A Bioeconomic Model to Predict Disease Movement

Fang Xie, Richard Horan, Christopher Wolf
Michigan State University

Kenneth Mathews, Jr
USDA, Economic Research Service

We gratefully acknowledge that funding for this work was provided by the USDA Economic Research Service Program of Research on the Economics of Invasive Species Management (PREISM).

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
(based on Eaton and Kortum, *Econometrica* 2002)

- 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*:

$$p_{ji} = c_i b_{ji} / z_i = \text{Effective MC of Production}$$

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(a cow from state *i* 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} = supply of cattle from *i* to *j*

$$\Rightarrow \quad x_{ji} = \frac{(c_i b_{ji})^{-\theta} x_j}{\sum_{k=1}^{N} (c_k b_{jk})^{-\theta}}$$

Gravity Model: Demand

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

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

- The FOC yields total demand by j:

$$x_j = \{\frac{E[p_j]}{\alpha_j(B_j - t_{sj} - c_j)}\}^{\alpha_j - 1}, \text{where } E[p_j] = \Phi_j^{-1/\theta}\Gamma(1+\frac{1}{\theta})$$

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

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

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

Estimating the Gravity Model

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

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

$$P_j = \Phi_j^{-1/\theta} = [\sum_{k=1}^{N} \left(c_k b_{jk}\right)^{-\theta}]^{-1/\theta}$$

- 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

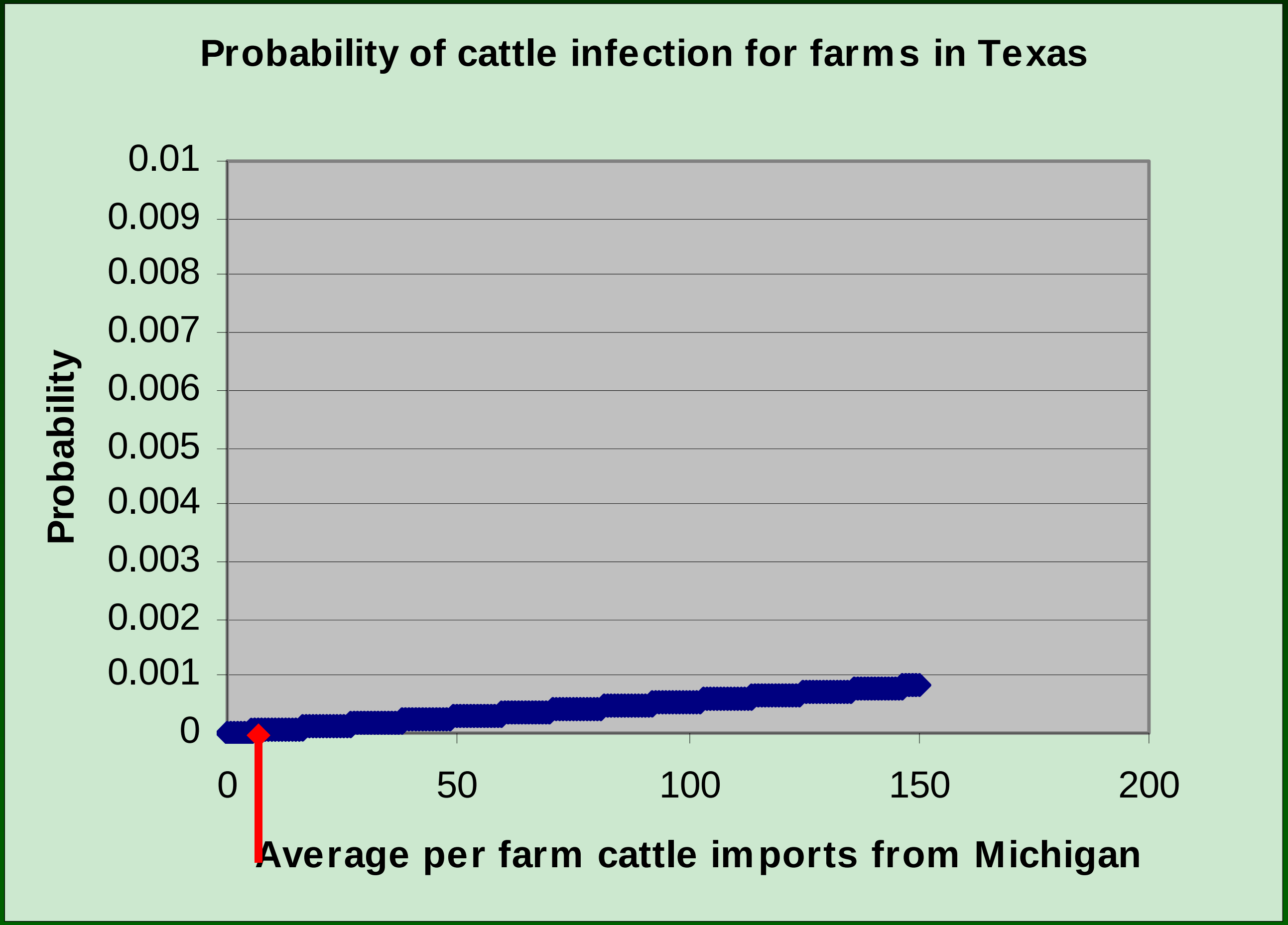
- Buyer's Transportation costs, t_{sj}
  - Calculated by multiplying average geographic distance from feedlot to major slaughterhouse with per mile cost $0.0186.
- Cattle price received at slaughterhouse, B_j
  - Source: USDA Agricultural prices 2001
- Zero trade flow
  - "Ad Hoc" approach
  - Heckman's sample selection model
  - The inverse mills ratio significant at 1% level

Estimation Results

	Coef.	Std. Error	P value	[95% Conf. Interval]	
Outward Dummy	0.50	0.23	0.029	-0.05	0.95
Input Cost	2.06	0.70	0.003	0.70	3.42
Distance	-1.29	0.12	<0.001	-1.53	-1.05
Disease status	-0.88	0.80	0.27	-2.44	0.69
Expected Profit	2.9	0.75	<0.001	1.44	4.37
Constant	-4.72	5.15	0.36	-14.8	5.39
Inverse Mills ratio	-3.57	0.15			

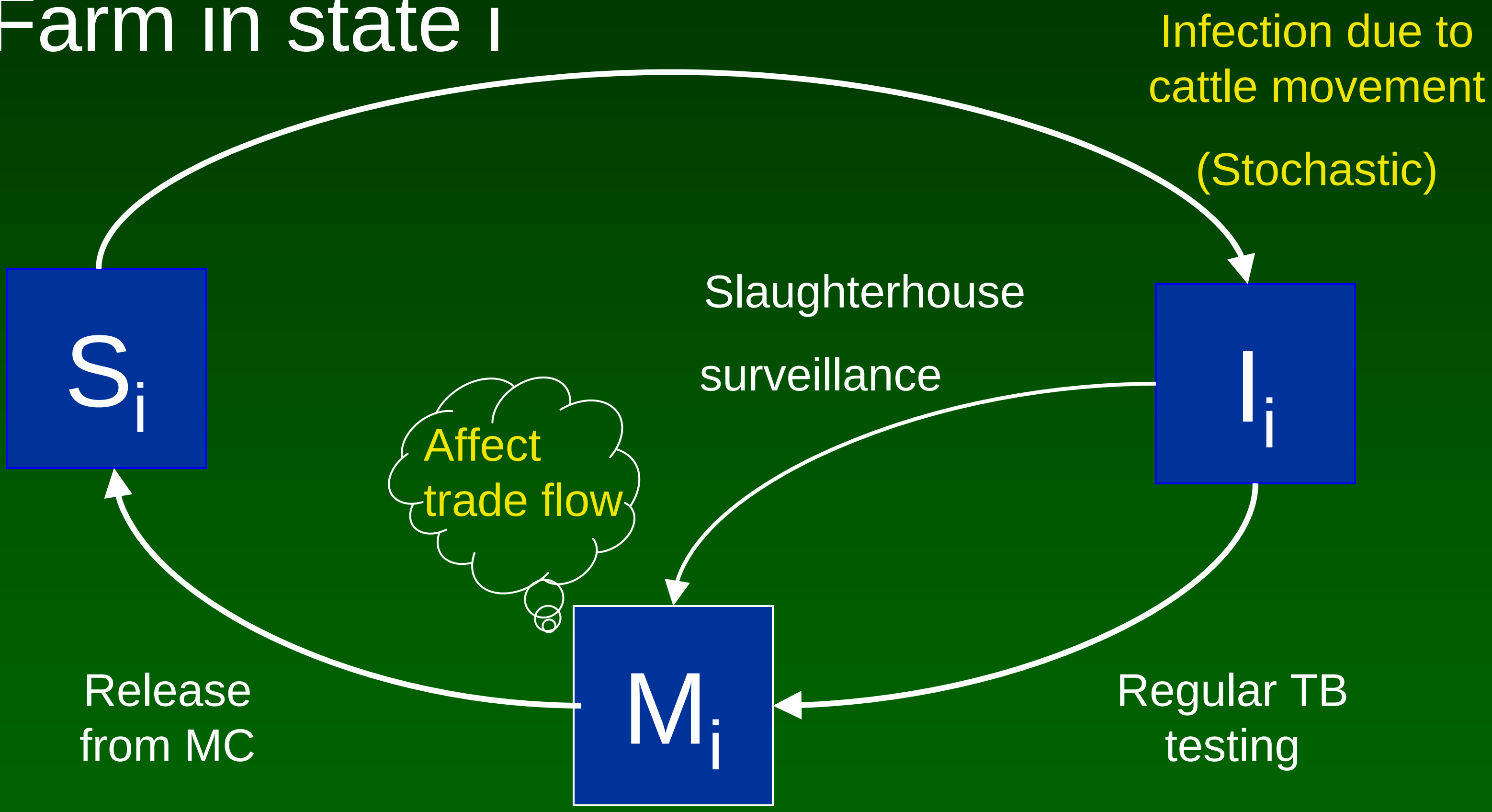






Probability of cattle infection for farms in Texas
Probability
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
50
100
150
200
Average per farm cattle imports from Michigan

Epidemiology Model

- Farm in state i



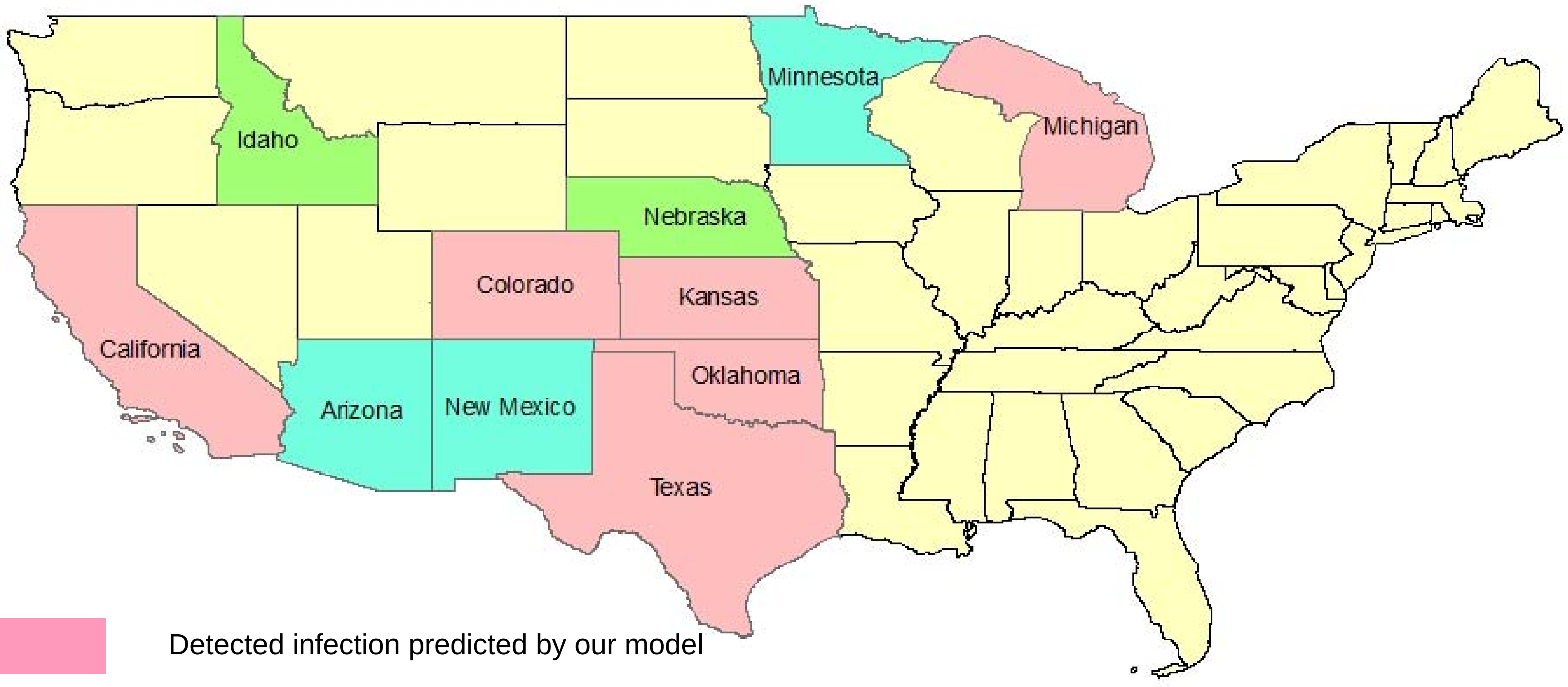
Epidemiology Model

- 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

Predicted New Infection (2001-2010)



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