A Bioeconomic Model to Predict Disease Movement

Fang Xie, Richard Horan, Christopher Wolf
Michigan State University

Kenneth Mathews, Jr
USDA, Economic Research Service

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Motivation

• TB eradication program experience

• Budget constraints mean targeted surveillance is important

• What can bioeconomic models do to improve surveillance efficiency?
Tuberculosis and Cattle Trade

- **Bovine Tuberculosis (bTB)**
  - An infectious disease caused by mycobacteria

- **Cattle movement and disease transmission**
  - Tens of millions of cattle are shipped yearly across the U.S. for feeding or breeding
  - Cattle movement is a key factor of bTB transmission
    - Epidemiology models need to account for economic behavior affecting transmission
Objectives

To develop a joint epidemiology/trade model to predict bTB transmission in US

• Develop an interstate cattle movement model
  – Based on market incentives, disease risks, and accompanying government interventions

• Develop an epidemiology model in which disease risks depend on human behavior
  – Disease transmitted via market interactions

• Predict regional disease risks
Gravity Models

• Economic application: to analyze trade patterns
  • Anderson 1979; Bergstrand 1985, 1989; Anderson and van Wincoop 2001, 2003; Eaton and Kortum 2002
    – Analogous to the physical theory of gravity
      • Trade flows depend positively on the economic sizes of two units, and negatively on distance between the units.

• Ecology application: to model invasive species risks
  • Bossenbroek et al. 2001, 2007
    – Estimate long-distance dispersal of zebra mussels between discrete points in heterogeneous landscapes
    – Gravity model used to model boat movements
      • No behavioral underpinnings
Gravity Model: Supply

- **Assumptions:**
  - Cattle are homogenous and produced in each state
  - States differ according to relative location, input costs, and trade restrictions
  - Production efficiency varies within each state
    - Efficiency parameter \((z_i)\) is random and follows a Frechet distribution function
Gravity Model: Supply

• Price for buyers in state \( j \) to buy one cattle produced in state \( i \):

\[
p_{ji} = \frac{c_i b_{ji}}{z_i} = \text{Effective MC of Production}
\]

c\(_i\): input costs

b\(_{ji}\): trade cost

  • Depends on distance and added trade costs arising from a bTB outbreak

• Buyers pay the lowest price across all sources:

\[
p_j = \min\{p_{ji}, i = 1, \ldots, N\}
\]

• \( \Pr(\text{a cow from state } i \text{ is sold into state } j) \) is:

\[
\phi_{ji} = \frac{x_{ji}}{x_j} = \frac{(c_i b_{ji})^{-\theta}}{\sum_{k=1}^{N} (c_k b_{jk})^{-\theta}}
\]

where \( x_{ji} = \text{supply of cattle from } i \text{ to } j \)

\[
x_{ji} = \frac{\left(\frac{c_i b_{ji}}{z_i}\right)^{-\theta} x_j}{\sum_{k=1}^{N} (c_k b_{jk})^{-\theta}}
\]
Gravity Model: Demand

- Buyers in state $j$ buy cattle and later resell for slaughter:

$$\max_{x_j} E[\text{PROFIT}] = (B_j - t_{sj} - c_j)x_j^{\alpha_j} - E[p_j]x_j$$

- The FOC yields total demand by $j$:

$$x_j = \left\{ \frac{E[p_j]}{\alpha_j (B_j - t_{sj} - c_j)} \right\}^{\alpha_j^{-1}}$$

where $E[p_j] = \Phi_j^{-1/\theta} \Gamma(1 + \frac{1}{\theta})$

and $\Phi_j = \sum_{k=1}^{N} (c_k b_{jk})^{-\theta}$

- Plug demand from $j$ into previous supply relation solve for $x_{ji}$:

$$x_{ji} = \frac{[\Gamma(1 + \frac{1}{\theta})]^{\alpha_j^{-1}} (c_i b_{ji})^{-\theta}}{[\alpha_j (B_j - t_{sj} - c_j)]^{\alpha_j^{-1}} \Phi_j^{1 + \alpha_j^{-1} \theta}}$$
Estimating the Gravity Model

• Take the natural log of both sides of $x_{ji}$:

$$\ln x_{ji} = \text{constant} - \theta \ln(c_i b_{ji}) - (\alpha_j - 1) \ln(\alpha_j (B_j - t_{sj} - c_j)) + \theta(1 + \frac{\alpha_j - 1}{\theta}) \ln P_j$$

\begin{align*}
P_j = \Phi_j^{1/\theta} = [\sum_{k=1}^{N} (c_kb_{jk})^{-\theta}]^{-1/\theta}
\end{align*}

• Anderson and van Wincoop (2004) suggest a technique provides consistent estimates of (*)
  – Replace $\ln P_j$ with a outward region dummy $O_j$, that indicates whether a state is a net importer or a net exporter of cattle.
Data to Estimate Gravity Model

• Cattle movement, $x_{ji}$, among 48 states
  – Source: interstate livestock movement data from the USDA Economic Research Service

• Input costs, $c_i$
  – Average feed prices in dollars per hundredweight

• Distance, $d_{ji}$
  – Distance between the center points of the two states
Data to Estimate Gravity Model

- **Buyer’s Transportation costs, $t_{sj}$**
  - Calculated by multiplying average geographic distance from feedlot to major slaughterhouse with per mile cost $0.0186$.

- **Cattle price received at slaughterhouse, $B_j$**
  - Source: USDA Agricultural prices 2001

- **Zero trade flow**
  - “Ad Hoc” approach
  - Heckman’s sample selection model
  - The inverse mills ratio significant at 1% level
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Probability of cattle infection for farms in Texas

Average per farm cattle imports from Michigan

Probability
Epidemiology Model

• Farm in state $i$

$S_i$  
$M_i$  
$I_i$

Infection due to cattle movement (Stochastic)

Slaughterhouse surveillance

Affect trade flow

Release from MC

Regular TB testing
Epidemiology Model

• **Stochastic force of infection**
  – The probability that a farm becomes infected via cattle purchases follows a Bernoulli random process
    • Depends on the number of cattle traded from state j to state i.

• **Feedback between the EPI model and the economic model**
  – Trade flow affects the force of infection in the EPI model
  – Trade restrictions induced by detection of new TB infection also affects trade flow
Simulation (2001-2010)

- Initial Values
  - Oregon, Kansas and Michigan initially have undetected infected herds
    - \( I(2001) = 1, 1, 8 \) respectively (USDA-APHIS)
  - No herds under movement control in 2001
    - No detected herds: \( M(2001) = 0 \)
Detected infection predicted by our model
Detected infection not predicted by our model
Predicted infection, currently under investigation

- MN, AZ, and NM infection likely from Mexico
Conclusions

• No evidence that producers’ market transactions are affected by social or private risks
  – Small infection risk for individual farms
  – Lack of data on actual disease risk
    • Only MI lacked disease free status in 2001

• Cattle trade affects disease dynamics
  – Biggest purchasers face largest risks

• Factors like input cost also affect trade flow, hence disease risks

• Predictions can be used to help target surveillance efforts