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Mapping U.S. cattle shipment networks: Spatial and temporal patterns of trade communities from 2009 to 2011

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ABSTRACT

The application of network analysis to cattle shipments broadens our understanding of shipment patterns beyond pairwise interactions to the network as a whole. Such a quantitative description of cattle shipments in the U.S. can identify trade communities, describe temporal shipment patterns, and inform the design of disease surveillance and control strategies. Here, we analyze a longitudinal dataset of beef and dairy cattle shipments from 2009 to 2011 in the United States to characterize communities within the broader cattle shipment network, which are groups of counties that ship mostly to each other. Because shipments occur over time, we aggregate the data at various temporal scales to examine the consistency of network and community structure over time. Our results identified nine large (>50 counties) communities based on shipments of beef cattle in 2009 aggregated into an annual network and nine large communities based on shipments of dairy cattle. The size and connectance of the shipment network was highly dynamic; monthly networks were smaller than yearly networks and revealed seasonal shipment patterns consistent across years. Comparison of the shipment network over time showed largely consistent shipping patterns, such that communities identified on annual networks of beef and diary shipments from 2009 still represented 41–95% of shipments in monthly networks from 2009 and 41–66% of shipments from networks in 2010 and 2011. The temporal aspects of cattle shipments suggest that future applications of the U.S. cattle shipment network should consider seasonal shipment patterns. However, the consistent within-community shipping patterns indicate that yearly communities could provide a reasonable way to group regions for management.

1. Introduction

Network analysis provides a conceptual framework to investigate patterns of animal movement. When networks are used to describe livestock shipments, the production units of interest are represented as nodes, and the shipment of animals between them are represented as edges (Dubé et al., 2011). Network analysis can then be used to describe features of the livestock industry (Buhnerkempe et al., 2013), evaluate the animal welfare or economic consequences of shipment practices (Håkansson et al., 2016), and study disease spread (Fèvre et al., 2006).

For a given network, shipment patterns can be better understood by considering higher-order network phenomena such as communities, which are defined as sets of nodes in the network with high levels of connections among them and low levels of connections to other nodes (Newman, 2010). While many livestock shipment networks have communities that also represent geographic regions (Lentz et al., 2011; Grisi-Filho et al., 2013), communities are properties of the shipment network (Buhnerkempe et al., 2016). As a result, these communities describe the underlying structure of the industry based on how the commodity of interest flows without imposing arbitrary geographic or administrative boundaries. These communities are most useful if they consistently describe shipping patterns and capture variability among seasons or years (Green et al., 2011). However, most communities are identified on a static network, where the data are aggregated over a

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year or multiple years (Kao et al., 2006; Green et al., 2011; Lentz et al., 2011; Grisi-Filho et al., 2013). In reality, these shipments can be dynamic over time, and considering higher resolution temporal data may result in changes to the network structure (Nöremark et al., 2011; Mweu et al., 2013; Dutta et al., 2014).

A national scale, data-driven description of the U.S. livestock shipment network has recently become possible based on movement data from Interstate Certificates of Veterinary Inspection (ICVI; Buhnerkempe et al., 2013). For non-slaughter shipments of cattle across state lines, ICVIs certify that an accredited veterinarian has inspected the animal's health and that the testing requirements of the destination state are met prior to shipment. Previous analyses of livestock movement patterns in the U.S. have been based on questionnaires (Bates et al., 2001; Marshall et al., 2009; McReynolds et al., 2014) or expert opinion (Liu et al., 2012) and were smaller in scale. Thus, although ICVIs were not designed for tracing cattle movements, they are an improvement over previous descriptions of livestock shipments because they are the most comprehensive and consistently collected shipment data for the U.S. ICVIs also include the origin and destination county for the shipment as well as temporal information for the shipment (Portacci et al., 2013). This allows shipment networks to be constructed, where each county is a node in the network and the directional shipments of cattle in the ICVI data are represented as edges between them, along with temporal information to inform our understanding of temporal variability in the network structure. A basic description of a static, annually aggregated cattle shipment network based on ICVI data from 2009 is presented by Buhnerkempe et al. (2013).

In this study, we use three years of ICVI data from 2009 to 2011 to consider two alternative hypotheses for the spatial and temporal patterns of cattle shipments in the U.S. First, network structure may vary in time and communities identified on a static network from one year will be unable to describe shipment patterns in future months or years. This hypothesis describes an industry where shipment patterns are dominated by the influence of grass and feed availability, such that shipment timing and locations (as represented by network communities) respond to the price of feed and cattle. Second, network structure may be time invariant if movement patterns are dominated by the influence of fixed infrastructure. In the U.S., the feedlot-slaughter system is a particularly concentrated, spatially fixed, infrastructure that may buffer drought or economic drivers of livestock shipments. To evaluate these hypotheses, we describe the underlying structure of trade communities and build network models of data aggregated at daily, weekly, monthly, and yearly time scales to examine features of the networks that remain stable or change through time.

2. Methods

2.1. Data collection

To explore temporal variability in the U.S. cattle shipment network, we compiled ICVI data from 2009, 2010, and 2011. The 2009 ICVI data consist of a 10% systematic sample of cattle ICVI records for shipments leaving a state (Buhnerkempe et al., 2013). ICVI records are maintained and stored by the state veterinarian's office in both the state where the shipment originated and the state of destination. We requested origin ICVIs to avoid duplicated records. This dataset included all states in the U.S. with the exception of New Jersey (no response), Alaska (zero origin ICVIs), and Hawaii (zero origin ICVIs), resulting in 19,817, non-slaughter shipment records from 2433 counties in 47 states from 2009. Because our analyses address questions about the timing and consistency of interstate shipping patterns, we further excluded 713 additional shipments if the ICVIs were issued in 2009 but not sent until 2010 or if a shipment was both sent and received by the same state. For this study, we further compiled a 10% systematic sample of cattle export ICVI records using similar methods to 2009 from the following states in 2010 and 2011: California (CA), Iowa (IA), Minnesota (MN), New York (NY), North Carolina (NC), Tennessee (TN), Texas (TX), and Wisconsin (WI). These eight states were chosen to compare U.S. cattle shipment networks among years based on multiple criteria. The primary criterion for inclusion of a state in the 2010 and 2011 sampling was that states were identified as influential to the flow of cattle in 2009 based on high values for a number of network statistics such as out-degree, in-degree, and betweenness (Buhnerkempe et al., 2013). Secondary criteria stipulated that the state generated large potential outbreaks in a disease spread model (Buhnerkempe et al., 2014), allowed representation from both diverse geographic locations and locations traditionally representing a beef or dairy focus, and met additional expert opinion provided by USDA regarding the relevance of the states chosen to the U.S. beef and dairy industries. This subset of states includes 35% of operations and 36% of U.S. cattle based on summaries from the USDA National Agricultural Statistics Service (NASS; USDA, 2012).

We constructed networks by aggregating the ICVI data to the county level, such that each county represents a node in the network and each edge defines the directional shipments between nodes. Edges in the network are either unweighted or weighted by the number of shipments moving between the counties. Previous analyses have compared data aggregated at additional scales (state-level, and 50 and 500 km grid sizes). The 50 and 500 km grids generate 2350 and 46 equally sized nodes, which is roughly similar to the number of counties (3108) and states (48) in the contiguous U.S., respectively. This work suggests that a county level aggregation is the most appropriate scale because it captures heterogeneity in shipments better than coarser scales and is an administrative unit (Buhnerkempe et al., 2013). By analyzing the temporal patterns of cattle shipments, we extend the analyses in Buhnerkempe et al. (2013), where the ICVI data were aggregated across an entire year in 2009. Because the patterns of live animal transport in the beef and dairy industry are different (Bates et al., 2001), we constructed separate networks for beef and dairy shipments. However, production type was only specified in the ICVI's for 64% of shipments in 2009, 54% in 2010, and 48% in 2011. To estimate whether the remaining shipments contained beef or dairy cattle, we used a classification tree analysis to calculate the probability of unknown shipments being either beef or dairy and assigned them according to the higher probability (detailed methods and evaluation in Buhnerkempe et al., 2013).

2.2. Community detection

To identify communities within the U.S. cattle shipment network, we aggregated the 2009, 10% ICVI data into an annual network at the county scale and identified groups of highly connected counties by applying a community detection algorithm to both the unweighted network and the network weighted by the number of cattle shipments. We do not consider communities based on data from 2010 or 2011 because data from only eight states were collected for those years. Communities are formed by maximizing the modularity, Q, where

$$Q = \frac{1}{2m} \Sigma_{i,j} \left[A_{i,j} - \frac{k_i k_j}{2m} \right] \delta \left(c_i, c_j \right) .$$

In this equation, $A_{i,j}$ is the weight of the edge between i and j. For the unweighted networks used in this analysis, $A_{i,j}$ is 1 if an edge exists, $k_i = \Sigma_j A_{i,j}$ is the sum of the edges attached to i, and c_i is the community to which i is assigned. The delta function is 1 if $c_i = c_j$ and