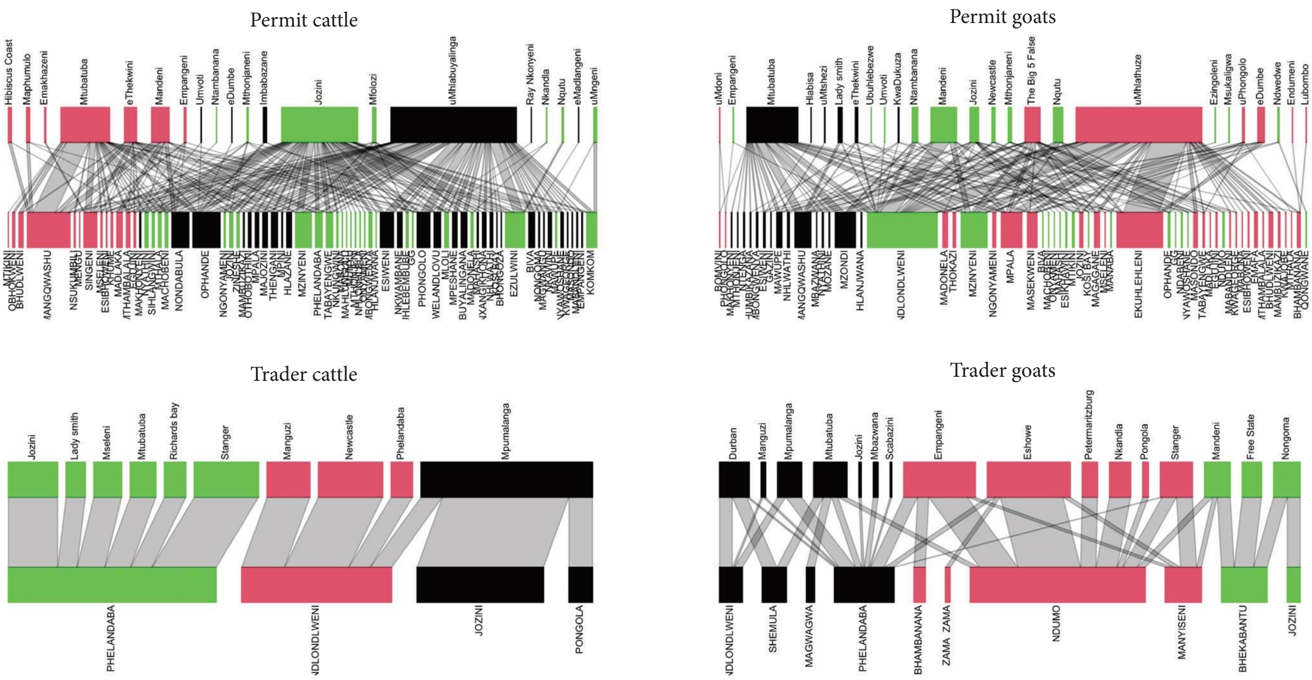


FIGURE 6: The three largest modules detected for each stratified bipartite network and their relationships. Origins are at the bottom and the destinations at the top.

goats network from the same permit data had more compartment diversity and web asymmetry (Table 3).

Analysis showed that from the permit data, goats showed higher *C*-score values for dip tanks than cattle, indicating a higher level of compartmentalization in these networks (Table 3). Compartmentalization refers to how nodes (e.g. dip tanks or locations) are organized into distinct and localized groups within a network, providing useful guidelines for isolating specific areas to prevent widespread network disruptions.

The analysis presented here used two very different sources of information from different times: animal movement permit data and a livestock traders' survey where snowball sampling was used. We acknowledge the limitation in the sample size of the traders and understand the impact on the generalization of our findings; due to these limitations, we analysed the datasets separately, and the interview findings were used to complement the findings from the quantitative permit data only. The traders' data captured informal and unregistered movements, providing some insight into informal animal movement practices in the study area. Goats accounted for the majority of animals moved by the traders, suggesting that goat trade is the primary focus of the survey data. The utilization of two data sets from different times and sources enhances the validation of patterns across datasets to ensure that observed trends are not anomalies or biased by the limitations of a single dataset. We believe that the 11 traders provided essential insights into trading patterns, highlighting the main routes and common practices for livestock movement in the study area. This information provides valuable preliminary data for stakeholders interested in enhancing livestock movement surveillance and management.

The majority of cattle movements in the permit data did not state the purpose of the livestock movements, hindering a comprehensive understanding of the drivers behind these movements. However, some of the movements were cited for slaughter, grazing and drought-related reasons among those who did state the purpose. This lack of a specified purpose for a significant portion of movements in the permit data is a widespread issue in livestock movement [34]. Selling was the most common reason for movement reported by traders, but this may indicate that traders were less likely to know the purpose for which their customers bought the animals. It is also noteworthy that neither the traders nor the farmers cited breeding livestock for sale as a motive for animal movements. This suggests that if the animals are immediately slaughtered upon arrival at their destination, there is a lower risk of exposure and transmission of diseases to other animals compared to when they are kept for breeding. This highlights the importance of understanding the motivations behind animal movements to mitigate disease spread.

Most animal movements recorded from the permit data occurred between September and December, before the expected beginning of rainfall in the study area, reaching peaks in mid-November. The likely causes of movements between September and October are drought and the high demand for meat during the Christmas festive season in November and December. From 2015 to 2018, there was a crippling drought in the study area, 2015–2016 being the driest period induced by El Niño [35], forcing livestock farmers to relocate their animals to other areas for grazing. During this period, cattle farmers were reported to lose 43% of their herds, whereas goat farmers lost 29% in the study area [36]. In this study, most farmers indicated drought as one of the reasons for transporting their animals out of the study area. The animal movement pattern in 2016 differed from the rest of the years, with peaks recorded in February; this was the year with the highest number of animal movements out of the study area. The seasonal movement pattern in 2016 could also be because of drought, another reason could be due to incomplete data provided by KZNDARD. International comparisons can be challenging due to differences in husbandry practices, geography and the nature of diseases. However, the purpose of livestock movement among livestock traders worldwide is for selling purposes [37].

The continuous movement of goats throughout the year, as seen in the traders' data, is with peaks in March and between August and December. The peaks observed in March are likely due to the demand for meat in the Easter seasons and different traditional ceremonies that take place in the Zulu nation during this time. For example, one of the most important festivals in the Zulu culture is the Umkhosi Wokweshama (first fruits festival) that is held annually in December or January to show gratitude to the ancestors for a bountiful harvest by slaughtering cows or goats. During cultural celebration season, the demand for goats is high, and the livestock traders go to rural livestock farmers to obtain goats. Similarly, the movement between August and October is most likely due to drought-related factor.

There were distinct differences in movement patterns between species. The majority of the cattle movements were to the inland areas; goat movements predominantly were towards the coastal areas of the KZN province. Additionally, cross-provincial movements were evident, with goats being shipped to the Free State Province and cattle to the Northern Cape and Gauteng Provinces. Urban centers such as Durban, Ladysmith and Stanger municipalities were identified as key destinations for goat movements, particularly from dip tank areas like Manyiseni, Ndumo, Shemula and Ndlodlweni for cultural ceremonies and lobola (bride price) payments.

The Ndlondlweni dip tank area was identified as having the highest proportion of animal movements for both species. Along with Phelandaba dip tank, it also recorded the highest goat movements. These are both dip tanks with high centrality and highly connected hubs, with the potential for facilitating the transmission of diseases to the entire province and other places. Therefore, they should be prioritized for disease surveillance, especially for FMD, which is known to be endemic in the study area [6]. Additionally, brucellosis surveillance should be focused on these dip tanks, as it has been reported to be prevalent in the area [38, 39]. Furthermore, special emphasis should be placed on the surveillance of RVF in this region due to its favourable environmental conditions for the transmission of RVFV. This is especially important as the region shares borders with Eswatini to the west and Mozambique to the north. The area is also located at the wildlife–livestock interface, and it is an area of concern due to the presence of, or potential for, the introduction and spread of TADs such as RVF and FMD. Recent studies have shown ongoing circulation of RVFV among individually identified cattle and goats [12], as well as in wildlife from the study area [40].

In this study, some data were missing from early 2015 in the permit dataset. Additionally, some origins and destinations were left unspecified, resulting in their exclusion from the analysis. It is worth noting that the origins and destination locations datasets were recorded at different spatial scales. Furthermore, the traders' data were collected at a different period, and only 11 traders participated in the survey; more participants will likely influence the results. For these reasons, the methodology, as well as the results presented in this study, cannot be generalized outside our study location.

We did not explore wildlife's role in RVF and FMD outbreaks in the study area, as this was beyond the scope of our objectives. However, this could indeed be a valuable direction for future research. It is also possible that the traders' dataset may contain recall bias. In addition, the possible effects of the COVID-19 pandemic on data collection for trader survey data, as well as the general movement of animals, should be considered. It is unclear whether traders modified their trading activities in 2020 in such a way that would differ from earlier or later (present) time periods; economic impacts from the pandemic may have driven higher or lower movements.

Ideally, the trader survey will be repeated in future years to allow for comparison and include a wider number of entities market value chain. Similarly, further work could assess the specific disease prevention and control knowledge, attitudes and practices employed in the source and destination areas to determine where there may be gaps (e.g. biosecurity, quarantine, traceability, vaccination, disease detection and reporting) requiring attention.

5. Conclusions

To the best of our knowledge, this is the first exploration of the application of bipartite network analysis to animal trade data. The study offers insightful information about the patterns of livestock movements in the north-eastern province of KZN. Certain locations were identified as the source of the highest proportion of animal movements to locations outside the study area. These are potential hubs for promoting the transmission of diseases to the entire province and other places. Therefore, surveillance systems should be intensified in these areas to reduce risk of animal disease spread.

This study found that traders moved livestock across the province without a livestock movement permit and shipped goats across the province and to the coastal areas of KZN. Enforcing the use of animal permits by livestock traders will assist state veterinary authorities in preventing and controlling the spread of disease. To mitigate disease risks, it is essential to identify the carriers of TADs to prevent the potential spread of infectious diseases to other areas.

The distinct characteristics of cattle and goat movements from permit and trader data emphasize the complexity of the livestock movement pattern and trade system. This underscores the importance of considering various factors when designing effective management and control measures.

Data Availability Statement

All the data are contained within the article and the Supporting Information.

Ethics Statement

The study was and conducted under the terms approved by the University of Pretoria, Faculty of Veterinary Science and Faculty of Humanities Research Ethics Committees (REC), Project number REC151-19 on October 3, 2019.

Consent

The investigators obtained informed consent of the chief veterinary officer of the KZNDARD and from the local *izinkosi* (kings or chiefs), and signed informed consent was obtained from each respondent before their participation in the survey.

Disclosure

The funders had no role in the study's design; in the collection, analysis or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Conceptualization: Y.B.N. and P.N.T.; methodology: Y.B.N. and P.N.T.; validation: P.N.T., P.J.G. and Y.B.N.; formal analysis: Y.B.N., P.N.T. and P.J.G.; investigation: Y.B.N. and P.N.T.; resources: P.N.T., E.E. and Y.B.N.; data curation: Y.B.N., P.N.T. and P.J.G.; writing–original draft preparation: Y.B.N., P.N.T. and P.J.G.; writing–review and editing: Y.B.N., P.N.T. and P.J.G.; supervision: P.N.T. and E.E.; project administration: P.N.T. and E.E.; and funding acquisition: P.N.T. and E.E. All authors have read and agreed to the published version of the manuscript.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. (*Supporting Information*) Supporting Information Table 1. Membership of the modules detected in each stratified network. This table outlines the membership of the nodes within the modules identified in the stratified networks. It provided a breakdown of how the origins (dip tanks) and the destination locations were grouped into modules based on their interactions, providing insights into the structural organization of the networks. Supporting Information Table 2. Definitions and estimates of social network metrics and their interpretation in this study. This table defines the key social network metrics used in the analysis, such as centrality measures, clustering coefficients and density. It explains their interpretation in the context of this study, helping readers understand the significance of the network properties analysed. Supporting Information Table 3: Descriptive statistics of the one-mode and projected networks. This table presents descriptive statistics for both the one-mode and projected networks, including measures such as the number of nodes, edges, degree, neighbours, modules and network diameter. These statistics provide a comprehensive overview of the network structures and their values. Supporting Information 4: Livestock traders' questionnaire. Supporting Information 4 contains the questionnaire used to collect data from livestock traders. It details the questions, responses and data collection options. This information is crucial for understanding the data sources and the context in which the network analysis was conducted.

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