

Local and wide-scale livestock movement networks inform disease control strategies in East Africa

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Supplementary Materials

Supplementary Methods

Local livestock movements

Participatory mapping. *Location of focus.* The Serengeti District has a human population of 250,000 ¹ and a livestock density of 84/km² (Unpublished National Livestock Branding Report) within an area of 9,000 km². Ngorongoro District is inhabited by 175,000 pastoral people in an area of 14,036 km² ¹, with livestock density of 103/km² (Unpublished National Livestock Branding Report).

Mapping tools. Quantum geographical information system (QGIS), version 3.18² software was used to construct maps at a variety of scales (1:2,500, 1:5,000 and 1:10,000) incorporating downloaded Google Earth satellite imagery on a gridded map base. The image dimension was 1 metre by 1 metre at each scale (representing 2.5 km, 5 km and 10 km on a side, respectively), which ensured ease of sharing, and visibility and recognition of topographical features such as human settlements, hills, rivers/dams, roads, crop lands, utility centres etc (Fig. S2). In addition to these maps, wider scale (1:50,000) published topographic maps (with the addition of Tanzanian 2012 Census village boundaries) were printed at 1 metre by 1 metre (50 km on a side) and used to visualise livestock mobility corridors spanning across several villages, village borders such as hills and contours, large rivers and springs, rangelands, grass plains etc. (Fig. S3). All maps used were digital and their built-in coordinate systems were converted to Universal Transverse Mercator (UTM) projection and WGS84 datum to allow the participants to consistently identify the location and distances of key features across maps, aiding the mapping process. This provided a means to locate and estimate the size of livestock resources and crop lands more precisely.

Data collection. Before visiting each village, baseline information about grazing and watering patterns and other livestock-keeping characteristics was gathered for each village through consulting with the District Veterinary Office.

At village-level, a quick exploration of the digital maps was used to orientate participants and for map validation. To allow them to freely express themselves, the local language (Swahili and Maasai) was used for the discussion. Participants agreed on a clear layout of the community by combining the Google Earth images and topographic maps (Figs. S2 & S3). Subsequently, all relevant features and key resources were identified and located on the printed maps. Participants were also asked to list all livestock resource areas by name, identify their locations, and draw them on the map by hand (Figs. S3 & S4).

This activity was followed by broad discussions about animal movement characteristics of the village in relation to grazing and watering points, dips, resources containing minerals, livestock routes, sharing of grazing areas with wildlife and perceived disease risks. A structured list of questions guided the discussion to ensure consistency across villages and capture timeline of movements across seasons. All identified communal areas were categorised based on the absolute amount of use in wet, dry or both seasons, and ranked by the overall frequency of usage. However, given that the interpretation of seasons varies amongst villages, participants were asked to define the months corresponding to each season. For each type of resource area, participants described whether they were used by large or small herds or both, and the type of livestock species (i.e. cattle versus sheep and goats) that used them. These discussions were recorded using a digital field book and electronic voice recorder.

After each session, all key resource areas identified in the discussions were visited with the assistance of the village chairman. Their locations were validated, and their centres were geo-located using a hand-held global positioning system (GPS) device (Garmin eTrex® 10).

Wide-scale (trade-related) livestock movements

Collection and processing of data on trade-related livestock movements.

Livestock movement permits (LMPs) were used to gather data on traded livestock. Information extracted from the permits included the village of the market where livestock were traded, village of destination, number of each species (cattle, sheep or goats) moved, and date and routes used, including major villages, towns and features such as hills or rivers encountered before the final destination. However, information on villages of origin is not typically recorded on LMPs. To capture these details, a field team member was stationed at the permit issuing point for each market to retrieve slips (local authorisation permits) containing information on livestock owner and village of origin which was then matched to LMPs. This was only possible for Serengeti District due to the availability of a

dedicated field team member on every market day for the entire study period (January - December 2017). For the other districts, origin details were captured by a field assistant at each market who recorded village and number of all livestock traded on the market day by questioning owners of sold animals at movement permit issuing points. This information could only be gathered twice in the study period. Although it was not possible to match each origin data point to the exact destination, we were able to estimate the number of traded livestock that originated from each village or town. To augment this information, local livestock field officers, who are responsible for issuing permits in the district, were interviewed to identify major livestock catchment areas for each market. A short questionnaire was also administered to ten randomly selected livestock sellers and buyers to ascertain the origin of their livestock.

For each traded livestock species, data were aggregated at village level including primary origin, market at which they were sold, date, destination (village or town) and routes. To verify the completeness of the movement data extracted, the number of traded livestock obtained from the permit booklets were compared with government revenue reports that contained details of traded livestock for each district in the same year. To check for any inconsistencies, data cleaning was performed in the R programming language version 3.6.1 ³, using dplyr version 0.8.3 ⁴ and reshape2 version 0.8.8 ⁵ packages.

Data on human and livestock populations. Information on human population size for each rural or urban location where livestock were traded, originated or headed to was extracted from the 2012 Tanzanian census report ¹. Livestock population numbers were obtained from government livestock branding reports (unpublished). In a few cases where permits indicated a town as the origin or destination, the mean human and livestock populations of the town was used.

Supplementary Tables

Table S1. Definitions of common network parameters and other terms used in the study. These refer to all types of networks we built to illustrate village connectivity and movement of traded livestock: (1) directed and bipartite networks, whereby nodes were resource areas and villages, and edges represented linkages between them, (2) undirected weighted networks, whereby nodes were villages and edge weights represented the shared resources between two villages and the frequency of use, and (3) directed weighted networks, whereby nodes were villages of livestock origin or destination, or market locations, while the edge weights were a function of the number of livestock traded between villages.

Network parameter	Definition
Degree	The number of connections to or from a node (village) in a defined period (e.g. day, month or year). The bipartite network has directed edges (village to resource areas) which indicate their in-and-out degree. The single-node (village to village) network was undirected so there were no specifications for in-degree (contacts to a village) or out-degree (contacts from a village). The more the number of edges between connected villages, the higher the degree or contacts for the villages.
In-degree and out-degree	Using simplified definitions in our study context, a village weighted in-degree was the volume of livestock that the village received from other villages, while out-degree was the volume of livestock that left the village to other villages.
Betweenness	The term is used to describe the frequency by which a node falls between pairs of other nodes on the shortest path that connects them ⁶ . In our study, the weighted village betweenness describes the extent to which a village occupies positions in the network that influence the connections of others ⁷ . As a measure of centrality, node betweenness can be used to evaluate its ability to exert control or flow within a network. Villages with high betweenness were broadly considered 'hub' villages. Betweenness values range from 0 (least) to 1 (highest)
Eigenvector centrality	The term indirectly measures centrality determined by the centrality scores of the nodes to which the node of interest is connected to ⁷ . In our study, the eigenvector centrality value was defined loosely as the extent of how connected a village was to well-connected neighbours. It approximates the importance of each village in the network by assuming that each village centrality is the sum of the centrality values of the villages that it is connected to. A high eigenvector score

	means that a village is connected to many villages, which have high scores themselves.	133 134
Density	Number of edges in the observed network relative to the total number of possible edges in a completely connected network.	135 136 137
Village/inter-village connection	Contacts of at least one herd from one village with herd(s) from other village(s) at any resource area or market, i.e. when a herd visits a resource area of another village or when traded livestock are moved between two villages. This applies to both directed and undirected networks	138 139 140 141 142
Village contact (Unweighted degree)	Unique contacts between villages in a simplified network. It refers to the number of village(s) a village is connected to at least once in a defined period: day, week, month or year.	143 144 145
Connected components	A connected component of an undirected graph is a maximal set of nodes such that each pair of nodes is connected by a path. This also shows the partitions in the network. A component value of 1 will suggest all pairs of nodes were connected by a path in the network.	146 147 148 149
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Table S2. Variables included in the gravity models of livestock trade in the Mara region, northern Tanzania. Logit (P_{ij}) is the probability of movement (model 1) and Log ($\mathcal{M}_{ij}$) is the number of livestock movements from origin to destination village or town (model 2). P_i and P_j are the population of origin and destination. D_{ij} is the distance between origin and destination. The equation includes also predictor variables (X_k) for origin or destination villages and their associated coefficients γ_k are random effects for source and destination village. The initial model equation was written as follows:

$$\text{logit}(P_{ij}) = \beta_0 + \beta_1 P_i + \beta_2 P_j + \beta_3 D_{ij} + \sum_{k=1}^8 \gamma_k X_k + h_i + h_j$$

Model 1

$$\log(\mathcal{M}_{ij}) = \beta_0 + \beta_1 P_i + \beta_2 P_j + \beta_3 D_{ij} + \sum_{k=1}^8 \gamma_k X_k + h_i + h_j$$

Model 2

Model parameter		Coefficient type	
D_{ij}	Pairwise distance of village of origin and destination (per standard deviation of the distribution)	Fixed effect	β_3
P_i	Livestock population number at origin (per standard deviation of the distribution)	Fixed effect	β_1
P_j	Livestock population number at destination (per standard deviation of the distribution)	Fixed effect	β_2
X_1	Human population number at origin (per standard deviation of the distribution)	Fixed effect	γ_1
X_2	Human population number at destination (per standard deviation of the distribution)	Fixed effect	γ_2
X_3	Market presence at origin (Yes/No)	Fixed effect	γ_3
X_4	Market presence at destination (Yes/No)	Fixed effect	γ_4
X_5	Origin was urban village/town (Yes/No)	Fixed effect	γ_5
X_6	Destination was urban village/town (Yes/No)	Fixed effect	γ_6
X_7	Abattoir at destination (Yes/No)	Fixed effect	γ_7
X_8	Market presence at origin and destination (Yes/No)	Fixed effect	γ_8
-	Origin village name	Random effect	h_i
-	Destination village name	Random effect	h_j

Table S3. Summary of livestock populations in the study area based on government-level data, and agropastoral and pastoral livestock and crop keeping characteristics based on participatory mapping sessions. IQR is the interquartile range of the median values for the livestock populations. Note that livestock population data of the pastoral setting relate to the Sale and Loliondo Divisions only, not to the whole district (Ngorongoro).

Category	Agropastoral	Pastoral
Total livestock		
Cattle	400,823	379,988
Goats	148,294	529,012
Sheep	194,855	531,191
Village-level livestock population estimates		
Cattle		
Mean	4,224	8,261
Median	3,737 [IQR: 2,242-5,159]	7,248 [IQR: 3,431-11,393]
Goats		
mean	1,564	11,500
median	1,315 [IQR: 832-1,858]	7,585 [IQR: 4,465-13,258]
Sheep		
mean	2,052	11,548
median	1,504 [IQR: 965-2,192]	6,944 [IQR: 4,139-11,023]
Mean household-level herd size		
Cattle	50	250
Goats	20	350
Sheep	10	200
Main source of livelihood		
Livestock	No	Yes
Crops	Yes	No

167 **Table S4.** Summary of key livestock herding characteristics practised by pastoral and
168 agropastoral villages in the study area in northern Tanzania.

Herding parameter	Herding pattern	
	Agropastoral	Pastoral
Land use plan	Not frequently used and difficult to enforce. Only 10/97 villages indicated that they had allocated permanent areas in the village for livestock grazing, cropping and human settlements.	Very few villages (2/46) have dedicated areas for grazing and human settlements.
Settlement, re-settlements, and camping	All village households had one permanent settlement. Crop- and livestock-related activities (e.g. grazing) were performed daily out in the field. Herds were returned back to settlements every day. Most households in all villages engaged in cropping more than livestock keeping. A few livestock-owning households (in 15 out of 97 villages) engaged in camping whereby cattle were moved to neighbouring villages for about 6-8 weeks until the beginning of the wet season.	The majority of village households (40/46) had one permanent and several temporary settlements. All livestock in the herds that were seasonally relocated were returned back to permanent settlements once or twice in a season depending on climatic conditions and rainfall patterns. Settlement and resettlement around rangelands were mostly influenced by forage levels, predation and risk of malignant catarrhal fever, a disease of livestock associated with wildebeest calving. Broadly, most herds were moved back to permanent settlements at the end of the wet season, where they would stay for 2-3 months before relocating to temporary settlements. About 6 villages considered themselves to be absolute pastoralists without permanent settlements and no crop activities.

Herding	Most households grazed small and large ruminant herds of all sizes together. Few livestock-keeping households with large herds (>100 cattle) travelled longer distances to large grazing fields to avoid crop cultivated areas. Herding decisions were not influenced by the need to access mineral salts or water.	Mixed livestock types were kept in the same household and were grazed together. However, 10% of livestock, including pregnant, young and sick animals were usually left at permanent settlements during long-distance migrations. Some herders reported moving at least one livestock herd between the temporarily and permanently located herds every 4 - 12 weeks depending on the location of the camping site and precipitation levels. Common community perceptions are that mineral salt is vital for reproduction therefore herding decisions are mostly influenced by a need for mineral salt supplements or water during extreme dry season.
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Table S5. Properties of livestock movement networks (see also Supplementary Materials, Figs. S7- S9) in agropastoral and pastoral production systems at each of the four major resource areas, grazing, watering, salting and dipping, identified through participatory mapping in two districts of northern Tanzania, Serengeti (agropastoral) and Ngorongoro (pastoral). Nodes are villages, while edge weights are a function of the number of shared resources between villages - an indication of the strength of contact.

Network statistics	Agropastoral				Pastoral			
	Grazing	Water	Salt	Dip	Grazing	Water	Salt	Dip
Size								
node	97	91	51	54	46	45	41	5
edge	5654	2880	1400	1715	9048	10901	5525	52
Betweenness								
min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
median	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00
mean	0.04	0.03	0.00	0.01	0.04	0.04	0.03	0.03
max	0.23	0.29	0.06	0.17	0.29	0.46	0.25	0.16
Eigenvector								
min	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
median	0.10	0.01	0.00	0.00	0.49	0.13	0.37	0.16
mean	0.21	0.05	0.10	0.15	0.45	0.24	0.33	0.43
max	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Village contact (unweighted degree)								
min	1	1	1	1	2	3	1	1
median	7	5	3	3	15	15	14	2
mean	7	5	3	4	16	16	12	2
max	19	19	8	13	28	30	23	2
Density	0.08	0.06	0.06	0.07	0.36	0.37	0.31	0.40

Table S6. Properties of livestock movement networks for each production system across seasons. Nodes are villages, while edges are the number of contacts among connected villages including a drought year we captured in the pastoral setting. All centrality measures are weighted.

Network statistics	Agropastoral			Pastoral			
	Wet	Dry	Year	Wet	Dry	Drought	Year
Size							
node	94	96	97	46	44	45	46
edge	2349	4487	11906	6256	4000	6656	23128
Betweenness							
min	0.00	0.00	0.00	0.00	0.00	0.00	0.00
median	0.02	0.01	0.01	0.01	0.02	0.01	0.01
mean	0.03	0.03	0.03	0.04	0.05	0.03	0.04
max	0.28	0.30	0.22	0.50	0.36	0.22	0.35
Eigenvector							
min	0.00	0.00	0.00	0.00	0.00	0.00	0.00
median	0.00	0.07	0.02	0.39	0.05	0.09	0.39
mean	0.08	0.17	0.14	0.32	0.17	0.22	0.36
max	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Village contact (unweighted degree)							
min	1	1	7	1	3	4	3
median	5	8	8	18	11	17	20
mean	5	8	9	15	13	17	20
max	9	22	22	28	24	31	33
Density	0.05	0.09	0.09	0.33	0.30	0.39	0.45
Proportion of connections contributed by top 20% high degree villages	0.29	0.35	0.49	0.35	0.32	0.45	0.47

205 **Table S7.** The number of livestock that were traded in the study districts in the year 2017.
 206 DC and TC are District Council and Town council, respectively.

District	Livestock category		
	Cattle	Sheep	Goats
Serengeti	18486	2227	3736
Tarime	7276	1231	1379
Bunda DC	6802	1528	6105
Bunda TC	3954	953	2261
Butiama	10772	466	3986

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208 **Table S8.** District of origin of traded livestock in the study area. DC = District Council, TC =
 209 Town Council.

District of market location	District of origin						
	Serengeti	Tarime	Bunda DC	Bunda TC	Butiama	Rorya	Musoma
Serengeti	21,879	76	201	0	344	0	0
Tarime	2,409	3,311	1,100	91	772	22	0
Bunda DC	1,300	67	12,037	1,028	26	0	0
Bunda TC	0	0	1,772	5,001	400	0	0
Butiama	2,166	31	77	9	12,985	0	6

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Table S9. Significant explanatory variables from the final binomial generalised linear mixed model of probability of traded livestock movements between village pairs. The continuous variable (pairwise distance between origin and destination) was scaled to mean zero and one standard deviation. CI denotes Confidence Interval.

	Estimate (95% CI)	P value	Odds Ratio (95% CI)
Pairwise distance between origin and destination (per standard deviation of the distribution)	-0.99 (-1.20 - 0.79)	$<10^{-6}$	0.37 (0.23 – 0.49)
Market presence at origin (Yes vs No)	1.37 (1.17 – 1.57)	$<10^{-6}$	3.96 (3.25– 4.74)
Market presence at destination (Yes vs No)	1.87 (1.67 – 2.09)	$<10^{-7}$	6.53 (5.31-8.00)

Supplementary Box

Box 1. Details of the four types of key resource areas that drove connectivity between villages in both agropastoral and pastoral systems.

- (a) *Grazing areas:* Movements to grazing areas occurred daily during the wet and dry seasons. Study participants reported that some villages have specific areas allocated to grazing, while others have open grazing plans where livestock are allowed to graze on pastures without restrictions. In agropastoral settings, a village was connected to seven (unweighted mean degree) other villages through 9.6 (116/12) links (i.e. weighted mean degree, which also indicate mean movement events where livestock herds from a village encountered herds from other villages) across several grazing areas in a month (Table S5). In pastoral settings, between-village connections at grazing locations were almost twice as numerous as in agropastoral systems despite the network having half the number of nodes (Table S5 and Figs. S7 & S8).
- (b) *Watering points:* Similar to grazing areas, study participants reported daily movements of livestock to water sources across seasons. However, in extremely dry periods, pasture is typically prioritised over water, hence livestock movements to water sources occur every other day. Each agropastoral village was connected to five others through watering points (Table S5 and Fig. S7), apart from three that had no contacts with other villages in a whole year. In the agropastoral settings, the links at watering points were fewer compared to grazing, while the opposite was observed in the pastoral settings (Table 1 and Figs. S7 & S8).
- (c) *Salting points:* Movements to salt licks, used as dietary supplements (particularly for cattle), occurred weekly and more often involved pastoralists compared to agropastoralists (Table S5 and Figs. S7 & S9). A village was connected to three (unweighted degree, agropastoral) and 12 (unweighted degree, pastoral) other villages through this resource area.
- (d) *Dipping points:* Routine (once or twice a month) dipping was practised in more than 56% (54/97) of agropastoral villages, but it was less common (11%, 5/46) in pastoral systems (Table S5 and Figs. S7 & S9). Consistent with this, a village was connected to 3.5 (unweighted mean degree, agropastoral) and 1.6 (unweighted mean degree, pastoral) other villages through livestock dips (Table S5).

Supplementary Figures

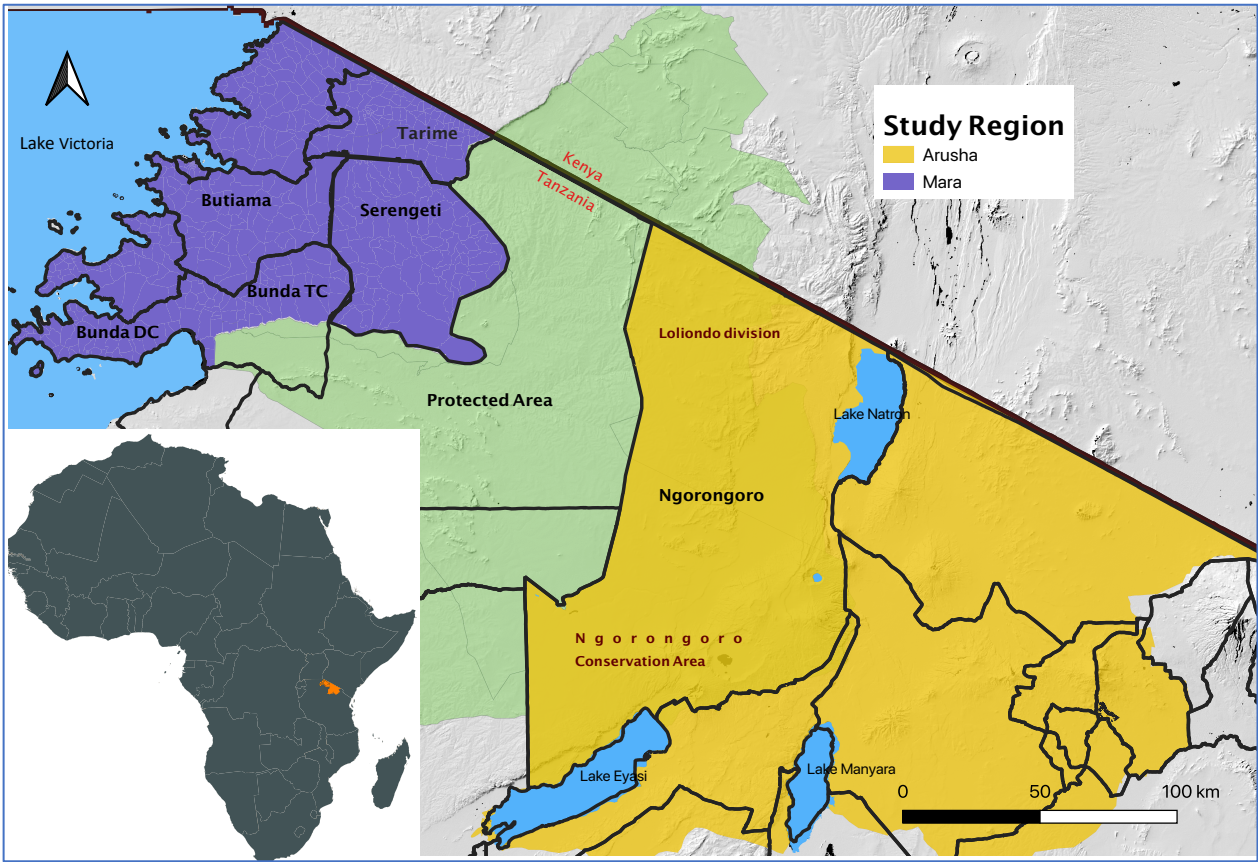


Figure S1. A map of the study area in northern Tanzania and its location within the map of Africa (left). The districts of focus to generate data on local-level livestock movements were Serengeti District (agropastoral) to the west of the Serengeti Ecosystem and Ngorongoro District (pastoral) to the east. Wide-scale (trade-related) movements were investigated in four agropastoral districts, Serengeti, Bunda, Butiama and Tarime, to the west of the Serengeti Ecosystem. The map was developed in Quantum geographical information system (QGIS), version 3.18².

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Figure S2. An example of a Google Earth digital map with built-in coordinate system at 1:2500 scale that was used to map livestock movements to key livestock resources in an agropastoral village (Nyamatoke). Topographical features shown include settlements, hills, roads, crop lands, grazing reserves and utility centres.



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Figure S3. Picture showing participants of a participatory mapping session in a pastoral community in Ngorongoro District, northern Tanzania, identifying key resource areas (e.g. rangeland and water source) and navigating livestock routes on printed base maps at 1:50000 scale.

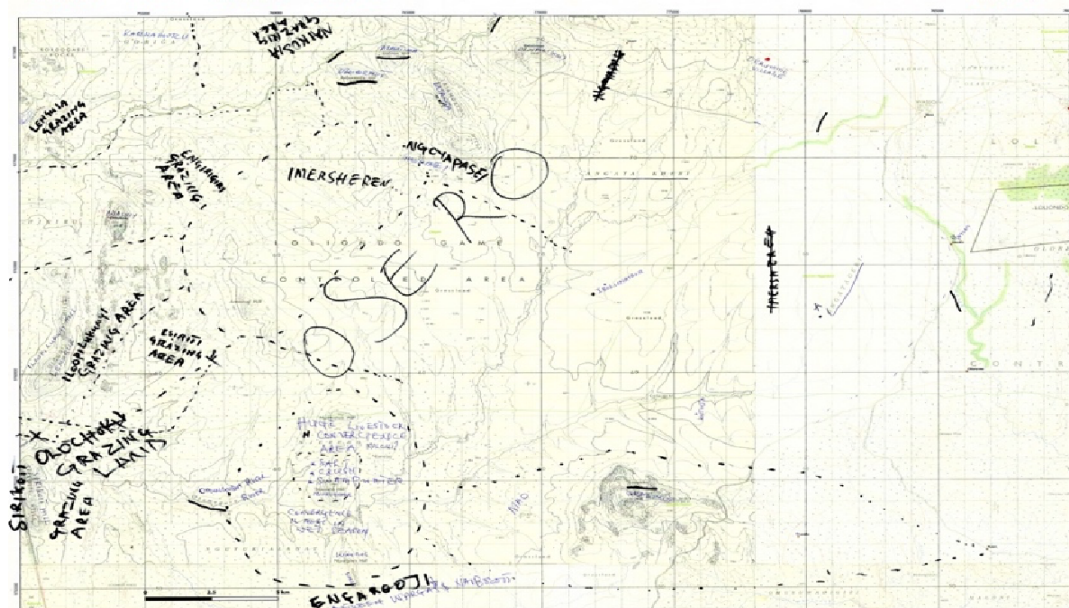


Figure S4. An example of a hand-drawn map (1:50000 scale) producing during a participatory mapping session showing different sections of the largest rangeland in Loliondo, Ngorongoro District, northern Tanzania.

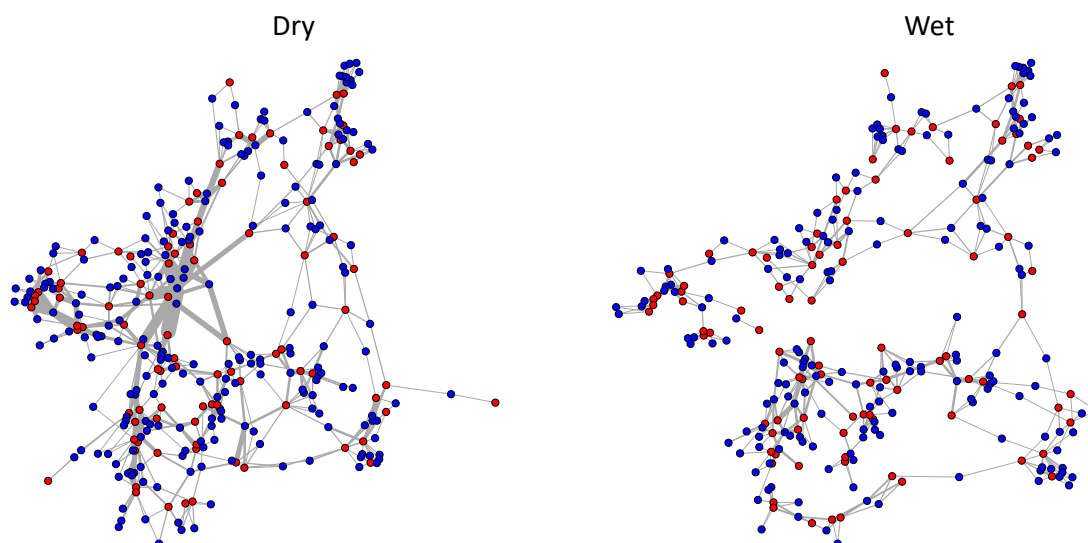


Figure S5. A weighted topological directed network showing seasonality of connected villages in the Serengeti District through shared resource areas during a month in the wet and dry seasons. Gray lines are weighted edges. Red dots are villages and blue dots are shared resource areas.

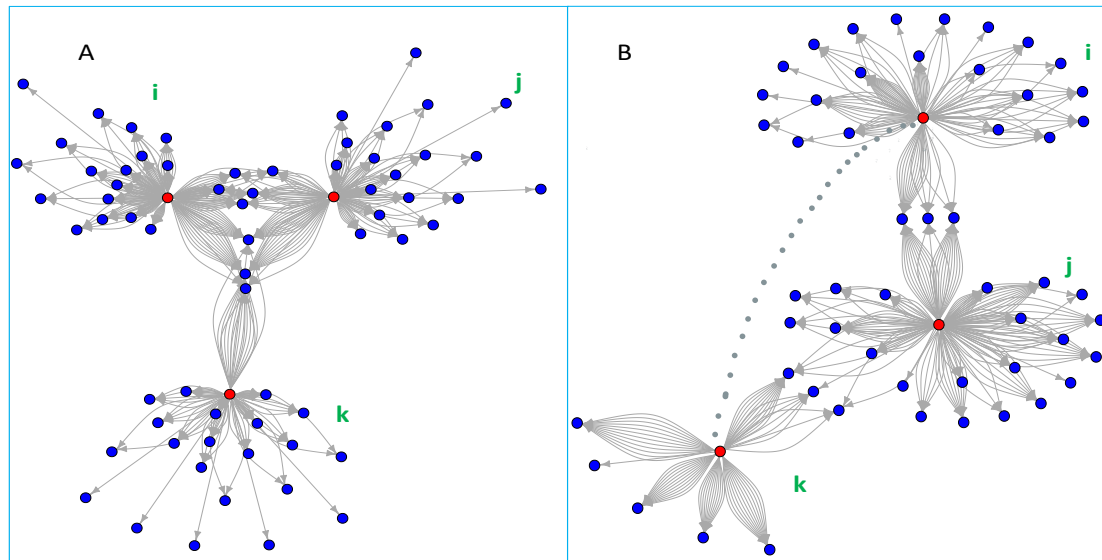
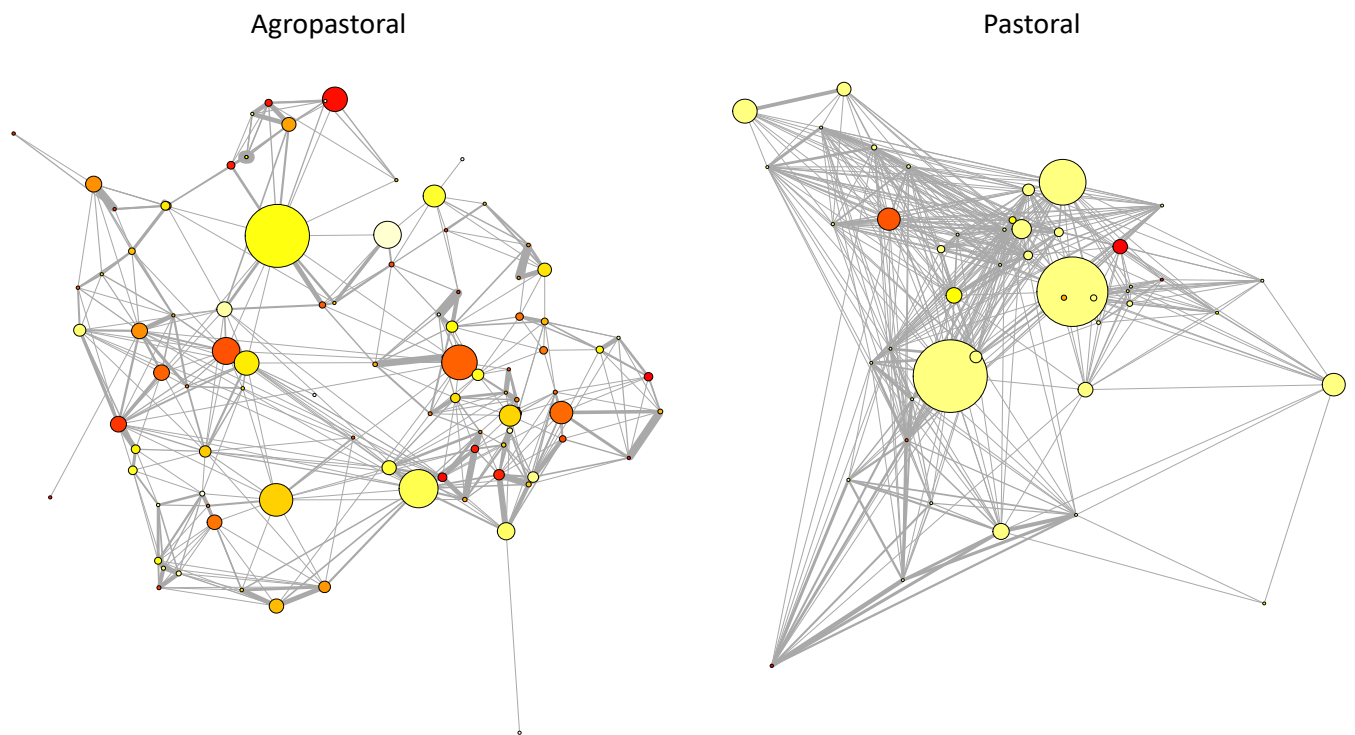


Figure S6. A schematic network of connectivity amongst villages (red nodes) through resource areas (blue nodes) shared by livestock herds in agropastoral and pastoral systems of northern Tanzania investigated in this study. The letters “i”, “j” and “k” refer to villages in the topological network. Panel A shows connectivity between the three villages through direct access to shared resource areas (i.e. instances where herds converge into the same resource areas located within the three villages). In panel B, connectivity is through direct access to shared resource areas between villages “i” and “j”, and “k” and “j”, while villages “i” and “k” are connected only indirectly (dotted line) (i.e. connectivity is being mediated by a third village).



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Figure S7. Spatial livestock movement networks of village connectivity in agropastoral and pastoral systems of northern Tanzania investigated in this study. The nodes (circles) are villages in their geographical position. The grey weighted edges represent shared resource areas (i.e. grazing, watering, salting and dipping areas) among connected villages. The weighted edges represent the centrality measure degree, i.e. the total number of contacts of a village relative to other villages. The length of each edge is the proportional distance between connected village centres. The node size is proportional to the network centrality measure betweenness for the village, i.e. the ability of a village to occupy positions in the network that influence the connections of others. Node colours refer to eigenvector centrality values, which quantify the extent to which a village with high degree was in contact with other high-degree villages. The colour red indicates the highest eigenvector centrality value.

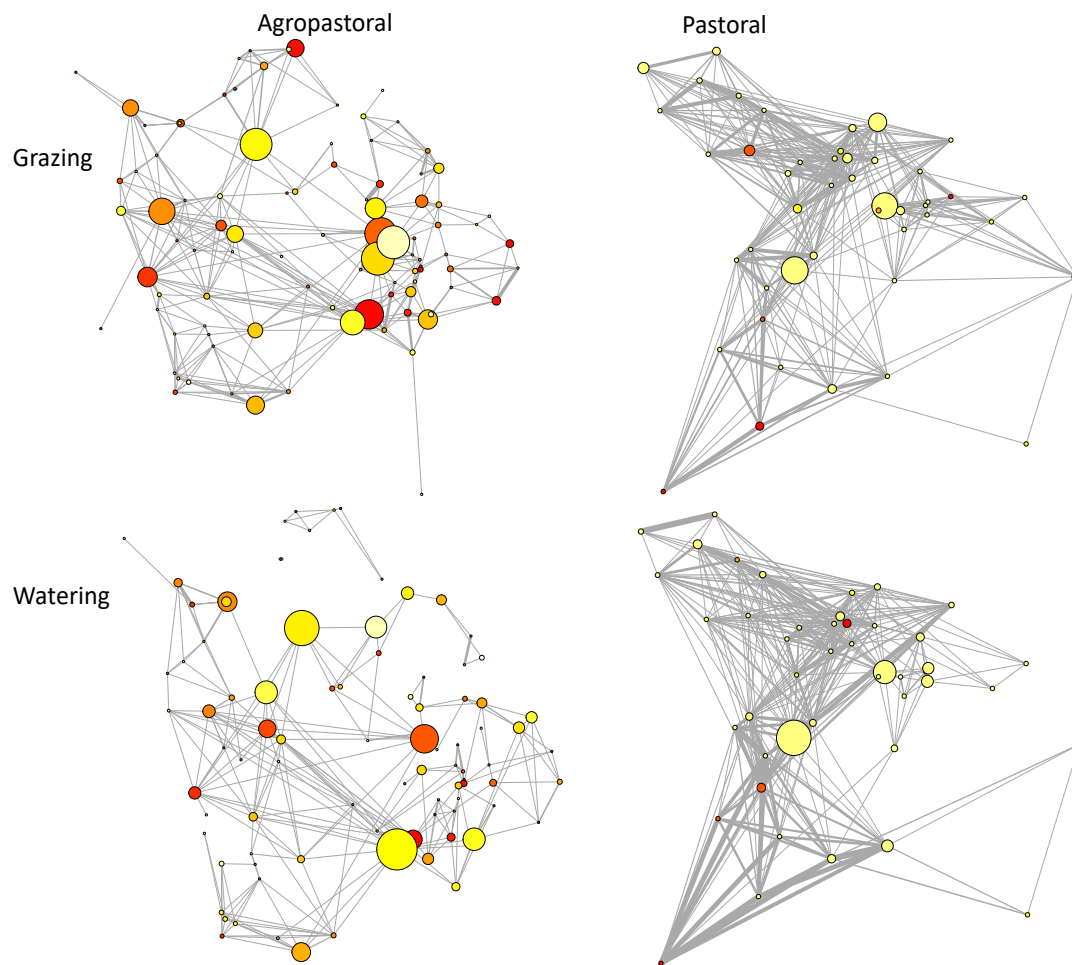


Figure S8. Networks of village livestock connectivity at grazing and watering locations across management settings, agropastoral and pastoral, of northern Tanzania investigated in this study. The nodes (circles) are villages in their geographical position, node sizes are proportional to the network centrality measure (betweenness) for the village, and node colours correspond to the centrality measure centrality value. The grey edges represent shared resource areas among connected villages, the number of edges is the centrality measure “degree”, while the length of each edge is the proportional distance between connected village centres. Degree measures the total number of contacts of a village relative to other villages, betweenness describes the ability of a village to occupy positions in the network that influence the connections of others and eigenvector value quantifies the extent by which a village with high degree was in contact with other high degree villages.

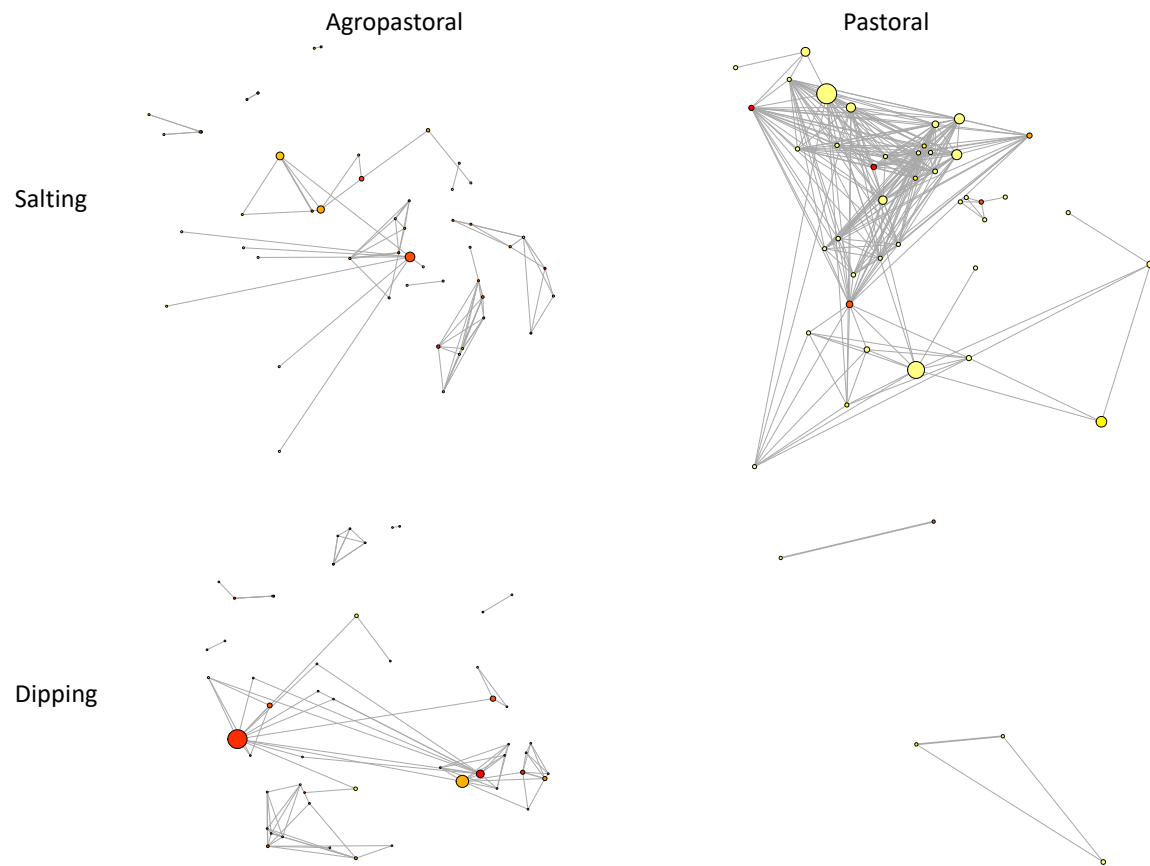


Figure S9. Networks of village livestock connectivity at salting and dipping points across management settings, agropastoral and pastoral, of northern Tanzania investigated in this study. The nodes (circles) are villages in their geographical position. Node sizes are proportional to the network centrality measure (betweenness) for the village and the node colour is the eigenvector centrality value. The grey edges represent shared resource areas among connected villages. The number of edges corresponds to the centrality measure degree, while the length of each edge is the proportional distance between connected village centres. Degree measures the total number of contacts of a village relative to other villages, betweenness describes the ability of a village to occupy positions in the network that influence the connections of others and eigenvector value quantifies the extent by which a village with high degree was in contact with other high-degree villages.

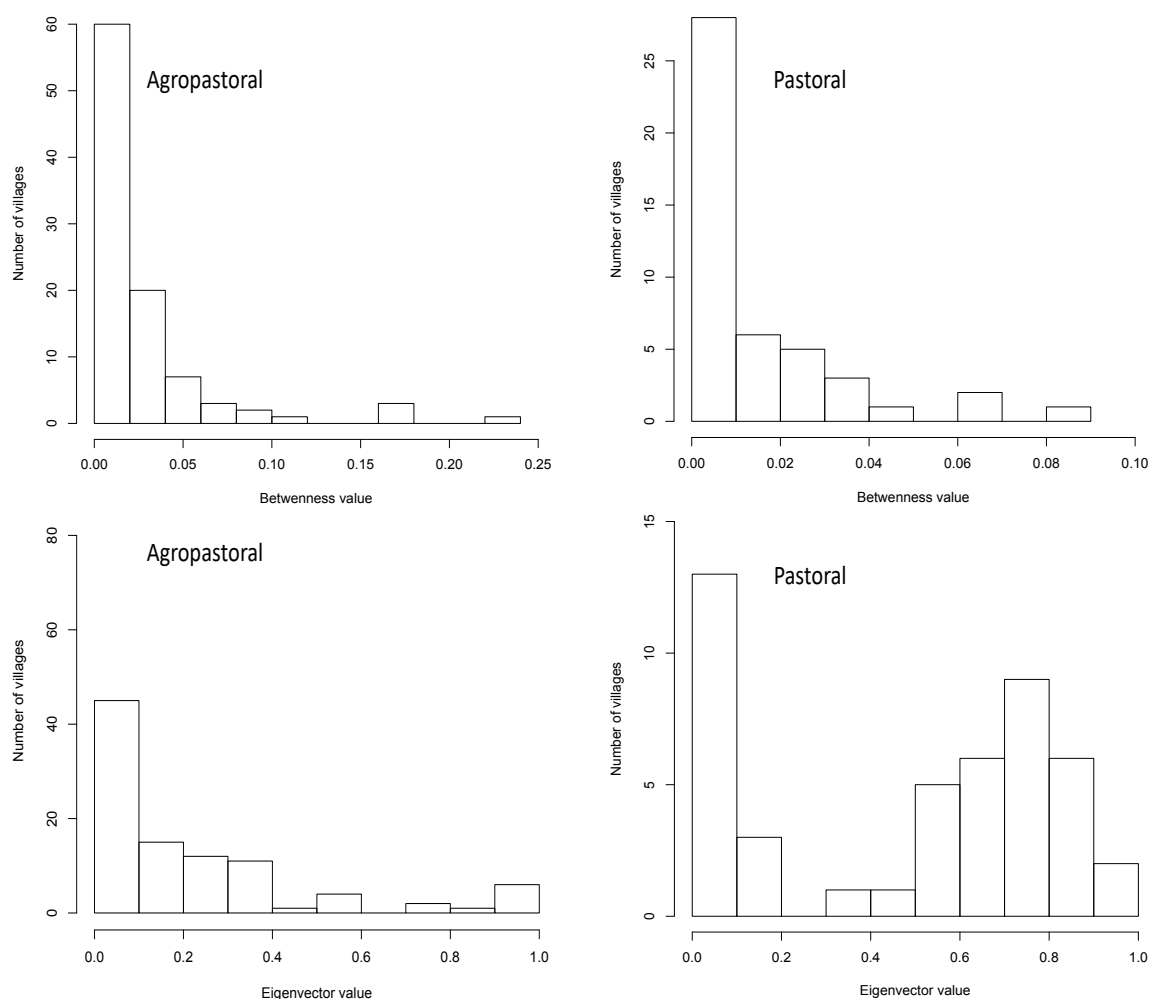


Figure S10. Distribution of normalised centrality betweenness and eigenvector centrality values for agropastoral and pastoral networks generated from participatory mapping data in northern Tanzania. Few villages had relatively high centrality values suggesting their importance in the network. Betweenness describes the ability of a village to occupy positions in the network that influence the connections of others and eigenvector values quantify the extent by which a village with high degree is in contact with other high degree villages.

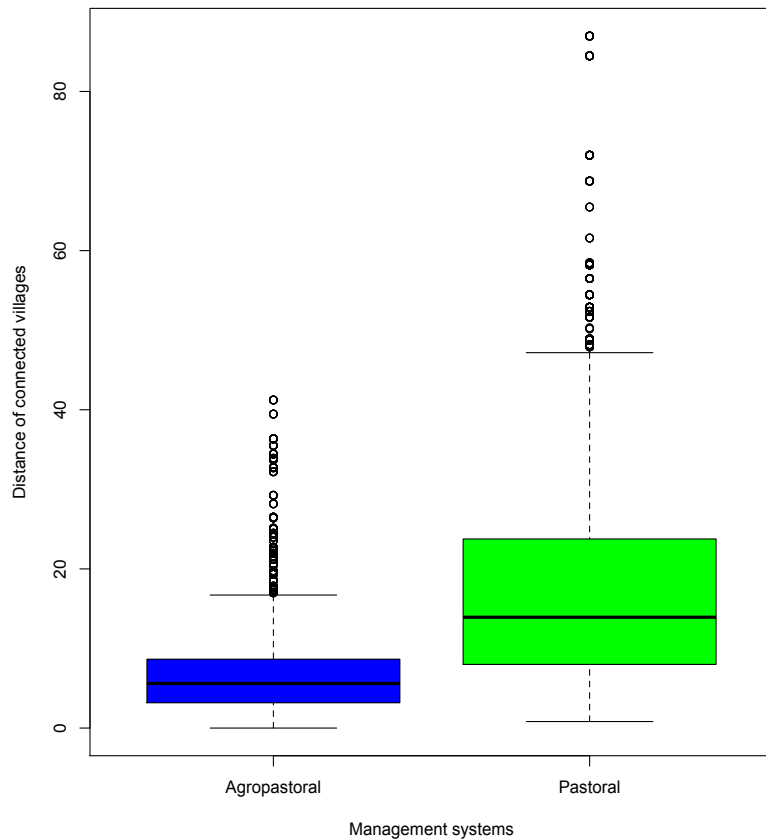
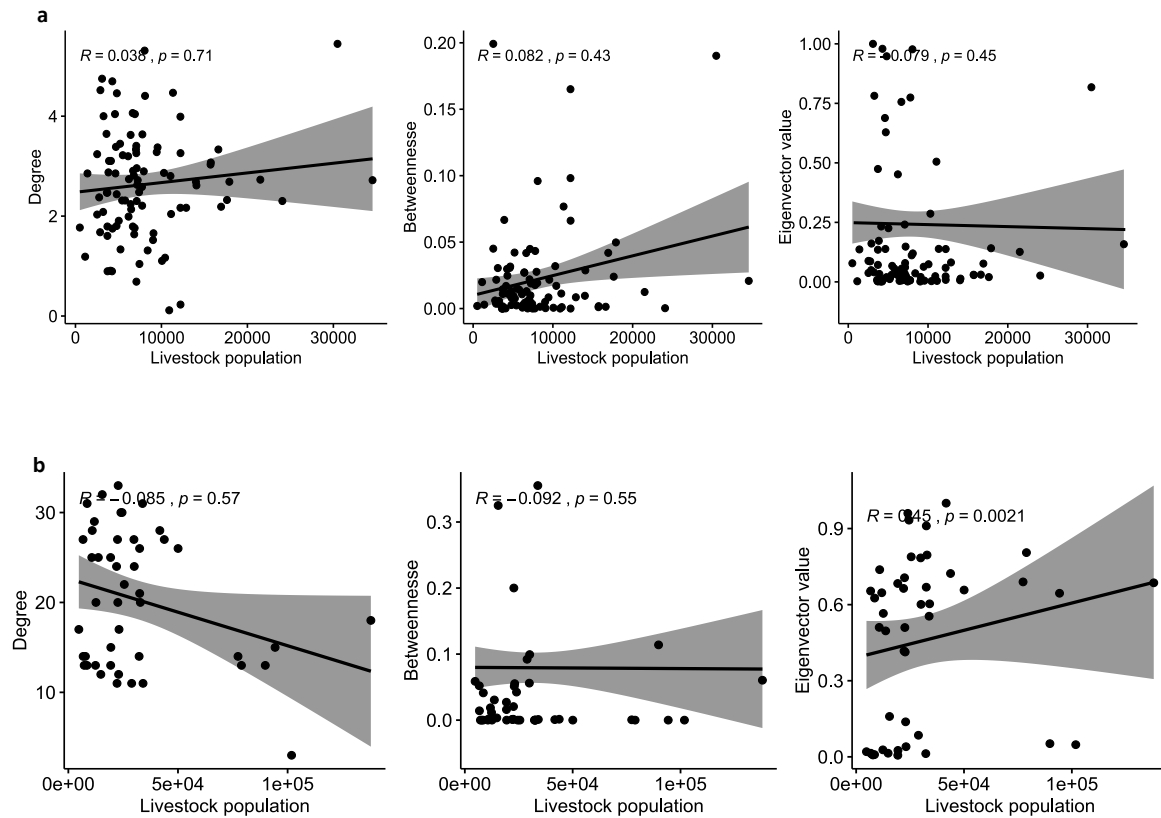


Figure S11. Distance (km) of connected villages across livestock management systems, agropastoral and pastoral, investigated in northern Tanzania.



316 **Figure S12.** Spearman correlation test showing the relationship between village livestock
317 populations (i.e cattle, goats and sheep) and the weighted and normalised network centrality
318 measures in (a) agropastoral and (b) pastoral livestock management systems investigated in
319 northern Tanzania as part of this study.

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