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Model-guided suggestions for targeted surveillance based on cattle shipments in the U.S.

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ABSTRACT

Risk-based sampling is an essential component of livestock health surveillance because it targets resources towards sub-populations with a higher risk of infection. Risk-based surveillance in U.S. livestock is limited because the locations of high-risk herds are often unknown and data to identify high-risk herds based on shipments are often unavailable. In this study, we use a novel, data-driven network model for the shipments of cattle in the U.S. (the U.S. Animal Movement Model, USAMM) to provide surveillance suggestions for cattle imported into the U.S. from Mexico. We describe the volume and locations where cattle are imported and analyze their predicted shipment patterns to identify counties that are most likely to receive shipments of imported cattle. Our results suggest that most imported cattle are sent to relatively few counties. Surveillance at 10 counties is predicted to sample 22–34% of imported cattle while surveillance at 50 counties is predicted to sample 43%–61% of imported cattle. These findings are based on the assumption that USAMM accurately describes the shipments of imported cattle because their shipments are not tracked separately from the remainder of the U.S. herd. However, we analyze two additional datasets – Interstate Certificates of Veterinary Inspection and brand inspection data – to ensure that the characteristics of potential post-import shipments do not change on an annual scale and are not dependent on the dataset informing our analyses. Overall, these results highlight the utility of USAMM to inform targeted surveillance strategies when complete shipment information is unavailable.

1. Introduction

Surveillance systems that can rapidly and accurately detect an outbreak are an essential component of disease management plans (Thurmond, 2003). For livestock diseases in the U.S., current surveillance efforts are based on the location where tests can be most readily obtained (e.g., slaughter surveillance; Ebel et al., 2008; Humphrey et al., 2014). This method is slower and has a lower detection probability than surveillance that targets sub-populations where transmission is most likely (Williams et al., 2009). Surveillance strategies that prioritize sub-populations with higher transmission risk are examples of *targeted surveillance* (or equivalently, *risk-based surveillance*). Identifying sub-populations with high transmission risk can prioritize surveillance and improve the time-to-detection for most outbreaks (Stärk et al., 2006).

Network analyses can inform surveillance programs by identifying the locations where the targeted sub-population can be sampled and by characterizing how the sub-population moves and mixes with the population as a whole (Bajardi et al., 2012; Buhnerkempe et al., 2016). 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 (Newman, 2010; Dubé et al., 2011). Two logistical challenges often limit the application of livestock shipment networks for disease surveillance in the U.S. First, many shipments are unobserved because the U.S. does not maintain a comprehensive, national-scale system to track cattle movements. To address this challenge, recent work has characterized the U.S. cattle shipment network using a 10% systematic sample of Interstate Certificates of Veterinary Inspection (ICVI). ICVIs are the most widespread data available for tracing cattle movements in the U.S. and are required for most non-slaughter shipments crossing state lines (Buhnerkempe et al., 2013; Portacci et al., 2013; Gorsich et al., 2016). Lindström et al. (2013) have developed a model, the U.S. Animal Movement Model (USAMM), to scale up the observed ICVI shipments into a full network

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that accounts for uncertainty in the sampled and unobserved shipments (Lindström et al., 2013). The second challenge when using network analysis to inform disease surveillance is that there are no clear methods to evaluate the sensitivity of results to the details of network structure (Keeling and Eames, 2005). Shipment networks may change over time from changing policies or economic conditions (Grear et al., 2014). It is, therefore, important to assess how variable networks are over time and how potential variation may influence surveillance strategies.

We address these two challenges in a surveillance application for cattle imported from Mexico into the U.S. We focus on this sub-population because importation of live animals is an important risk factor for foreign animal diseases (Humblet et al., 2009) and Mexican-origin cattle represent a large source of imported cattle (USDA-APHIS-VS, 2009a). Furthermore, molecular evidence indicates that cattle from Mexico and the U.S. share similar strains of bovine tuberculosis, suggesting that disease transmission between populations is possible (Tsao et al., 2014). Disease surveillance is limited because imported cattle are only tracked to their primary import destination. After importation, the shipments of cattle are broken up, distributed to unknown locations, and mixed, anonymously, with U.S. cattle. As a result, both USAMM and previous descriptions of cattle shipments do not track imported cattle separately from the remainder of the U.S. herd. Knowledge about how and where imported cattle are shipped once they are in the U.S. would allow sampling to accurately assess risk in this subpopulation (USDA-APHIS-VS, 2009b). We, therefore, use the sub-population of Mexican-origin cattle as a case study to highlight the utility of USAMM when complete shipment information is unavailable.

In this study, we integrate cattle import data with USAMM to describe the predicted shipment patterns of imported cattle. By simulating shipments based on USAMM, these descriptions represent our best understanding of cattle transport in the U.S. (Lindström et al., 2013). We describe the simulated shipment patterns of imported cattle to identify counties that could be targeted in surveillance efforts based on being highly likely to receive cattle from an importing county. A key assumption in these descriptive results is that domestic and imported cattle move similarly throughout the U.S. because current datasets do not distinguish between the two populations. Then, we evaluate the stability of our surveillance suggestions to changes in network structure over time. We use ICVI and brand inspection data from 2009 to 2011 to ensure that the characteristics of potential post-import shipments do not change on an annual scale and are not dependent on the dataset informing our analyses. These results inform current targeted surveillance efforts, and we further discuss how they could be used to develop a mark-recapture study to test assumptions about the movement of domestic and imported cattle within the U.S.

2. Methods

2.1. Veterinary Services Process Streamlining (VSPS) import data and USAMM

We obtained the records of all import shipments of Mexican cattle from the Veterinary Services Import Tracking System from 2009 and from the Veterinary Services Process Streamlining (VSPS) system for 2011. We did not use 2010 data owing to the transition between the data systems. Both systems track release or refusal papers issued at entry ports and are maintained by the United States Department of Agriculture (USDA)/Animal and Plant Health Inspection Service (APHIS)/Veterinary Services (VS). We have provided summary statistics from both data sources in Appendix A, Supplementary data. For each Mexican origin shipment, these data include the number of animals per shipment, the destination address, and the destination city and state. We note that import destinations recorded in the VSPS system may represent the office of the importing operation rather than the destination of the imported animals. However, our analyses do not depend on exact locations being recorded precisely, but they do depend on the destination county being accurately reflected by the destination field in the VSPS data. This is because we aggregated both import data and ICVI data to the county level based on previous analyses (Buhnerkempe et al., 2013).

We evaluated the shipment patterns of imported cattle by integrating the import locations and volumes specified in the VSPS data with cattle shipment predictions provided by USAMM. USAMM is a spatially explicit, distance kernel model. It uses Bayesian inference and data from a 10% systematic sample of cattle ICVIs from 2009 to predict county-to-county shipments in the U.S. (Lindström et al., 2013). Although ICVIs represent the best, national-level characterization of cattle movements in the U.S., they are only required when livestock cross state lines. Basing our surveillance suggestions on ICVI data alone would result in an underestimation of within-state movements. Furthermore, a complete, national-level sample of ICVI records is limited by their storage as paper records (Portacci et al., 2013). USAMM scales up the 10% sample of ICVI records into a complete description of cattle shipments, including predictions of within-state shipments. Details on model structure, parameterization, and validation are described in Lindström et al. (2013). We used the predicted shipments for all subsets of the industry because potential infections likely affect both beef and dairy populations. To explore an interactive map of predicted U.S. cattle shipments based on USAMM, please see https://usamm-gen-net.shinyapps.io/usamm-gen-net/.

2.2. Brand inspection data and additional years of ICVI data

We compiled two additional datasets to evaluate the shipment patterns predicted by USAMM (Fig. 1). These datasets were chosen because they provide information on cattle movements but are not incorporated in USAMM. Because USAMM is a data-driven model parameterized by 2009 ICVI data, we are confident in its ability to predict shipments captured by ICVIs from 2009. However, if large-scale differences occur between years or if different shipment data sources capture different types of shipments, predictions from USAMM will be less accurate.

The first dataset consists of brand inspection data from 2009 in California. We used brand inspection data to evaluate how well USAMM estimates within-state shipments and scales up the 10% sample of ICVIs. Brand inspection forms in California detail the transfer of both beef and dairy cattle between owners, the transfer of cattle outside the state, and the transportation of cattle to sale or to slaughter (Branding and Inspection, 2016). Similar to ICVI records, the brand inspection forms include the number of cattle to be transferred, the origin address, and the destination address. Unlike the ICVI records, the California brand inspection data record shipments within California and include shipments to slaughter. Because brand inspection data are also frequently stored as paper records and are only available in a subset of western states, we used these data as an out-of sample evaluation and compared movement predictions and surveillance suggestions from California only. We focused on California because of the readily accessible electronic brand inspection data available and because California was the third largest importer of Mexican cattle in 2009 and 2011 (Appendix A, Supplementary data).

The second dataset consists of a 10% systematic sample of ICVI data from eight states in 2009–2011. We used these data to evaluate the consistency of our surveillance suggestions to changes in shipping patterns over time. These eight states included California, Iowa, Minnesota, New York, North Carolina, Tennessee, Texas, and Wisconsin. Additionally, data from Nebraska were available from 2009 and 2011. We chose these eight states to compare U.S. cattle shipments 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,