The Impact of Movements and Animal Densities on Continental Scale Cattle Disease Outbreaks in the U.S

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• Data:
  Interstate Cattle Transport Network
• Scaling up & filling in:
  Nation-wide Cattle Movements
• Framework for Disease Spread
ICVI Data Quick Summary

- 10% of 2009 Cattle Export ICVIs
- 19,000+ ICVIs
- 2433 counties from 49 states
- 1500+ student hours
- Currently expanding to multiple years
Data Match Multiple Descriptions of US System

- Dominated by shipments to and from Great Plains states
- 45% feeding / 17% breeding / 7% show
- Cattle amassed in large central feeding system from numerous, relatively small holdings (59% \( \leq 50 \) head)
- Beef/dairy shipments matches US herd (3:1, NASS)
Data Suggest County Scale

Number of In Shipments
Why Model Movement Data?

• Scale up 10% sample to full network
• Fill in unobserved intrastate movements
• Incorporate uncertainty- benefits of Bayesian approach
• Prediction
Distance Dependent Movement

- Kernel parameters to estimate
  - Width
  - Shape
  - Total number of movements
Source Sink Dynamics

- Spatially explicit, coarse summary of cattle industry

**Historical cattle inflow**

**Farm number per county**
U.S. Animal Movement Model

DATA
- ICVI data, 10% of interstate movements of cattle, county-level origin and destination
- Historical inflow of cattle, state-level
- Number of cattle farms per county

MODEL FITTING
- \( N_s \): total number of movements from state, \( s \)
- \( V_s \): width of distance kernel for movements from, \( s \)
- \( K_s \): shape of distance kernel for movements from, \( s \)

MODEL VALIDATION
- COUNTY LEVEL
  - OBSERVED NETWORK
  - FULL NETWORK GENERATION (county-county \( n \) realizations with parameter uncertainty)

- STATE LEVEL
  - Network Comparison
    - Node-level statistics
    - Global statistics (also with randomized networks; not illustrated)
  - Link identity and weight comparison (mantel test)

KERNEL GENERATED NETWORKS
sampled to be comparable to observed network
Predicts Network Characteristics

Data = state of origin and distances

Validating kernel predicted movements

Network structure

$N_s$: total number of movements from state, $s$

$V_s$: width of distance kernel for movements from, $s$

$K_s$: shape of distance kernel for movements from, $s$

Full network generation (county to county $n$ realizations based on parameter uncertainty)

Sampled to be comparable to observed network: 10% of interstate movements, county-scale
Predictions had a high correlation to the **identity** and **volume** of links geographically.
Model Movements With Uncertainty

Observed vs. Simulated Movements

California

Nebraska

New York
Caveats and Improvements

• One year of data
  – Collected and analyzing 2 additional years

• Intrastate Validation
  – NAHMS data
  – Formal expert elicitation
  – Brand inspection

• Overdispersion

• Seasonality
  – Improvements to model structure
  – Additional years
U.S. Disease Outbreak Model

- Stochastic metapopulation model
  - counties are patches
- Within counties, individual premise is unit of infection
- Susceptible-Exposed-Infectious-Detected-Removed

**Two modes of transmission**

**Long range movement based on shipping animals**
- Parameters estimated from ICVI data using USAMM
- Uncertainty in movement incorporated from USAMM

**Local, non-movement contacts from aerosol, direct or fomite transmission**
- Density and distance dependent transmission
- Spatially localized within and between neighboring counties
- Used parameterization based on 2001 FMD outbreak in UK
- Applied sensitivity analysis to 5 parameters to explore impact on outputs
- Additional NASS data on US premises density and size distribution
Basic Equation:

\[ W_C \frac{S_C I_C}{F_C} + \sum_{C} B_{C,C_1} \frac{S_C I_{C_1}}{F_{C_1}} + \sum_{C_2} M_{C,C_2} \frac{S_C I_{C_2}}{F_{C_2}} \]
Long Distance Movement Spread

- Daily probability of movement from USAMM
- Probability of I to S premise based on proportion of total premises in S and I classes
- Uses NASS data to determine total premises
- Assumes premises chosen randomly within county
Within County Spread

- Probability of $I$ to $S$ contact based on proportion of total premises in $I$ and $S$ categories
- Distance decay of transmission
Between County Spread

- Probability of I to S contact based on proportion of total premises in I and S categories
- Distance decay of transmission
This is a phenomenological integration of all non-movement mechanisms of spread including (but not limited to):

- Feed Trucks
- Milk Trucks
- Shared Equipment
- Shared Personnel

*challenging to parameterize
100 simulations of an infection seeded in each county, Each simulation uses a different realization of USAMM

- **Epidemic extent:**
  - number of counties infected
- **Infection risk:**
  - number of times a focal county is infected when infection is seeded in every other county in turn

We investigated the impact of movement restrictions on disease spread

- No control
- County Level Movement Ban
  - all movements from an infected county cease when the first livestock are detected in that county.
- State Level Movement Ban
  - all movements from an infected state cease when the first livestock are detected in that state.
Model Outbreak Predictions

No movement controls

Epidemic extent

Infection risk

Worst-case

Median
Movement and Local Spread

A

B

Nodes Infected

High out-degree
low density

Low out-degree
high density

PC 1

PC 2
Output is Sensitive to Disease Transmission Parameters

![Graph showing relative transmission risk vs distance (km) with lines for different values of $\alpha$ and $\theta$.](image)

- $\alpha = 1.0, \theta = 1.0$
- $\alpha = 3.0, \theta = 1.0$
- $\alpha = 1.0, \theta = 3.0$
- $\alpha = 3.0, \theta = 3.0$
- $\alpha = 4.6, \theta = 1.6$

![Bar plot showing effect size for different parameters.](image)
Output is Sensitive to Disease Transmission Parameters

...but does not vary geographically.
Considering Movement Bans

Worst-case

Epidemic extent

Infection risk

No movement ban

County Movement ban
Sensitivity Analyses on Disease Control

Mean epidemic extent

Delay (days) 0 14 21 7

Effectiveness 100% 90% 75% 50% 0%
Conclusions: FAD Uncertainty

• Worst-case predictions are for introduction to the Central Plains or Ohio River Valley
  – Up to 1200 counties and 120,000 cattle premises

• Epidemics driven by combination of movement and farm density

• County level movement bans implemented quickly (even if less effectively) are similar to state level movement bans
  – Delay in movement ban implementation suggests effective, state level bans needed

Sensitivity analysis suggests that qualitative geographic results are robust to parameterization
Conclusions: Act Quickly

- Worst-case predictions are for introduction to the Central Plains or Ohio River Valley
  - Up to 1200 counties and 120,000 cattle premises

- Epidemics driven by combination of movement and farm density

- County level movement bans implemented quickly (even if less effectively) are similar to state level movement bans
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In-Progress Improvements

More data
• Movement Inference from multiple years

Model Developments
• Farm location
• Seasonality and updates to movement components

Application
• Vaccination
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Questions?
Predicts Network Characteristics

Network Centrality
- Captures most of distribution
- Missing extreme highly central counties