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Mapping the Cattle Trade Network in Ethiopia: Empirical Evidence from Tigray, Oromia and Addis Ababa Major Cattle Markets, Ethiopia

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Abstract

In this study, we have constructed the cattle trade network within the Ethiopia cattle industry. The mapping and description of the cattle trade network were investigated using social network analysis mainly in Tigray, Oromia and Addis Ababa major cattle markets. The objectives of this paper were to map the spatial pattern of the domestic cattle trade network at cattle market level, characterize and describe the domestic cattle trade network structure and to identify key cattle markets for market interventions. Based on the social network analytical tool, the study attempted to visualize the topological structure of the cattle trade network spatially. According to the different network parameters estimated, the cattle trade network is found to exhibit both small-world and scale-free properties. It was also found that the cattle trade has a low density, suggesting low connectivity among cattle markets (network density = 0.011, i.e. only 1.1% of all theoretically possible links are present). The paper also provides empirical evidence that the cattle trade network is characterized by assortative association, suggesting that cattle markets have a propensity to trade with the same region or locally (regional assortativity coefficient = 0.42, versus a degree-assortativity coefficient of 0.16). The network's small-world structure is evidenced by a short average path length (2.54) and a network diameter of seven links, together with a clustering coefficient (0.127) roughly three times higher than comparable random networks. Furthermore; the paper provides empirical evidence that the cattle trade network is characterized by assortative association (regional assortativity coefficient = 0.42, versus a degree-assortativity coefficient of 0.16), suggesting that cattle markets have a propensity to trade with the same region or locally.

Keywords: cattle trade network; social network analysis; Ethiopia; market centrality; livestock marketing

Background

The application of network theory of socio-economic systems has started within the last decades. To this end, a large body of studies has increasingly addressed the study of socio-economic systems in the framework of network theory (Fagiolo et al., 2007). The idea that real world socio-economic systems can be described as networks is not new in the academic literature (Wasserman & Faust, 1994).

Furthermore, there has recently been increasing interests in conducting network-related research within international trade studies (Fagiolo et al., 2007; Jessica & Michael, 2015; Li et al., 2003;

Serrano & Boguña, 2003). In the previous years, the gravity model appeared to be the most popular model to explain international trade. However, nowadays the network analysis also plays a significant role in international trade studies. In fact, network analysis has some advantages over the gravity model (Biggiero & Basevi, 2009).

Livestock, and cattle in particular, occupy a central place in the Ethiopian economy and in rural livelihoods. Ethiopia holds one of the largest cattle populations on the continent, and the sector underpins draught power, milk and meat supply, savings, and cash income for a large share of smallholder and pastoral households across the country (CSA, 2018; FAO, 2016). Cattle marketing in Ethiopia is organized through a tiered system of primary (rural assembly), secondary and terminal markets, through which animals are moved, often over long distances and through multiple intermediary transactions, before reaching their final consumption, processing or export destination (Jabbar et al., 2007; Hailemariam et al., 2008). Because these successive movements link geographically and institutionally distinct markets to one another, the resulting trade pattern is, by construction, a network phenomenon, even though the literature on Ethiopian livestock marketing has to date been dominated by linear value-chain framings that describe successive market stages without directly characterizing how individual markets are connected to one another.

Understanding the structure of this network carries practical stakes that go beyond market description. Trade linkages between markets are simultaneously disease-transmission pathways: elsewhere, the contact networks generated by livestock movement have been shown to shape the spread of pathogens far more than aggregate trade volumes alone (Kao et al., 2006), and a broadly similar logic applies to how price signals and market information propagate between markets. Identifying which markets function as hubs, as bridges between otherwise weakly connected parts of the network, or as peripheral nodes therefore has direct and practical relevance for both market-development policy and animal-health surveillance.

Cattle trade can be considered as a network. This trade network can be represented as a directed, weighted, incomplete, and asymmetric graph in which each market is a node and the bilateral trade links are the edges. The network is directed as each market is unlikely to trade at equal amounts from each other (Duman, 2016).

In this analysis, we have constructed the cattle trade network within the Ethiopia cattle industry. The mapping and description of the cattle trade network were investigated using social network analysis mainly in Tigray, Oromia and Addis Ababa major cattle markets. In doing so, this paper provides much information to the policy makers by unveiling the complex cattle trade networks. Previously, most of the studies dwelt up their efforts on cattle trade/value chain mapping and analysis. Such approaches are linear analysis by their nature and do not offer much insight to policy makers.

The contribution of this paper is its application of network approach on domestic cattle trade flows. Although network analysis has been widely used for international trade, such a perspective is missing for domestic trade. Apart from enabling us to visualize the trade flows and make the most important agents (countries, regions, cities or firms) visible, network analysis helps us systematically describe the cattle trade network using the estimated network parameters that has economics interpretations.

The objectives of this paper were to (1) map the spatial pattern of the domestic cattle trade network at cattle market level (2) characterize and describe the domestic cattle trade network structure (3) to identify key cattle markets for market interventions.

Methods

Market site selection

The study sites were purposively selected Mekele from Tigray region, Sebeta and Bishoftu from Oromia region; and Addis Ababa (at Shegole, Kality and Kara cattle markets) as a starting point as they are the ETHICOBOT project sites. As the next step, based on the snowball sampling and the importance of the markets, the Adama, Assela, Dhera, Shashemene, Awassa (South region), and Debrebirhan (Amhara region) cattle markets were included. The selected cattle markets represent the main trade routes and part of a north–south transect covering parts of the central highlands of Tigray, Amhara and Oromia regions, and the transect that connects Adama and Dire Dawa (Jabbar et al., 2007).

To extend the coverage of the network further, cattle markets at Sagure and Harar were also surveyed directly, reflecting their role as important trading points along the Oromia and Harari cattle-trade corridors, respectively.

Data collection

A cross-sectional study of the cattle markets was conducted between January 2019 and March 2019. Cross-sectional data were collected through focus group discussions and key informant interviews (KII) with livestock experts and traders at each cattle market site. Each market was visited along with livestock experts once and 6 to 10 cattle traders were actively searched for in the cattle markets and the FGDs were held; a cattle trader was defined as a cattle seller who sells cattle that have been bought before, but were not bred by the same person.

For the snowball-sampled markets in particular, key informants were selected specifically among cattle traders who routinely travelled to and traded in remote cattle markets, and who therefore had direct, first-hand knowledge of the cattle trade flow from source markets through to their ultimate destinations, rather than only local or partial knowledge of the wider trading system. This criterion was applied to reduce the risk of the referral chain under-representing distant or lower-volume trading partners. In addition to this primary FGD and KII data, the study drew on published cattle value chain studies covering the study areas to cross-check and complement the mapped trade routes.

Qualitative data were obtained during the FGDs about the source and destination of the cattle with reference to the cattle market site under investigation. Ultimately, the cattle trade network mapping was done in terms of geographical pattern (routes of animals). Besides secondary data about the monthly number of cattle sold and average price were also obtained from the respective trade offices.

FGDs were complemented with semi-structured interviews to key informants, who understood overall pattern, operations and functionality of the cattle markets. Thus, key informants were the livestock market experts and cattle traders whom were identified by these initial key informants

or through discussion in the focus group discussions. Where available, secondary data on animal movements from past studies conducted were also collected.

Cattle trade network construction

Data on the origins, destinations, and approximate monthly volumes of cattle movements between markets, gathered from the FGDs, KIIs, and secondary trade-office records described above, were combined to build a directed cattle trade network for the study area, following the general network-construction approach used for livestock trade systems elsewhere (Motta et al., 2017). Markets constituted the nodes of the network, and a directed link (edge) was defined as the reported movement of cattle from an origin market to a destination market. The resulting network was analysed as a single, annually aggregated cross-section; because data collection took place over a single January-March 2019 window rather than a full annual cycle, seasonal (dry- versus rainy-season) variation in network structure, which has been documented in other livestock trade systems (Motta et al., 2017), could not be assessed here and is noted as a direction for future work in the Limitations section.

Method of data analysis

Network analysis

Description of the cattle trade network in the study area was carried out using several descriptive parameters (Wasserman & Faust, 1994). These estimated social network parameters are the size (number of nodes), the number of links, the average degree (the degree of a node is the number of nodes to which it is directly linked), the average path length (the average number of links along the shortest paths-or geodesic- between all pairs of nodes), the diameter (the longest of geodesic length), the clustering coefficient (proportion of neighbours of a node that are linked to each other) and the assortativity (correlation between the degrees of linked nodes). Besides, identification of key markets that was solely based on their node centrality measures were conducted.

Network computations, including the topology, centrality, and key-actor analyses described below, were carried out primarily using the igraph package in R, with UCINET (Borgatti et al., 2006) also used.

To assess whether the observed cattle trade network exhibits a small-world structure, its clustering coefficient and average path length were compared against those of an ensemble of 1,000 randomly-generated networks of equivalent size (same number of nodes and edges), following the small-world criterion of Watts and Strogatz (1998): a network is considered small-world if its clustering coefficient is significantly higher than that of comparable random networks while its average path length remains comparable to or lower than theirs. Similarly, the degree distribution of the network was examined for evidence of a scale-free structure (Barabási & Albert, 1999) by fitting a power-law regression to the log-log plot of node degree against frequency.

Node-level metrics

Nodes centrality: One of the main objectives of Social network analysis is to identify nodes that are ‘important’ in terms of the extension of their relation with other nodes in the network. The ‘importance’ of the nodes, sometimes referred to as centrality, is often characterized by computing a set of three measures, referred to as degree centrality, betweenness centrality and closeness centrality (Koschutski et al., 2005).

The degree centrality of node i (Dc_i) is a measure of the number of contacts that node i has. A node with a high value of Dc is more connected to other nodes of the network than a node with a low value of Dc . Computation of degree centrality is intuitive for nodes in undirected networks because the value of Dc_i of node i equals the sum of contacts of the node. In directed networks, however, two measures of Dc_i can be obtained depending on the direction of the contacts: (i) the influence or outdegree (Do_i), which refers to the number of contacts that originated from node i ; and (ii) the support or in-degree (Di_i), which refers to the number of contacts that node i receives.

In terms of the adjacency matrix X of an undirected network, degree centrality is simply the row (or column) sums of the adjacency matrix. If Dc_i is the degree centrality of actor i and x_{ij} is the (i, j) entry of the adjacency matrix, then degree centrality is:

$$Dc_i = \sum_j x_{ij} \quad (1)$$

Depending on the nature of the network ties, we can interpret degree centrality in a variety of ways. In this study, the tie is cattle trade link, degree centrality is the number of cattle trade links a node has.

Betweenness centrality (Freeman, 1979) is a measure of how often a given node falls along the shortest path between two other nodes. More specifically, it is calculated for a given focal node by computing, for each pair of nodes other than the focal node, what proportion of all the shortest paths from one to the other pass through the focal node (Borgatti et al., 2013). These proportions are summed across all pairs and the result is a single value for each node in the network. The formula for the betweenness centrality of node j is given by

$$b_j = \sum_{i < k} \frac{g_{ijk}}{g_{ik}} \quad (2)$$

where g_{ijk} is the number of geodesic paths connecting i and k through j , and g_{ik} is the total number of geodesic paths connecting i and k . A node's betweenness is zero when it is never along the shortest path between any two others. This can occur when the node is an isolate, or when every alter of a node is connected to every other alter. Betweenness reaches its maximum value when the node lies along every shortest path between every pair of other nodes.

Eigenvector centrality is an indirect measure of centrality determined by the centrality scores of the nodes to which the node of interest is connected. Here it is presented as the variation of degree centrality in which the number of nodes count adjacent to a given node (just like degree centrality), but weight each adjacent node by its centrality (Borgatti et al., 2013) and given by the formula:

$$e_i = \lambda \sum_j x_{ij} e_j \quad (3)$$

where e is the eigenvector centrality score and λ (lambda) is a proportionality constant called the eigenvalue. The equation basically says that each node's centrality is proportional to the sum of centralities of the nodes it is adjacent to – in effect, when it comes to eigenvector centrality, a node is only as central as its network.

Network level metrics

The density is the proportion of links that are present in the network compared to all possible links. The measure ranges from 0 to 1, where 0 means that there are no links and 1 means that all theoretically possible links are present (Wasserman & Faust, 1994).

Reciprocity: Proportion of edges showing mutual connections (Measure of the tendency of vertex pairs to form mutual connections between each other) (Motta et al., 2017). Reciprocity is measured (Borgatti et al., 2006):

$$R = \frac{(A_{ij}=1) \text{ and } (A_{ji}=1)}{(A_{ij}=1) \text{ or } (A_{ji}=1)} \quad (4)$$

where A_{ij} indicates a link from i to j . A high degree of reciprocity indicates that people choose one another (Valente, 2010).

The degree assortativity measures whether markets tend to be connected with similar degree (value close to 1), to be connected to markets with different degree (value close to -1) or if connection is not dependent of degree (value close to 0) (Newman, 2002).

Average path length: the distance l_{uv} between two vertices u and v is defined as the number of edges along the shortest path connecting them. The average path length

$$l = (l_{uv}) = \left[\frac{1}{N(N-1)} \right] \sum_{u,v \in V} d(u, v) \quad (5)$$

Where l_{uv} is a measure of how a network is scattered. Sometimes, the diameter d of a graph is defined as the maximum path length between any two connected vertices in the graph. However, in other situations the concept of diameter relates to the average path length, i.e., $d = l$. The so-called small-world property appears to characterize many complex networks (Memon et al., 2007).

Diameter: the shortest distance/path length between the two most distant connected nodes in the network (=the longest of all the calculated path lengths) (Motta et al., 2017).

Clustering coefficient: many complex networks exhibit an inherent tendency to cluster. In social networks this represents a circle of friends in which every member knows each other. The clustering coefficient is a local property capturing “the density” of triangles in a graph, i.e., two vertices that both are connected to a third vertex are also directly connected to each other (Memon et al., 2007). The clustering coefficient is defined as

$$C_i = \frac{2}{k_i(k_i-1)} \sum_{j,h} a_{ij} a_{ih} a_{jh} \quad (6)$$

Hence, the clustering coefficient allows to calculate the proportions of nearest neighbors of a node that are linked to each other (in our context, if there exists a link between two markets who have a common trading market). The average clustering coefficient,

$$C = \frac{1}{N} \sum_i c_i \quad (7)$$

Key actors analysis

A correlational analysis between the eigenvector and betweenness centrality was employed to identify the key markets. The residuals of the linear regression were used to identify central markets as the ones displaying a greater predicted value than the observed one. The size of the regression residuals, in combination with the results from the correlation analysis, were used to identify key markets and define their functional roles within the network (Motta et al., 2017).

Gate-keepers: the nodes characterized by high betweenness centrality and low eigenvector centrality values. These are central nodes in terms of their ability to bridge between the functional basis of the network and the wider community of nodes.

Pulse-takers: Represent the functional basis of the network, are nodes with the shortest paths therefore easy access to other central nodes as well as to the rest of the network. They are characterized by high eigenvector centrality and low betweenness centrality values.

Dual functionality: nodes with both high eigenvector centrality and betweenness centrality values. These nodes play both as a gate-keepers and pulse-takers.

Cohesive analysis

Beyond node- and network-level metrics, the overall connectivity and structural cohesion of the network were examined through a set of cohesive sub-group analyses, following the general approach set out by Motta et al. (2017). First, a core-periphery analysis was conducted to distinguish densely-connected core markets from more sparsely-connected peripheral markets. Second, the network's strongly and weakly connected components were identified: a strongly connected component is a subgroup of markets that are mutually reachable from one another when the direction of trade links is taken into account, whereas a weakly connected component disregards this directionality. The largest (giant) strongly and weakly connected components (GSCC and GWCC, respectively) were computed, since these provide, respectively, a lower- and an upper-bound proxy for the potential extent of epidemic or information spread over the network. Finally, the community structure of the network – that is, sub-groups of markets that are densely connected to one another but only sparsely connected to markets in other sub-groups – was examined [Author: please state here which community-detection algorithm was used to identify the 17 communities reported in the Results, e.g., the Infomap/Rosvall-Bergstrom random-walk method used by Motta et al. (2017), the Louvain method, or another approach, together with the software package and any resolution parameter used, so that the analysis is reproducible].

Limitations of the sampling approach

The market list combines three purposively selected project sites, two additional purposively surveyed trading points (Sagure and Harar), and a wider set of markets reached through snowball referral. To limit the risk that this referral process under-represents distant or lower-volume trading partners, key informants for the referral-sampled markets were deliberately selected from among cattle traders with direct, multi-market trading experience — rather than informants with only local knowledge — and the resulting trade routes were cross-checked against published cattle value chain studies for the study areas. Even so, the sample is not a full census of all cattle markets in Ethiopia, and the reported network topology should be interpreted as representative of the sampled north–south transect and its immediate trading partners rather than of the complete national cattle trade system.

Geographical Cattle Distribution in Ethiopia

The cattle population densities were computed as number of animals per km² at regional level. The thrust is to show how the cattle population are distributed spatially across the country. The source of the cattle population is based on the livestock sample survey of the central statistics Agency (CSA 2017/18) of Ethiopia. Hence, the spatial pattern of the cattle population is shown in Figure 1 below. The map shows that the cattle population are unevenly scattered across the country. The Ethiopian highlands are found to be highly populated. In this regard, the SNNPR, Amhara and, Harari are the highly populated regions with respect to cattle population (Samson & Frehiwot, 2014). High populations of cattle per km² were found in Amhara, SNNPR and Harari regions. According to a study conducted by (Jabbar et al., 2007) to determine geographic distribution of livestock population in Ethiopia found a similar result with the finding of this study. They obtained that the highest numbers of cattle were found along a north–south transect covering parts of the central highlands of Tigray, Amhara and Oromia regions, and the transect that connects Adama and Dire Dawa.

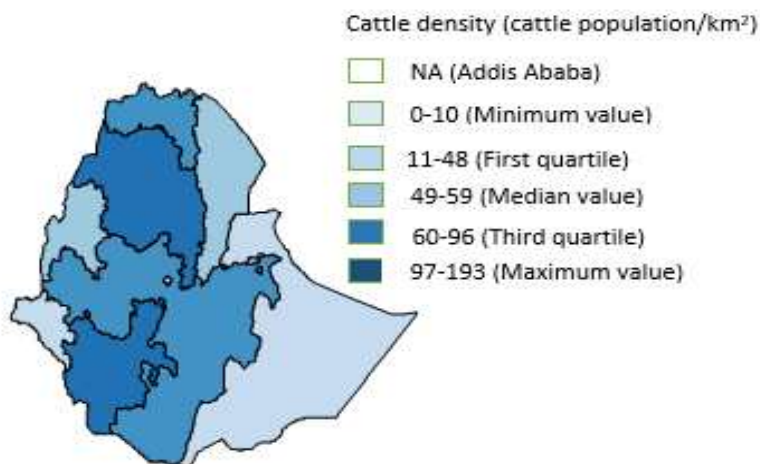


Figure 1: Cattle population density by region in Ethiopia. Regional cattle population density (head/km²) computed from the CSA 2017/18 livestock sample survey.

Infrastructure Development: Road Network and Cattle Market

Road is one of the very important infrastructure in the livestock marketing system. The type of road connecting an area determines the type of buyers that can get access to its market. It also affects the profitability of most of the participants in the livestock market (Hailemariam et al., 2008). To this end, the proximity of cattle markets to a road network is estimated. As presented in Figure 2, about 50% of the cattle markets were found to be within 10 km radius from the all-weather roads. While the rest 14% and 36% of the cattle markets were found to be between 10 km to 25 km, and greater than 25 km radius from the all-weather roads, respectively. Hence, most of the cattle markets are located on roads sides with a road link. This implies the development of the cattle markets depended on development of the road network.

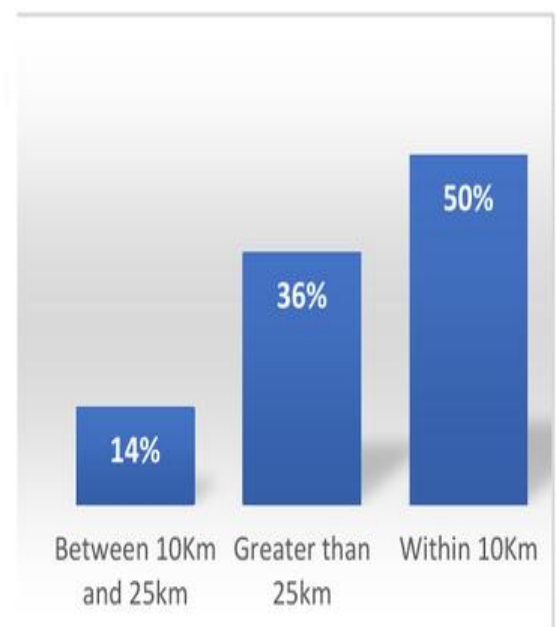
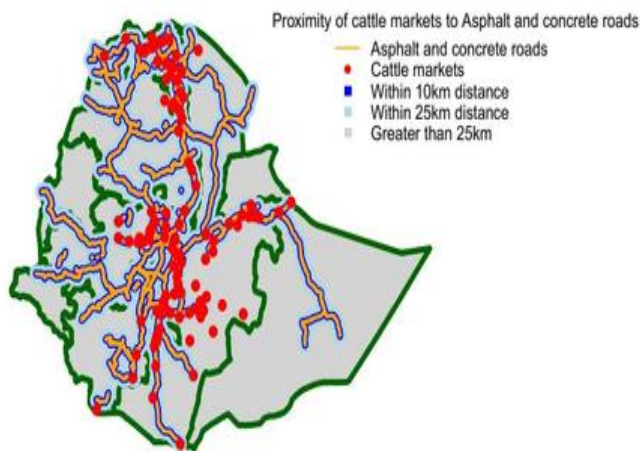


Figure 2: Cattle market locations relative to the all-weather road network (Left), Percentage of cattle markets within 10 km, 10–25 km, and beyond 25 km of an all-weather road (Right).

Results and Discussions

Network topology

The average path length and the clustering coefficient (CC) of the empirical cattle trade network in the study area were 2.54 and 0.127, respectively. In comparison, the mean average path length of 1000 simulated random networks was 5.79 (range = 2.67-10.05), whereas the 90th percentile of CC was below 0.044, three times lower than the empirical cattle trade network. These network characteristics are consistent with a small-world structure (Watts & Strogatz, 1998). On average, markets were connected to 2.53 others (range 1-13), with 1.261 average incoming (range 0-9) and 1.261 outgoing (range 0-5) connections.

The degree distribution for all markets involved in the cattle trade network was positively or right-skewed with only a small proportion of markets being highly connected (7% of the markets held 48% of the connections, while 93% of the markets held the 52% connections) (Figure 3A). The node degree distributions were appeared heavy tailed, suggesting a scale-free structure. Many real networks (even if they have a different nature) have this structure, characterized by the fact that most of the nodes have only few neighbors, whereas few nodes (the so-called hubs) have many neighbors. Furthermore, Figure 3B shows the log-log distribution of the degree centrality values of the nodes of cattle trade networks under study.

Plots show a power law distribution. The log-log regression equation shows that the determination coefficient (R^2) and the power (as the coefficient of x). The alpha is 1.45 and coefficient of determination is 0.83.

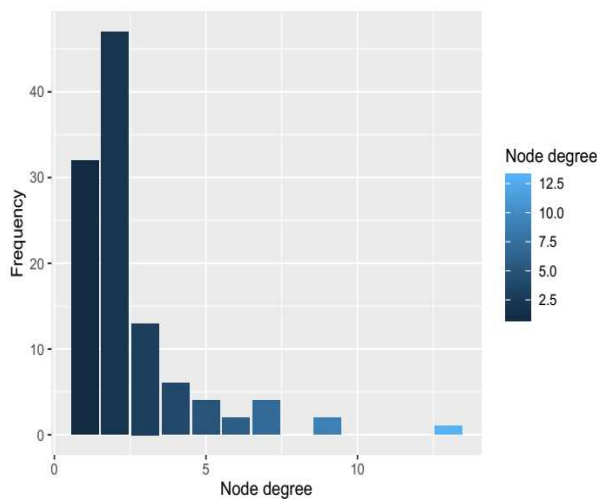


Figure 3A: Degree distribution of the cattle trade network

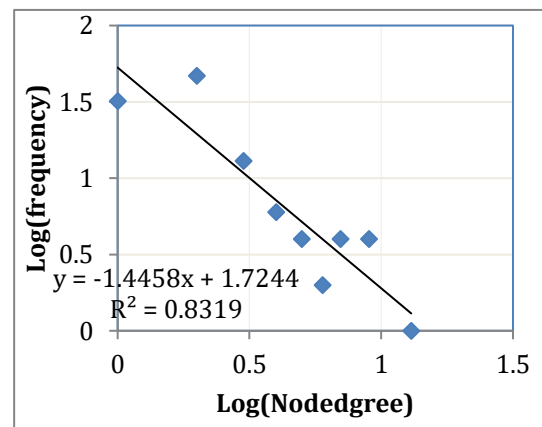


Figure 3B: Log-log degree distribution of cattle trade networks

The study identified seven regions in the cattle trade network that involved cattle trade in the study area based on cattle marketplaces at districts level from each region. The circular visualization in Figure 4 below summarizes the cattle trade network. The origin and destination of traded cattle are represented in this circular map. Each sector of the circle in the (Figure 4) represents regions from the study area or neighboring regions, namely Amhara, Somali, South and Afar involved or linked by the cattle trade flow within the cattle trade network. In this circular map, the outward cattle flow is represented by those links, which start from the base of each sector while inward cattle flow or movements do not reach the base of the relevant sector. For instance, the Oromia and Tigray regions trade most of their animals within the same region compared to other regions.

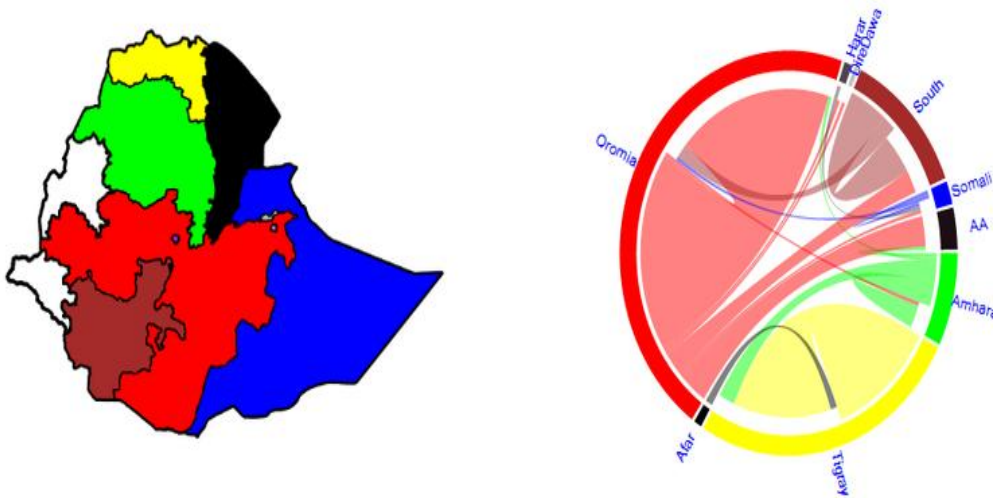


Figure 4: Circular representation of the cattle trade network in the study area by region, Ethiopia. Chord widths represent the relative volume of cattle trade flowing between regions.

The results of Table 1 further show the percentage of cattle trade links that move between each pair of regions identified on the cattle trade network displayed in Figure 3. Accordingly, about 73 and 100 percent of cattle trade links sent and received within the same region for Oromia and Tigray, respectively. Suggesting that only 23 percent sent out to other regions for Oromia region and none for Tigray region.

Table 1: Percentage distribution of cattle trade links between regions

Source \ Destination	Amhara	Tigray	Afar	Oromia	Harari	Dire Dawa	South	Somali	Addis Ababa
Amhara	46	38	0	8	0	0	0	0	8
Tigray	0	100	0	0	0	0	0	0	0
Afar	0	100	0	0	0	0	0	0	0
Oromia	1	0	0	73	1	1	9	1	12
Harari	0	0	0	0	0	0	0	100	0
Dire Dawa	0	0	0	0	0	0	0	0	0
South	0	0	0	27	0	0	73	0	0
Somali	0	0	0	50	0	0	0	50	0
Addis Ababa	0	0	0	0	0	0	0	0	0

Note: cell values are the percentage of a source region's (row) outgoing cattle-trade links that terminate in each destination region (column) e.g., 73% of Oromia's outgoing links stay within Oromia. These are percentages, not raw counts of trade connections.

The network displayed a low density (0.011) of connections, with only 1.1% of the possible links present. When viewed independently, the Tigray region has a denser network (3%) while Oromia region has a network density of 1.6%. The reciprocity of the network was 0.0287, indicating that only just 2.9% of the connections among markets were reciprocal, or bidirectional. The degree assortativity was 0.16: this positive assortative value indicates a tendency for markets preferentially connect with markets of similar degree centrality.

Furthermore, the study investigated the propensity of the network to prefer links between markets of the same region using assortativity coefficient. The corresponding assortative coefficient for the region is 0.42 and higher than degree assortativity coefficients. The study also shows that a minimum of seven steps were required for connecting the two most distant reachable nodes, as measured by the network diameter. The visualization of the actual path of the diameter showed that it extended from Shambu, across the Oromia Region ending to Addis Ababa city (Figure 6, in the appendices).

Key Actor Analysis

All the studied centrality measures, degree, eigenvector centrality and betweenness centrality have a moderate linear correlation among themselves caused by low density of the trade network (Spearman correlation $r > 0.289$) (Table 2). The smallest correlation coefficient resulted between eigenvector centrality and betweenness centrality ($r = 0.289$) and was applied to detect markets not having a linear relation between these metrics. The key actor analysis was conducted at three levels, namely whole network level (i.e., including Oromia, Addis Ababa and Tigray regions market networks.), separately at each region (Tigray and Oromia). The attempt is to identify the key role played by markets either at whole level or at regional level (see appendices, Figure 8).

Table 2: Correlation coefficients between node centrality measures

	Degree	Betweenness	Eigenvector
Degree	1.0000	0.6359	0.3000
Betweenness	0.6359	1.0000	0.2891
Eigenvector	0.3000	0.2891	1.0000

For the whole cattle trade network, five markets were identified as critical in the network: two were defined as the nucleus for structural functionality of the network (“pulse-takers”), none as being fundamental in connecting parts of the network (“gate-keepers”). This implies the Tigray and Oromia regions are isolated in terms of cattle trade network. However, two markets were found as having both these attributes as pulse-takers and gate-keepers (see in the appendices, Figure 10). A similar result has also observed in Oromia region cattle trade network as well, which found none found as being gate-keepers, whereas two observed as pulse-takers and three as being dual-function (Figure 8). In the case of Tigray region cattle trade network, it was identified nine markets as critical in the network; four markets were defined as pulse-takers, three markets as being gate-keepers of the network and two as dual-functions who have both these attributes (see in the appendices, Figure 9).

Cohesive analysis

The cattle trading network of the study area was organized around seven cores (respectively Bishoftu, Adama, Dera, Shashemene, Bale Robe, Awassa and Addis Ababa nodes) and involved a periphery of 104 markets that were connected to the different cores. Among the total 111 markets involved in the network, 104 markets were identified strongly connected components. Of these strong components, 101 contained only one node, one contained two nodes, the other one contained three, while the largest included 5 markets, located in both the Oromia and South regions of Ethiopia and representing, therefore, 5% of all markets.

A further investigation of the network structure revealed that 17 communities were identified within the cattle trade network. These communities entailed markets range from 1 to 42 markets. In this network, the two largest communities had 42 and 21 markets. These two communities together accounted for 56% of all the markets. The largest community which included 42 markets were found to be from Oromia, Addis Ababa and South nation regions. The other largest community which involved 21 markets were found from Tigray region. The results of the community detection method confirmed that the cohesion among regions namely Oromia, South and Addis Ababa while isolation of Tigray region (see in the appendices, Figure 11). The 17 different nodes/shades communities are highlighted with different colors.

Discussion

The findings above map the domestic cattle trade network in Ethiopia for the first time using a social-network lens, moving beyond the linear value-chain framing used in earlier studies (see Background). The remainder of this section interprets what that structure implies substantively.

The node degree distributions of the cattle trade network were evaluated and appeared heavy tailed, suggesting a scale-free structure (Barabasi & Albert, 1999). Such characteristic in network appears network growth is driven by preferential attachment. The result shows that only a small proportion of markets being highly connected (i.e., 7% of the markets held 48% of the connections, while 93% of the markets held the 52% connections). Suggesting that most of the nodes (markets) tends to link in buying or selling to the most connected nodes (markets). This implies that the cattle market is influenced by a few key markets called hubs, which have higher degree centrality, in terms of market information mainly cattle price.

The other aspect is the network exhibits a small-world property as well. This is evidenced by a relatively shorter average path length and higher clustering coefficient (which also larger than the network density) compared to a random network generated with same number of nodes and connections. Besides, the clustering coefficient and network density are equal in completely random graph. The result implies that our real network (i.e., the cattle trade network) is statistically more clustered than if they were random graphs. Therefore, cattle markets tend, on average, to establish trade relationships with markets that are also linked with each other. This suggests that local ties still play a significant role. Small-world contact structures (Watts & Strogatz, 1998) have previously been found in livestock contact networks in the Great Britain. In Ethiopia a study by (Mekonnen et al., 2019) investigated the patterns of cattle movement and size of animal moved between farms contributed to the potential for BTB transmission. The

authors found that the dairy cattle movements among farms show a smaller number of long-range links and consistent with small world effects.

In general, the network has low density. Viewed independently, the Tigray region sub network has a higher network density than the Oromia region. The higher network density of Tigray region might explain it has a smaller number of cattle markets in the network than Oromia region. This implies markets in Tigray region are more integrated within regional level than country level. The weak trade integration between regions (namely, Oromia and Tigray) reflects the weak cattle trade flows between these two regions. The reciprocity of the network was 0.0287. The low reciprocity of the network shows that the majority of the trade links are not bilateral (Fagiolo et al., 2007). Hence, the cattle trade network is asymmetric.

The degree assortativity was 0.16; this positive assortative value indicates a tendency for markets to preferentially connect with markets of similar degree centrality. Furthermore, the study investigated the propensity of the network to prefer links between markets of the same region using assortativity coefficient. The corresponding assortative coefficient for the region is 0.42 and higher than degree assortativity coefficients. A similar result has found by (Lentz et al., 2016). Hence, markets have a preference to trade with the same region. This result implies new nodes connect not necessarily to central nodes (markets) but also connect to those that are close by in a geographical sense (Ter Wal & Boschma, 2009).

Most of the centrality measures show correlation among themselves and with degree centrality. The correlation coefficient ranges from a moderate 0.63 (between degree centrality and betweenness) to a low 0.28 (between eigencentrality and betweenness). The low correlation among centrality measures are driven by the low network density.

The key actor analysis identified the key markets, which has a significant importance in improving the cattle market in the country. These markets are important in the function of the cattle market, flow of information, cattle movement (exchange) and price transmission. Hence, these key markets can be considered as a starting point for market upgrading intervention or disease surveillance strategies (Motta et al., 2017).

Conclusions

The study explored the cattle trade network in Ethiopia and, by applying centrality measures derived from the network analysis, unveiled and described the network topologies, and identified the key markets.

We found the cattle trade network in Ethiopia exhibits both small-world and scale-free properties. It was also found that the cattle trade has a low density suggesting low connectivity among cattle markets.

The paper also provides evidence the cattle trade network is characterized by assortative association. Suggesting that markets have a preference to trade with the same region or locally.

In particular, Shashemene, Adama and Addis Ababa emerged as dual-function (pulse-taker/gate-keeper) hubs at the whole-network level — markets that are simultaneously well-embedded in the flow of trade information and structurally positioned to bridge otherwise disconnected parts

of the network. These are the most defensible starting points for market-upgrading investment or disease-surveillance placement that the data support, ahead of any single-region hub identified separately in Tigray or Oromia.

Competing interests

[Author to insert competing interests statement, e.g. “The authors declare that they have no competing interests.”]

Author's contributions

[Author to insert individual contributions, e.g. study design, data collection, analysis, drafting and revising the manuscript, for each named author.]

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Appendices

Figure 6: Diameter of the cattle trade network. Clockwise from top left: national overview of the diameter path; whole-network graph with the diameter path highlighted; regional zoom of the area containing the diameter; detailed path from Shambu to Addis Ababa.

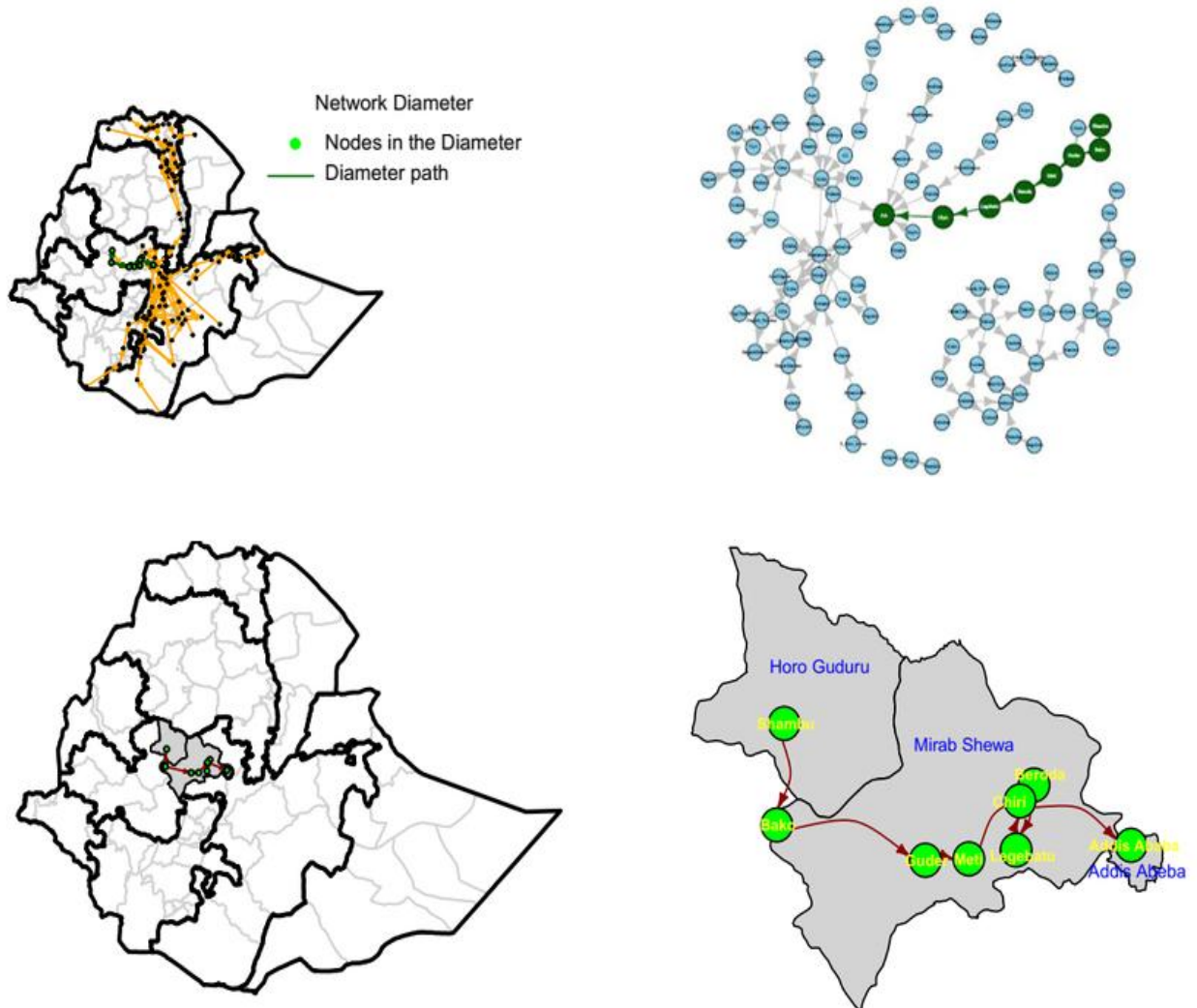


Figure 7: Cattle trading network in the study area and neighbouring areas (Amhara, Afar, Somali and South regions). Node size is proportional to degree centrality; arrows indicate the direction of cattle movement.

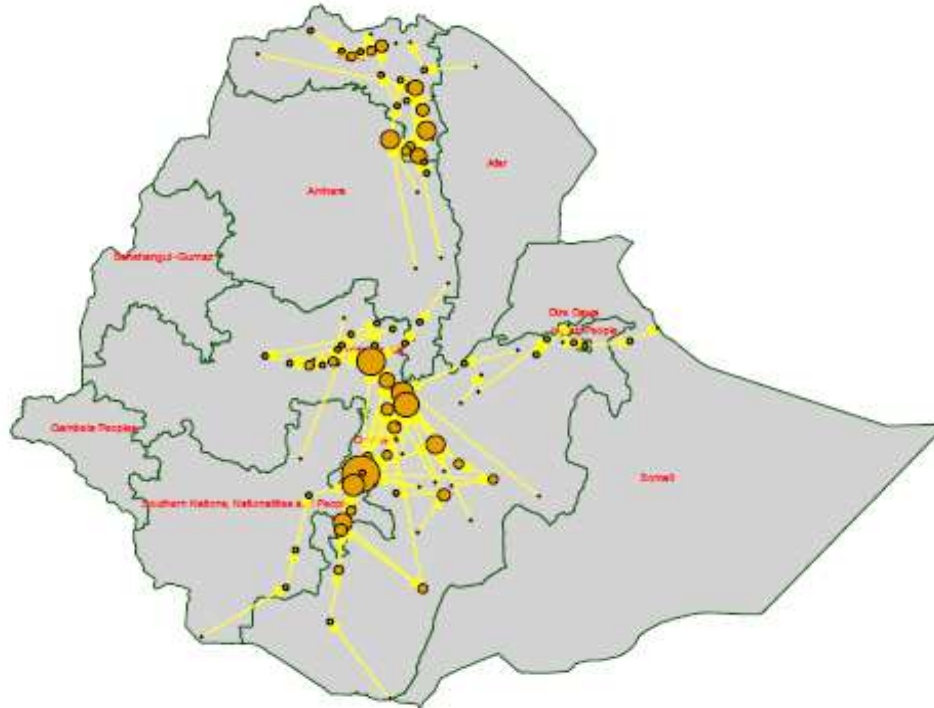
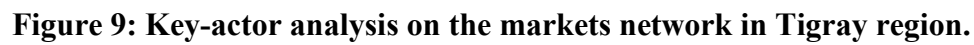


Figure 8: Key-actor analysis on the markets network in Oromia region. Quadrants classify markets as pulse-takers, gate-keepers, dual-function, or neither, based on eigenvector and betweenness centrality.

Correlation between eigenvector centrality and betweenness centrality is to identify markets with different roles within the trading network. “Gate-keepers”, in the bottom-right quadrant, are central entities in terms of their ability to bridge between the functional nodes of the network and wider community of nodes. In the top-left quadrant, “pulse-takers” are the nodes with the shortest paths to all other nodes having easy access to the other central markets as well as to the rest of the network. Nodes in the top-right quadrant have both abilities. Markets in the bottom left quadrant tend to have no particular role. The size of the labels is relative to the value of their residuals obtained through linear regression of betweenness over eigenvector centrality, indicating the extent of their deviation from a linear relationship.



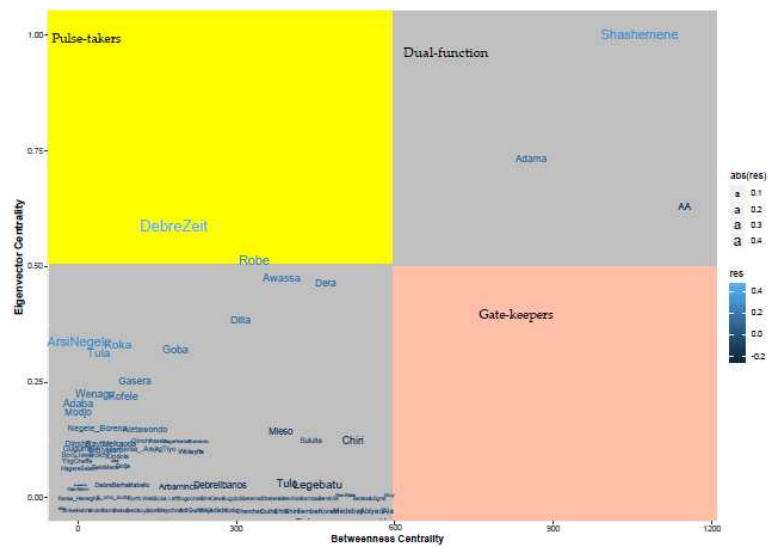


Figure 11: Communities of the cattle trade network. The 17 detected communities are shown in different colours/shades.

