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

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,
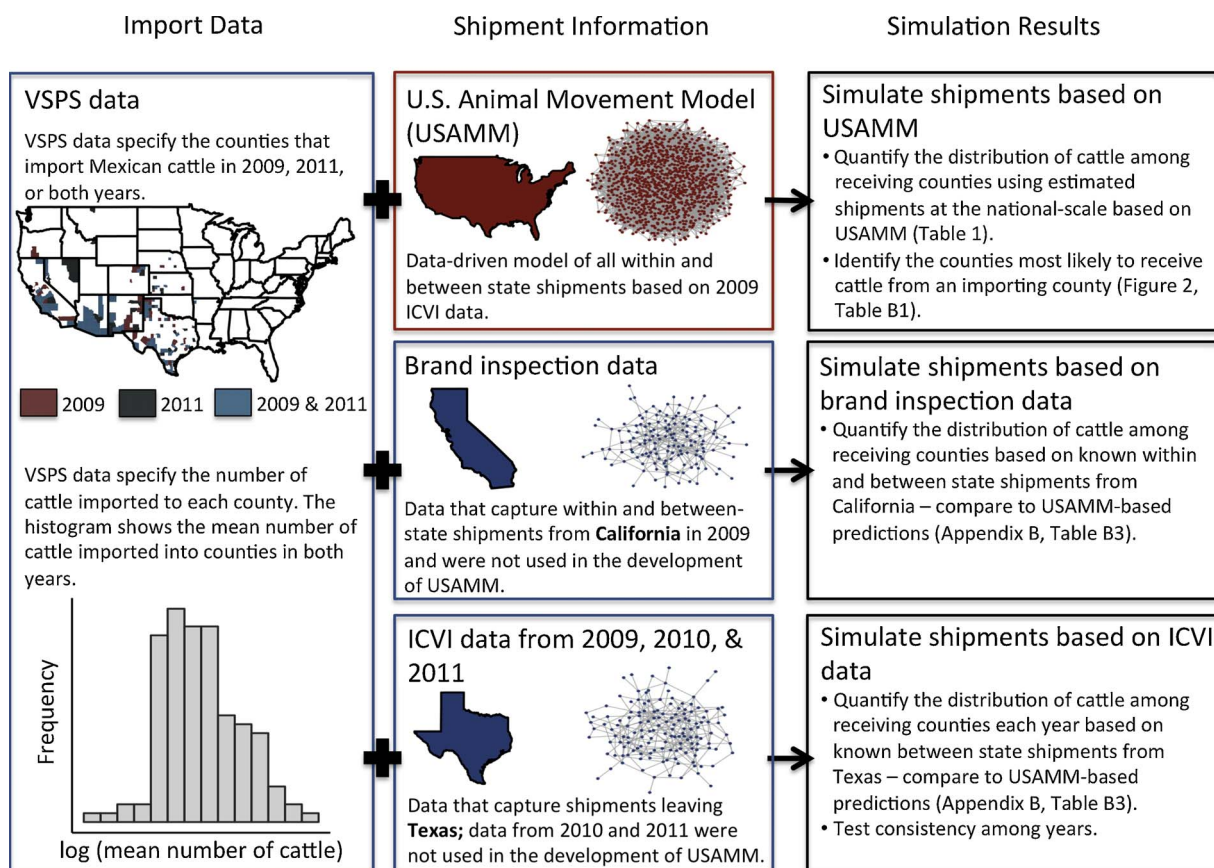
Import Data · Shipment Information · Simulation Results

Fig. 1. Conceptual diagram showing the data sources and simulation results.

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 diverse geographic locations, and met additional expert opinion provided by USDA regarding the relevance of the states chosen to the U.S. industry. Detailed data collection and entry methods are provided in Gorsich et al. (2016).

2.3. Simulating cattle shipments to identify counties for targeted surveillance

We integrated the VSPS import data with USAMM by simulating the movement of each imported head on the average shipment network from 1000 different realizations of USAMM. Each simulation contained two steps. First, we specify the number of cattle imported into each import county. The number of imported cattle is defined by the mean number of cattle imported into each county in 2009 and 2011 in the VSPS data. Second, we simulated the movement of each head on the shipment network predicted by USAMM. We simulated shipments stochastically, with the probability of a shipment between county A and B calculated as the number of shipments between the two counties divided by the total number of shipments leaving county A. For each simulation, we recorded the number of cattle reaching each county. We performed a sensitivity analysis by varying the probability each head will be shipped out of the importing county from 0 to 1 to ensure our suggestions are not dependent on this parameter. We refer to these simulations by the percent of cattle shipped out of their import county (e.g. approximately 80% of cattle are shipped when the probability each head will leave is set to 0.8). We also did not attempt to recreate the number of cattle per shipment and instead assumed that imported cattle are shipped individually over one edge of the network. This assumption may result in an overestimate of the total number of counties reached by imported cattle if groups of cattle are moved together

(Appendix B, Supplementary data), but can be refined as more information on imported cattle becomes available (see Discussion). We used these USAMM-based simulation results to identify the counties most likely to receive cattle from an importing county. In Appendix B, Supplementary data, we show that our assumption about the number of cattle per shipment does not influence the identification of these counties. We conducted all simulations using R statistical software (R Development Core Team, 2014).

All cattle imported into the U.S. are marked with blue ear tags at the time of import. However, cattle may not be re-observed if sampling does not occur in the locations where cattle have moved or if the ear tag was lost or removed. We, therefore, simulated random tag loss by varying the probability each head is unobserved from 0 to 1 in the USAMM-based simulations described above. We evaluate the resulting percent of cattle in the simulations that can be unobserved while still accurately representing the distribution of cattle among receiving counties in the simulation. These results were summarized into six summary statistics that evaluated how well the observed cattle capture the total movement of imported cattle: the number of unique counties reached, the percent of observed cattle entering the top 10 and 50 counties, the percent of observed animals moving between each state, and the skewness and kurtosis of the distribution of observed cattle among counties. Skewness, kurtosis, and the percent of observed cattle entering the top 10 and 50 counties all measure the distribution of Mexican cattle among counties and were used to identify quantitative trends in how the evenness of the distribution changes with the percent of unobserved cattle. It is important to note that these surveillance suggestions remain based on the assumption that domestic and imported cattle move similarly throughout the U.S. because both USAMM and previous descriptions of cattle shipments do not track imported cattle separately from the remainder of the U.S. herd. Thus, although it represents the best available information on cattle shipments, we also

discuss of how this assumption should be refined if more information on the shipment of imported cattle becomes available.

2.4. Evaluation of targeted surveillance suggestions with California brand inspection data

We used brand inspection data from California to evaluate our re-commendations based on USAMM because it includes almost all within and between state shipments from California. We constructed shipment networks with counties as nodes and edges as the shipments captured in the California brand inspection data. We refer to this network as the brand inspection network. We simulated the shipment of imported cattle on the California brand inspection network following the same steps that we used to simulate shipments on the USAMM network. Specifically, we specify the number of cattle in each import county in California based on the VSPS data. Then, we simulated the shipment of each head from its import county to a destination county based on the brand inspection network. We calculated the same six summary sta-tistics based on these simulations (the number of unique counties reached, the percent of observed cattle entering the top 10 and 50 counties, the percent of animals moving between each state, and the skewness and kurtosis of the distribution of cattle among counties) and compared them to summary statistics from the USAMM-based simula-tions described above.

2.5. Evaluation of targeted surveillance suggestions with additional years of ICVI data

We used ICVI data from 2009 to 2011 to test for annual variation in shipping patterns. We compared the distance shipments travelled in the 10% ICVI data from each state. We calculated shipment distances as the geodesic distance between the origin and destination county centroids. We used the Kruskal-Wallis test to compare distances among years and a Bonferroni correction to account for multiple comparisons from ap-plying the test to each state. Our statistical analyses and simulations focused on the overall shipping patterns of all cattle unless specified otherwise. We note, however, that the patterns of live animal transport in the beef and dairy industry are different (Bates et al., 2001) and have provided supplementary information analyzing the shipment patterns of both industries separately (Appendix B, Supplementary data). Therefore, for the Bonferroni correction, we adjusted the individual confidence level upward from at least 95% confidence to at least $100(1 − 0.05/k)\%$ confidence, where k is set equal to 27 for the 9 states compared for beef shipments, dairy shipments, and overall for both industries considered together. Thus, significant changes among years occurred when p-values were less than p = 0.002. For states with

significant variation among years in the distance shipments travelled, we also visually explored the location to which shipments travelled and used Wilcoxon signed-rank tests to compare distances travelled be-tween each pair of years.

Then, we evaluated the stability of our surveillance suggestions to changes in post-import shipment patterns among years. This evaluation focused on shipments leaving Texas due to demonstrated differences in the volume of shipments (Gorsich et al., 2016) and its role as a major importer of cattle (Appendix A, Supplementary data; Fig. A1). We compiled additional data for Texas, resulting in a 30% systematic sample of ICVI data for 2009–2011. We chose a 30% sample of ICVI records based on minimum sampling suggestions for partial data (Dawson et al., 2015). Dawson et al. (2015) evaluated the predictive power simulation models when only a subset of network information was available and showed that a 30% sample is the minimum sampling required for accurate predictions. We used the 30% sample of Texas ICVI records to create shipment networks for each year with counties as nodes and edges as the shipments in the ICVI data. We refer to these networks as the 2009, 2010, or 2011 ICVI networks.

We simulated shipments of cattle on each ICVI network following the methods described above. In these simulations, more cattle were imported in 2011 compared to 2009 (Appendix A, Supplementary data; Fig. A1). To compare the relative influence of variation in import vo-lumes, import locations, and changes in the shipment network, we conducted two sets of simulations on the ICVI networks. In the first set of simulations, the only variation comes from the yearly shipment networks (for 2009–2011). We standardized the import locations and volumes across years by using the mean number of imported cattle in 2009 and 2011 from the subset of counties represented in both years. In the second set of simulations, we used the yearly import records for 2009 and 2011 such that variation in shipping patterns results from annual differences in import volumes, locations, and the shipment network.

3. Results

3.1. Simulated shipment patterns of imported cattle

Counties in 13 states received imported cattle from Mexico (Arizona, Arkansas, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, Oklahoma Oregon, and Texas; Appendix A, Supplementary data, Fig. A1). Most counties were located in Arizona, California, New Mexico, and Texas (Fig. 2). The states that received the most imported cattle were New Mexico and Texas, with a total of 260,405 and 470,327 head of cattle in 2009 and 409,643 and 894,827 head of cattle in 2011, respectively. However, there was high
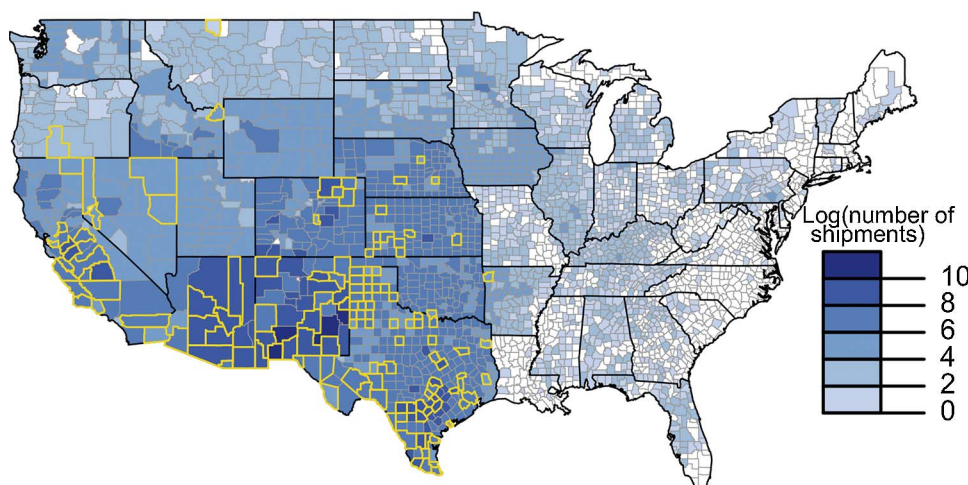
Fig. 2. Summary of simulation results from USAMM. Counties outlined in yellow received shipments from Mexico in either 2009 or 2011. The counties in blue were predicted to receive 1–46,252 head from si-mulations assuming all cattle leave their import county and were observed. Counties colored in white did not receive any simulated shipments. Colors are defined on the log scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Six summary statistics describing the predicted distribution of imported cattle in the U.S. after one shipment. Post-import shipment locations were predicted by USAMM, and we varied the probability that each head will be shipped out of its importing county and the probability it is unobserved. Summary statistics are organized based on the resulting percent of cattle shipped from their importing county. The percent of cattle re-observed in the 10 counties or 50 counties that receive the most shipments are calculated as the percent of the total number of animals. The percent of cattle leaving their import state is calculated as the percent of the total number of observed animals.

Percent Unobserved	No. Counties	Skewness	Kurtosis	% observed in 10 counties	% observed in 50 counties	% leaving import state
Results assuming 100% of imported cattle are shipped						
0%	2396	12.2	202.3	21.5	43.4	46.1
20%	2345	12.1	197.8	17.2	34.7	46.1
40%	2258	11.9	192.9	12.9	26.0	46.1
60%	2151	11.5	181.5	8.6	17.3	46.1
80%	1927	11.0	165.1	4.3	8.7	46.1
Results assuming 80% of imported cattle are shipped						
0%	2321	15.9	368.9	24.6	50.0	36.9
20%	2257	15.7	357.6	19.7	40.0	36.9
40%	2178	15.5	351.7	14.8	20.0	36.9
60%	2072	15.2	338.0	9.8	30.0	36.9
80%	1844	14.4	303.1	4.9	10.0	36.9
Results assuming 60% of imported cattle are shipped						
0%	2257	24.9	803.4	34.4	60.6	27.7
20%	2198	24.6	783.2	27.5	48.5	27.7
40%	2099	24.1	751.4	20.7	36.4	27.7
60%	1959	23.2	697.9	13.8	24.3	27.7
80%	1729	21.9	619.6	6.9	12.1	27.7

variability among counties in each state (Appendix A, Supplementary data, Fig. A2). For example, importing counties received a median of 2 (mean of 74) shipments or 305 (mean of 8778) head from Mexico, but could receive up to 3754 shipments or 395,983 head.

When simulating the shipments of cattle after import, most cattle were predicted to stay within their importing state or move towards the Central Plains states. If all cattle leave their import county and are observed, 46.1% of imported cattle were predicted to remain within their importing state (Table 1) and 20% were predicted to move to Colorado, Kansas, or Nebraska (Fig. 2). Figure B1 shows the simulation results when fewer cattle are shipped from their import county and Table B2 shows the simulation results when cattle are aggregated into larger shipment sizes (Appendix B, Supplementary data). In these simulations, fewer overall shipments occurred, but the predicted shipment patterns remained consistent. Specifically, the predicted distribution of imported cattle among the receiving counties was highly skewed. In simulations where all imported cattle leave their import county and are observed, 22% of all cattle were shipped to 10 counties and 43% of all cattle were shipped to 50 counties out of the 2396 counties reached (Table 1). Similarly, in simulations where only 60% or 80% of imported cattle are shipped from their import county, 34% and 25% of all cattle were shipped to 10 counties and 61% and 50% were shipped to 50 counties, respectively. The 50 counties that were most likely to receive imported cattle during these simulations were relatively insensitive to shipment probability and are provided in Appendix B, Supplementary data, Table B1.

A highly aggregated distribution of cattle, with most individuals sent to a few counties, occurred even when a large proportion of cattle are not observed due to loss of ear tags or incomplete sampling. The predicted number of unique counties reached, skewness, and kurtosis of the distribution of cattle among receiving counties was consistent until up to 90% of cattle were unobserved (Fig. 3a). There was some variation in these statistics when cattle have a lower probability of being shipped from their importing county, but the overall pattern remained consistent (Table 1; Fig. 3a). For example, when 90% of cattle were unobserved, re-observing the remaining 10% of cattle captures between 58 and 61% of the maximum unique counties reached, 76–86% of the maximum skewness, and 58–74% of the maximum kurtosis (Table 1).

3.2. Evaluation of surveillance suggestions with California brand inspection data

The distribution of simulated shipments among destination locations specified in the brand inspection data supports surveillance suggestions based on USAMM (Fig. 3b). All of the measured statistics remained relatively stable until up to 90% of cattle were unobserved (Appendix B, Supplementary data; Table B3). When 90% of cattle were unobserved, re-observing the remaining 10% of imported cattle was predicted to capture 52–78% of the maximum unique counties reached, 86–90% of the maximum skewness, and 66–80% of the maximum kurtosis of the distribution of Mexican cattle shipped from counties in California (ranges based on varying the probability an imported head leaves the importing county from 0.2 to 1).

3.3. Tests for annual variation in shipping patterns based on ICVI data

Based on ICVI data from California, Minnesota, Nebraska, New York, North Carolina, Tennessee, and Wisconsin (Table 2), there was no significant variation in the distance shipments travelled among years. Shipments from Texas travelled further in 2011 than previous years (2011 > 2010, p < 0.0001; 2011 > 2009, p < 0.0001; Fig. 4a) because more beef shipments went to Kansas, Florida, Iowa, and North Dakota compared to earlier years (Appendix B, Supplementary data, Fig. B2). Shipments from Iowa travelled shorter distances in 2009 compared to 2011 (2011 > 2009, p < 0.0001, 2010 > 2009, p < 0.003; Fig. 4b) because more dairy shipments went to Minnesota and Missouri compared to later years (Appendix B, Supplementary data, Fig. B3). Despite these shifts, the main receiving states remained consistent between years. Based on our 10% sample, Colorado, Kansas, Nebraska, New Mexico, and Oklahoma, each received on average 10, 19, 6, 15, and 13% of the shipments from Texas per year, respectively. Similarly, Illinois, Minnesota, Missouri, Nebraska, and Wisconsin, each received on average 6, 25, 20, 18, and 9% of the shipments from Iowa per year, respectively.

3.4. Evaluation of surveillance suggestions with additional years of ICVI data

To evaluate if annual variation in the shipping patterns from Texas alter surveillance suggestions, we simulated the shipment of imported
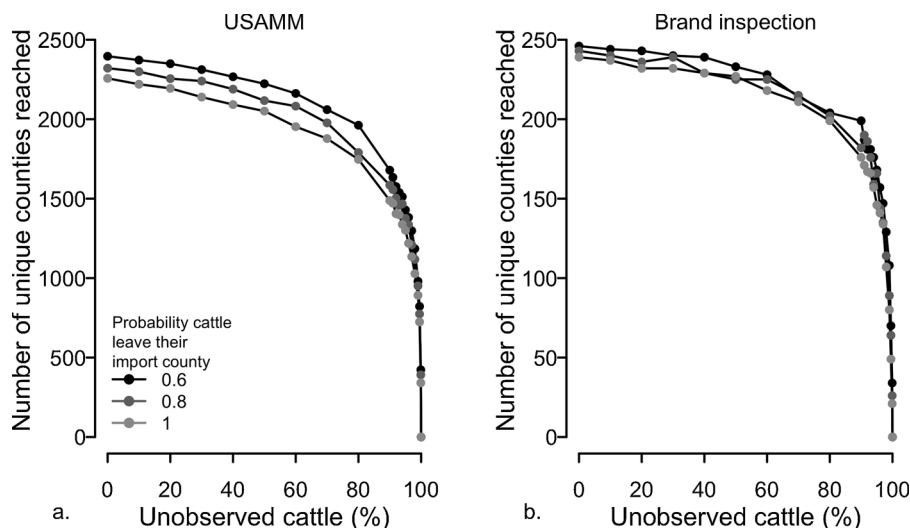
Fig. 3. (a) The predicted number of unique counties reached remained relatively stable until over 90% of cattle were unobserved. Post-import shipments were simulated based on the shipment network from USAMM and the average numbers of imported cattle from 2009 and 2011. Line colors indicate the probability that each head leaves its import county. (b) For shipments of cattle imported only into California, the predicted number of unique counties reached also remained relatively stable until over 90% of cattle were unobserved.

Table 2
The median distance travelled by all shipments represented in ICVI data in 2009, 2010, and 2011. Hypothesis tests were conducted separately for beef shipments, dairy shipments, and both shipment types together. *Because multiple comparisons were used, the threshold for significant p-values is p = 0.002. At this level, significant differences were only observed in Iowa and Texas. Significance tests for Nebraska compare 2009 and 2011 with a Wilcoxon signed-rank test.

State	Median Distance (km)			p-value		
	2009	2010	2011	Beef	Dairy	Overall
California	958.0	1043.2	1116.7	0.304	0.004	0.199
Iowa	123.4	172.6	195.2	0.024	< 0.001*	< 0.001*
Minnesota	275.0	241.3	317.1	0.095	0.059	0.313
North Carolina	803.3	839.5	1168.1	0.813	0.674	0.682
Nebraska	310.7	–	310.0	0.497	0.080	0.358
New York	567.2	442.5	476.0	0.763	0.092	0.089
Tennessee	916.8	953.5	903.1	0.034	0.774	0.083
Texas	750.3	764.3	843.7	< 0.001*	0.019	< 0.001*
Wisconsin	308.3	308.5	371.5	0.334	0.236	0.099

cattle on ICVI networks built separately from data in 2009, 2010, and 2011. Thirty-four counties in Texas imported cattle in both 2009 and 2011. Simulations when import volumes and locations were held constant at 655,782 head from these 34 counties resulted in similar spatial predictions each year (Fig. 5) but with more unique counties being
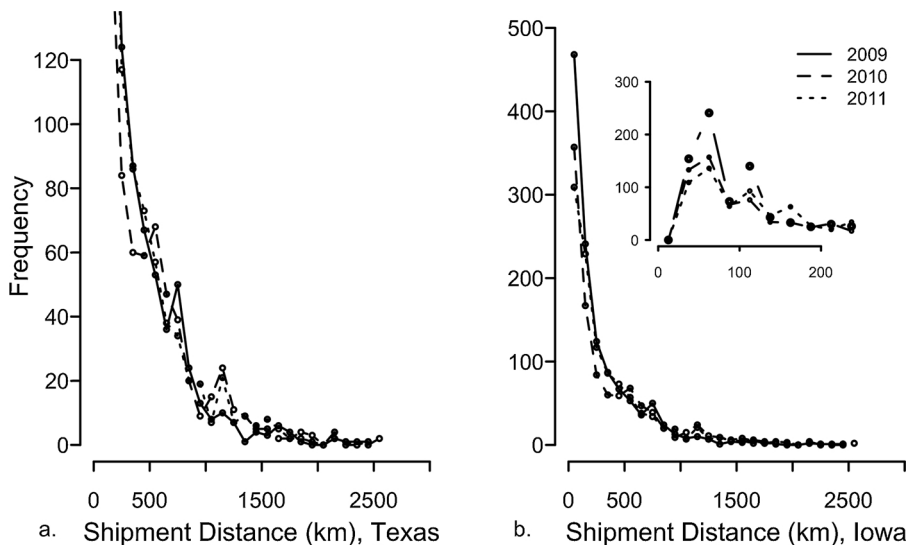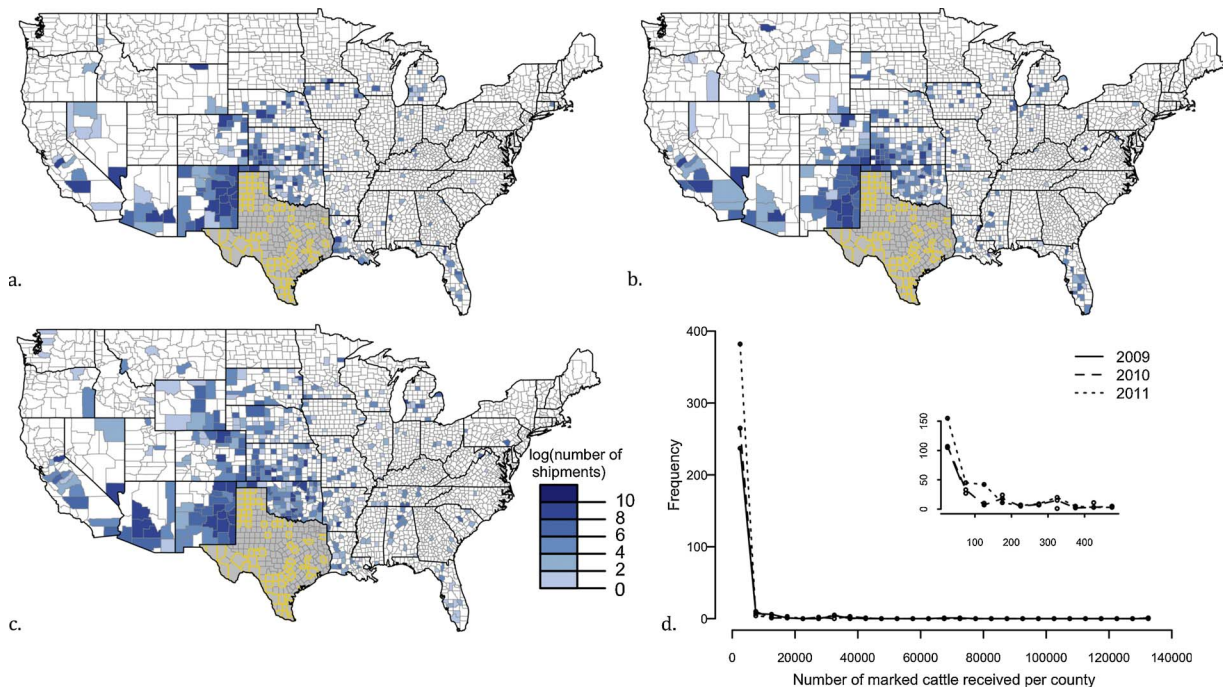
reached in 2011 compared to earlier years (Fig. 6). Of the 258, 284, and 398 counties predicted to receive cattle in 2009, 2010, and 2011, 128 counties were common to each year (Fig. 5). These 128 common counties were predicted to receive 75, 80, and 74% of all cattle in simulations on 2009–2011 ICVI networks and reflect a highly aggregated distribution of cattle among counties (Fig. 5d). Similarly, the top 10 counties consistently captured 61–65% of the cattle (65%, 65%, and 61% for 2009, 2010, and 2011).

Simulations where import volumes and locations vary between years resulted in the movement of 343,637 head of cattle imported to 45 counties in 2009 and 800,357 head of cattle imported to 44 counties in 2011. There was minimal variation in summary statistics describing the simulated movement of these cattle (Table B3). There were also minimal changes to the number of unique counties reached and no changes to the percent of cattle received by the top 10 counties (Fig. 6).

4. Discussion

In this study, we integrate data on the volume and initial locations of imported cattle with the first comprehensive network model of U.S. cattle shipments, USAMM. Our results inform potential targeted surveillance strategies by identifying the counties most likely to receive imported cattle after one post-import shipment. Shipment based suggestions for foreign animal disease surveillance in the U.S. have been

Fig. 4. Distance histograms for all shipments leaving Texas and Iowa. Shipments from Texas travelled further in 2011 than previous years; shipments from Iowa travelled more locally in 2009 compared to later years. The inset figure displays the frequency of shipments from Iowa travelling less than 250 km.

Fig. 5. Predicted destination locations after one shipment for cattle imported to Texas in (a) 2009, (b) 2010, and (c) 2011. The import locations and volumes are consistent across years based on the average number of imported cattle in 2009 and 2011 from the subset of counties represented in both years. (d) The predicted number of cattle received per destination county remained relatively constant over time.
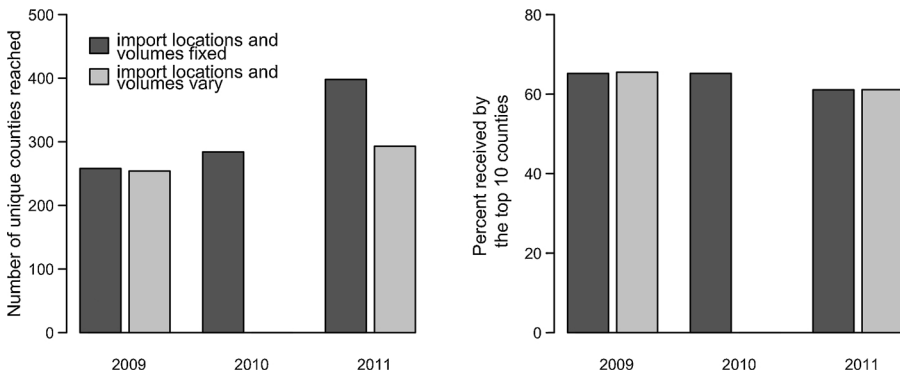
Fig. 6. Summary statistics describing the simulated shipment of cattle from Texas to destination counties specified in the ICVI networks. (a) The number of unique counties reached by imported cattle increased from 2009 to 2011. (b) When ranking counties by the number of cattle they received, the percent of cattle received by the top 10 counties was consistent over time. Dark gray bars indicate results where only network structure varied among years because import locations and volumes were fixed at their average values. Light gray bars indicate ICVI simulations where import locations, import volumes, and network structure varied among years.

successful on a smaller scale (Ribeiro-Lima et al., 2015). Yet, the national scale analysis in this work was only possible with the comprehensive information on livestock shipments provided by USAMM (Lindström et al., 2013). In the U.S., data collection and availability remain the largest challenges for model-guided emergency planning and policy development.

Our simulation results suggest that the hub-like structure of the U.S. cattle network promotes feasible surveillance of imported cattle. Specifically, after importation, most cattle were predicted to move through a few key counties, creating a highly aggregated distribution of imported cattle among destination counties. In simulations where all cattle were observed, 10 counties received 22% of post-import shipments; 50 counties received 43% of post-import shipments, and 100 counties received 56% of post-import shipments (Table 1). If shipments based on USAMM accurately describe the shipments of imported cattle, targeting these counties for surveillance will allow more efficient disease surveillance in imported cattle. Appendix B, Supplementary data provides a list of these counties predicted to receive high volumes of imported cattle after one shipment (Table B1).

Simulations on networks created with California brand inspection data and additional years of ICVI data from Texas resulted in comparable surveillance suggestions compared to USAMM-based simulations.

These analyses address an additional challenge in using livestock shipment data for planning and policy development: evaluating the sensitivity of a model's suggestions to the details of data collection and changes in network structure over time. Our approach is unique compared to spatial surveillance suggestions elsewhere (Bajardi et al., 2012) because the true patterns of cattle shipments in the U.S. are unknown. USAMM currently incorporates uncertainty in the observed and unobserved shipments by using Bayesian inference and a hierarchical framework for parameter estimation (Lindström et al., 2013). By showing that our USAMM based suggestions are consistent with suggestions based on two additional datasets, California brand inspection data and additional years of ICVI data from Texas, we show that our suggestions do not change on an annual scale and are not dependent on the specific shipment dataset informing our analyses.

Although the results presented in this paper highlight the feasibility of targeted surveillance for imported cattle, it should be considered as one step in a broader model-guided field work methodology (Restif et al., 2012). The temporal resolution required to provide more local-scale surveillance or response suggestions should also consider the epidemiology of the pathogen of interest. Whereas, a coarse temporal scale may be suitable for a slowly-transmitting pathogen such as bovine tuberculosis, finer temporal resolution predictions are needed for a

rapidly-transmitting pathogen such as the foot-and-mouth disease virus. Furthermore, our suggestions are based on three assumptions. First, because USAMM currently aggregates shipments over an entire year, our suggestions could be refined to account for finer temporal patterns in import volumes or shipments (Brommesson et al., 2016; Gorsich et al., 2016). Second, the counties identified in Appendix B, Supplementary data, Table B1 are based on the assumption that cattle are shipped independently. If imported cattle are aggregated evenly into larger shipments or if larger shipments are preferentially sent to counties receiving high numbers of shipments, these counties will remain important for sampling (Appendix B, Supplementary data, Table B2). Third, because we represent cattle movements with USAMM, we do not represent shipment patterns of imported cattle separate from the remainder of the U.S. herd. This is an essential assumption that should be evaluated as surveillance proceeds. For example, all cattle imported into the U.S. are marked with blue ear tags and re-observing these ear tags at surveillance locations would provide data on the shipment patterns of imported cattle. When analyzed with capture-mark-recapture techniques (King, 2012), these data can provide quantitative estimates of shipment patterns that account for uncertainty due to lost ear tags. Thus, although our approach represents our best understanding of cattle shipments in the U.S., one year of data collection at counties identified for surveillance could refine our initial predictions, estimates, and surveillance suggestions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.prevetmed.2017.12.004.

References

Bajardi, P., Barrat, A., Savini, L., Colizza, V., 2012. Optimizing surveillance for livestock disease spreading through animal movements. J. R. Soc. Interface 9, 2814–2825.
Bates, T.W., Thurmond, M.C., Carpenter, T.E., 2001. Direct and indirect contact rates among beef, dairy, goat, sheep, and swine herds in three California counties, with reference to control of potential foot-and-mouth disease transmission. Am. J. Vet. Res. 62, 1121–1129. http://dx.doi.org/10.2460/ajvr.2001.62.1121.
Branding and Inspection (No. California Code of Regulations. Article 4 §§ 895–899),
2016.
Brommesson, P., Wennergren, U., Lindström, T., 2016. Spatiotemporal variation in distance dependent animal movement contacts: one size doesn't fit all. PLoS One 11, e0164008. http://dx.doi.org/10.1371/journal.pone.0164008.
Buhnerkempe, M.G., Grear, D.A., Portacci, K., Miller, R.S., Lombard, J.E., Webb, C.T., 2013. A national-scale picture of US cattle movements obtained from Interstate Certificate of Veterinary Inspection data. Prev. Vet. Med. 112, 318–329.
Buhnerkempe, M.G., Tildesley, M.J., Lindström, T., Grear, D.A., Portacci, K., Miller, R.S., Lombard, J.E., Werkman, M., Keeling, M.J., Wennergren, U., Webb, C.T., 2014. The impact of movements and animal density on continental scale cattle disease outbreaks in the United States. PLoS One 9, e91724. http://dx.doi.org/10.1371/journal.pone.0091724.
Buhnerkempe, M.G., Webb, C.T., Merton, A.A., Buhnerkempe, J.E., Givens, G.H., Miller, R.S., Hoeting, J.A., 2016. Identification of migratory bird flyways in North America using community detection on biological networks. Ecol. Appl. 26, 740–751. http://dx.doi.org/10.1890/15-0934.
Dawson, P.M., Werkman, M., Brooks-Pollock, E., Tildesley, M.J., 2015. Epidemic predictions in an imperfect world: modelling disease spread with partial data. Proc. R. Soc. B: Biol. Sci. 282. http://dx.doi.org/10.1098/rspb.2015.0205.
Dubé, C., Ribble, C., Kelton, D., McNab, B., 2011. Introduction to network analysis and its implications for animal disease modelling. Rev. Sci. Tech. Int. Off. Epizoot. 30, 425–436.
Ebel, E.D., Williams, M.S., Tomlinson, S.M., 2008. Estimating herd prevalence of bovine brucellosis in 46 USA states using slaughter surveillance. Prev. Vet. Med. 85, 295–316. http://dx.doi.org/10.1016/j.prevetmed.2008.02.005.
Gorsich, E.E., Luis, A.L., Buhnerkempe, M.G., Grear, D.A., Portacci, K., Miller, R.S., Webb, C.T., 2016. Mapping U.S. cattle shipment networks: a longitudinal analysis of regionalization and stability for disease management. Prev. Vet. Med. 134, 82–91.
Grear, D.A., Kaneene, J.B., Averill, J.J., Webb, C.T., 2014. Local cattle movements in response to ongoing bovine tuberculosis zonation and regulations in Michigan. USA. Prev. Vet. Med. 114, 201–212. http://dx.doi.org/10.1016/j.prevetmed.2014.03.008.
Humblet, M.-F., Boschiroli, M.L., Saegerman, C., 2009. Classification of worldwide bovine tuberculosis risk factors in cattle: a stratified approach. Vet. Res. 40, 50. http://dx.doi.org/10.1051/vetres/2009033.
Humphrey, H.M., Orloski, K.A., Olea-Popelka, F.J., 2014. Bovine tuberculosis slaughter surveillance in the United States 2001–2010: assessment of its traceback investigation function. BMC Vet. Res. 10, 182. http://dx.doi.org/10.1186/s12917-014-0182-y.
Keeling, M.J., Eames, K.T.D., 2005. Networks and epidemic models. J. R. Soc. Interface 2, 295–307. http://dx.doi.org/10.1098/rsif.2005.0051.
King, R., 2012. A review of Bayesian state-space modelling of capture–recapture–recovery data. Interface Focus 2, 190–204. http://dx.doi.org/10.1098/rsfs.2011.0078.
Lindström, T., Grear, D.A., Buhnerkempe, M., Webb, C.T., Miller, R.S., Portacci, K., Wennergren, U., 2013. A Bayesian approach for modeling cattle movements in the United States: scaling up a partially observed network. PLoS One 8, e53432. http://dx.doi.org/10.1371/journal.pone.0053432.
Newman, M.E.J., 2010. Networks: An Introduction. Oxford University Press, New York.
Portacci, K., Miller, R.S., Riggs, P.D., Buhnerkempe, M.G., Abrahamsen, L.M., 2013. Assessment of paper interstate certificates of veterinary inspection used to support disease tracing in cattle. JAVMA—J. Am. Vet. Med. Assoc. 243, 555–560.
R Development Core Team, 2014. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
Restif, O., Hayman, D.T.S., Pulliam, J.R.C., Plowright, R.K., George, D.B., Luis, A.D., Cunningham, A.A., Bowen, R.A., Fooks, A.R., O'Shea, T.J., Wood, J.L.N., Webb, C.T., 2012. Model-guided fieldwork: practical guidelines for multidisciplinary research on wildlife ecological and epidemiological dynamics. Ecol. Lett. 15, 1083–1094. http://dx.doi.org/10.1111/j.1461-0248.2012.01836.x.
Ribeiro-Lima, J., Enns, E.A., Thompson, B., Craft, M.E., Wells, S.J., 2015. From network analysis to risk analysis-An approach to risk-based surveillance for bovine tuberculosis in Minnesota, US. Prev. Vet. Med. 118, 328–340.
Stärk, K.D.C., Regula, G., Hernandez, J., Knopf, L., Fuchs, K., Morris, R.S., Davies, P., 2006. Concepts for risk-based surveillance in the field of veterinary medicine and veterinary public health: review of current approaches. BMC Health Serv. Res. 6, 20. http://dx.doi.org/10.1186/1472-6963-6-20.
Thurmond, M.C., 2003. Conceptual foundations for infectious disease surveillance. J. Vet. Diagn. Invest. 15, 501–514. http://dx.doi.org/10.1177/104063870301500601.
Tsao, K., Robbe-Austerman, S., Miller, R.S., Portacci, K., Grear, D.A., Webb, C., 2014. Sources of bovine tuberculosis in the United States. Infect. Genet. Evol. 28, 137–143. http://dx.doi.org/10.1016/j.meegid.2014.09.025.
USDA-APHIS-VS, 2009a. Assessment of Pathways for the Introduction and Spread of Mycobacterium Bovis in the United States.
USDA-APHIS-VS, 2009b. A New Approach for Managing Bovine Tuberculosis: Veterinary Services–Proposed Action Plan.
Williams, M.S., Ebel, E.D., Wells, S.J., 2009. Population inferences from targeted sampling with uncertain epidemiologic information. Prev. Vet. Med. 89, 25–33. http://dx.doi.org/10.1016/j.prevetmed.2008.12.008.