Joint Management of Wildlife and Livestock Disease

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Wildlife diseases

- Major global problem
  - Human health
    - 61 % of human pathogens are zoonotic
  - Livestock
    - 77% of livestock pathogens are zoonotic
  - Recreation
    - Hunting and fishing
  - Conservation
    - TB in Lions in Krueger Park
    - Brucellosis in Yellowstone Bison

Ecological Literature on Infectious Diseases

- Conventionally, management recommendations come from this literature
- Primary focus has been on pathogens infecting a single host
- Recent interest in diseases infecting multiple hosts

Management of Wildlife Diseases

- First-Best: remove or treat infected individuals
  - Often not identifiable prior to post-mortem testing

- Actual approaches are non-targeted: second-best
  - Traditional strategies derived from ecological literature

  - Based on two related concepts
    - R0
    - Host-density thresholds

R_0: Basic Reproduction Rate of Pathogen

- Initial rate of growth in **disease-free** population
  - Disease invades or spreads when $R_0>1$
  - Disease diminishes in prevalence when $R_0<1$

- $R_0=1$ criterion used to guide management
  - Standard approach: use constant effort policy to reduce R_0 below unity and eradicate disease

R_0=1 Criterion is Problematic

- Defines a frontier of effort rates
  - An aggregate metric -- does not reflect risks to individual hosts
  - Does not guide effort choices
- Derived based on disease-free equilibrium
  - Used to guide post-infection management
  - Myopic management due to constant effort rates and focus on pre-infection state
- Criterion used to eradicate disease, but may not be efficient

Roberts and Heesterbeek (2003)

- Focus on host-density thresholds, not R_0
  - Pathogen cannot invade if host density is less than threshold
- Derive thresholds for reservoir populations
  - Target only reservoir hosts
  - Reservoir status is defined based on initial force of infection

Objectives

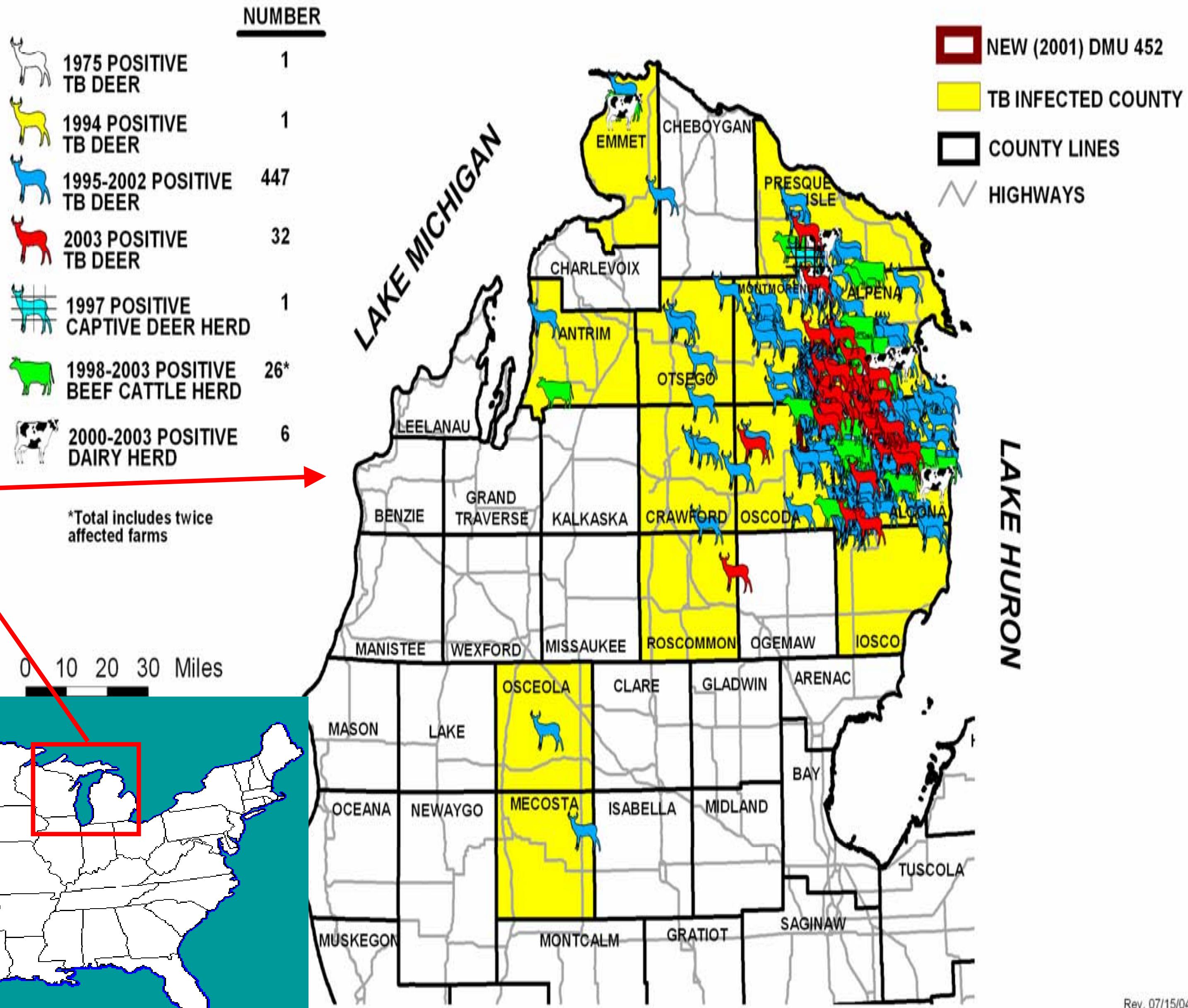
- Use a bioeconomic model to explore socially efficient management of an infected multiple host system
  - Numerical example: Bovine TB in Michigan white-tailed deer and cattle
- Explore the role of host-density thresholds
- Explore the notion of targeting the reservoir species
  - Deer in our model

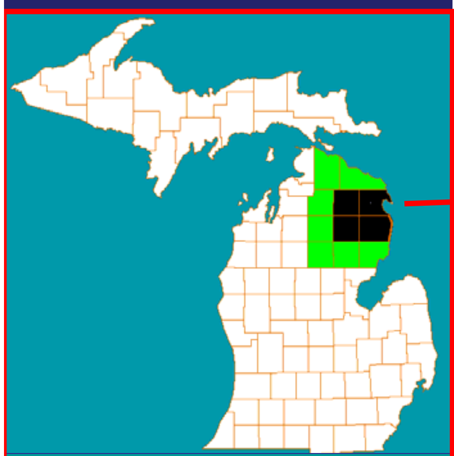
Prior literature on livestock-wildlife disease problems

- Prior livestock models
  - Explore disease dynamics within and between herds
    - Barlow et al. 1997, 1998
  - Ignore infectious interactions with wildlife
    - Chi et al. 2002; Scantlebury et al. 2004

- Prior wildlife models
  - Ignore interactions with livestock even when these motivate the analysis
    - Barlow 1996; Dobson and Meagher 1996; Horan and Wolf 2005; Fenichel and Horan 2007, Forthcoming

BOVINE TUBERCULOSIS SURVEY RESULTS
- White-tailed Deer and Cattle -





Deer Management Options

Management of harvests (h_D) and supplemental feeding (f)

Both are non-selective with respect to disease status

Cattle Management Options

Harvests of healthy cattle (h_c)

Test and removal of sick animals

} Selective with respect to disease status

Biosecurity investments (Z)

$$\dot{K} = Z - \delta K$$

SI Disease Model: Deer

$$N_D = S_D + I_D$$

$$\dot{S}_D = S_D g_D(N_D, f) - S_D \beta_{DD}(f) I_D - \beta_{DC}(K) I_C - h_D S_D / N_D$$

$$\dot{I}_D = I_D g_D(N_D, f) + S_D \beta_{DD}(f) I_D + \beta_{DC}(K) I_C - \alpha_D(f) I_D - h_D I_D / N_D$$

Similar model for cattle, except no dependence on feeding, and selective with respect to disease status

Re-scaled *SI* Model: Deer

N_D = total population

$\theta_D = I_D/N_D$ = disease prevalence rate

New Equations of Motion

$$\dot{N}_D = [g_D(N_D, f)]N_D - \alpha_D(f)\theta_D N_D - h_D$$

$$\dot{\theta}_D = \left[\beta_{DD}(f)N_D + \beta_{DC}(K)N_C\theta_C/\theta_D - \alpha_D(f)\right]\left[1 - \theta_D\right]\theta_D$$

Host-density Threshold for Deer

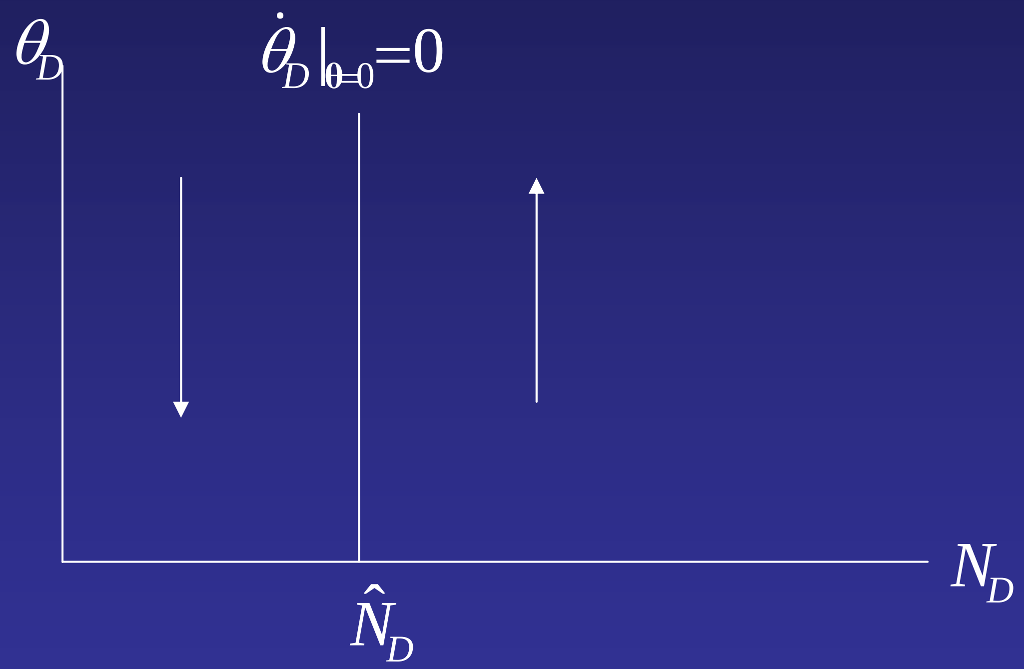
$\hat{N}_D(t)$ = the value of N_D(t) that solves $\dot{\theta}_D(t) = 0$

– The pathogen will not spread in population *i* when

$$N_D(t) \leq \hat{N}_D(t)$$

- Traditional focus is on the threshold defined at pre-infection equilibrium

Host-Density Threshold at Disease-Free Equilibrium



Criticisms of Conventionally-Defined Thresholds

- Exogenous
  - Based on all hosts being at disease-free equilibria
  - Time-invariant
  - Myopic

- Should be endogenous and time-varying.
  - Threshold = $\hat{N}_D[\boldsymbol{\theta}(t), N_C(t), K(t), f(t)]$

- Used to identity minimum effort levels for single control option
  - How should efforts be targeted by control, by species, and over time?

Bioeconomic Problem

- Bioeconomic problem:

$$\underset{h_D, h_{CS}, f, Z}{Max}\ SNB = \int_0^{\infty} [p_D(1-\theta_D)h_D + p_C h_{CS} - (c/q)h_D / N_D - wf - mN_C^2 - uZ]e^{-\rho t}dt$$

subject to $\dot{N}_i,\ \ \dot{\theta}_D,\ \ \dot{K},\ \ N_i(0),\ \ \theta_D(0),\ \ K(0), \qquad (i = D, C)$

MB from investing elsewhere in economy = Own rate of return to investing in cattle

(1)

$$\rho = a + \left[-\left(\frac{\partial \theta_C}{\partial N_C} N_C + \theta_C \right) + \frac{\phi_D}{\lambda_C} \frac{\partial \dot{\theta}_D}{\partial N_C} \right] + \frac{\dot{\lambda}_C}{\lambda_C} - \frac{2mN_C}{\lambda_C}$$

Marginal productivity of cattle

More cattle increases within-herd infectious contacts

Larger cattle population reduces threshold for deer

Capital gain

Marginal cost of larger herd

MB from investing elsewhere in economy = Own rate of return to investing in deer

(2)
$$\rho = \frac{\partial \dot{N}_D}{\partial N_D} + \left[\frac{\phi_D}{\lambda_D} \frac{\partial \dot{\theta}_D}{\partial N_D} - \frac{\lambda_C}{\lambda_D} \frac{\partial \theta_C}{\partial N_D} N_C \right] + \frac{\dot{\lambda}_D}{\lambda_D} + \frac{1}{\lambda_D} \frac{c h_D}{q N_D^2}$$

Marginal productivity of deer

Capital gain

Marginal cost savings

Larger deer population is an adverse change relative to own threshold

Larger deer population causes more infectious contacts with cattle

MB of investing elsewhere = MC of re-directing resources away from disease control

(3) $$\rho = \frac{\lambda_D}{\phi_D}\frac{\partial \dot{N}_D}{\partial \theta_D} + \left[\frac{\partial \dot{\theta}_D}{\partial \theta_D} - \frac{\lambda_C}{\phi_D}\frac{\partial \theta_C}{\partial \theta_D} N_C\right] + \frac{\dot{\phi}_D}{\phi_D} - \frac{p_D h_D}{\phi_D}$$

Marginal deer productivity impact of increased prevalence in deer

Larger prevalence in deer generates more Infectious contacts

Capital loss

Marginal damages to hunters from increased prevalence

Larger prevalence in deer increases Infectious contacts with cattle

Solutions are Feedback Rules

$$h_i(N_D, \theta_D), \qquad f(N_D, \theta_D),$$

$$K(N_D, \theta_D), \qquad N_C(N_D, \theta_D), \quad \theta_C(N_D, \theta_D)$$

Plug feedback rules into deer host density threshold

$$\hat{N}_D = \hat{N}_D(\theta_D, N_C(N_D, \theta_D), \theta_C(N_D, \theta_D), \\ K(N_D, \theta_D), f(N_D, \theta_D))$$

Now N_D on both sides of the equation.

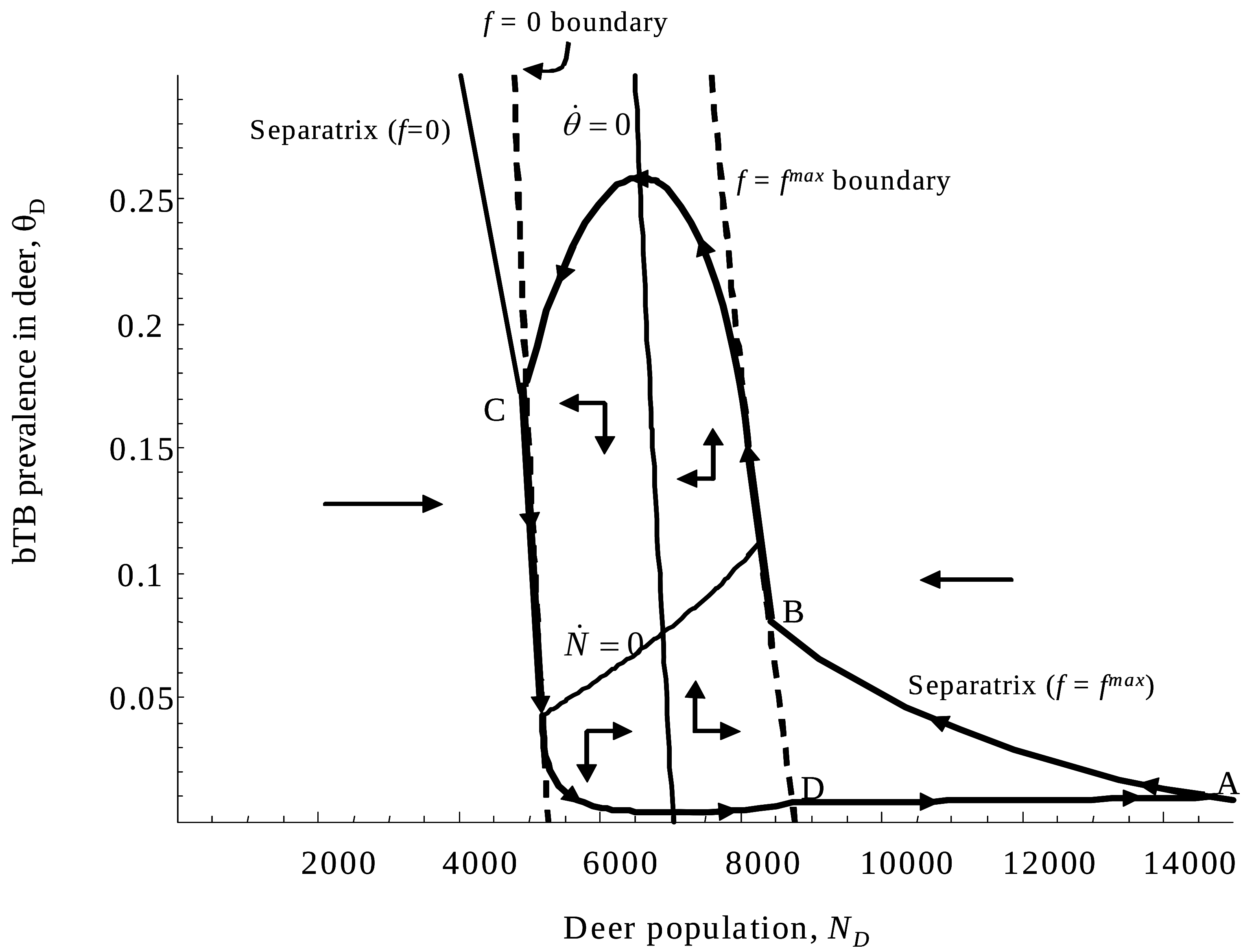
Re-solve for *optimal* host-density threshold: $\hat{N}_D(\theta_D)$

Solution

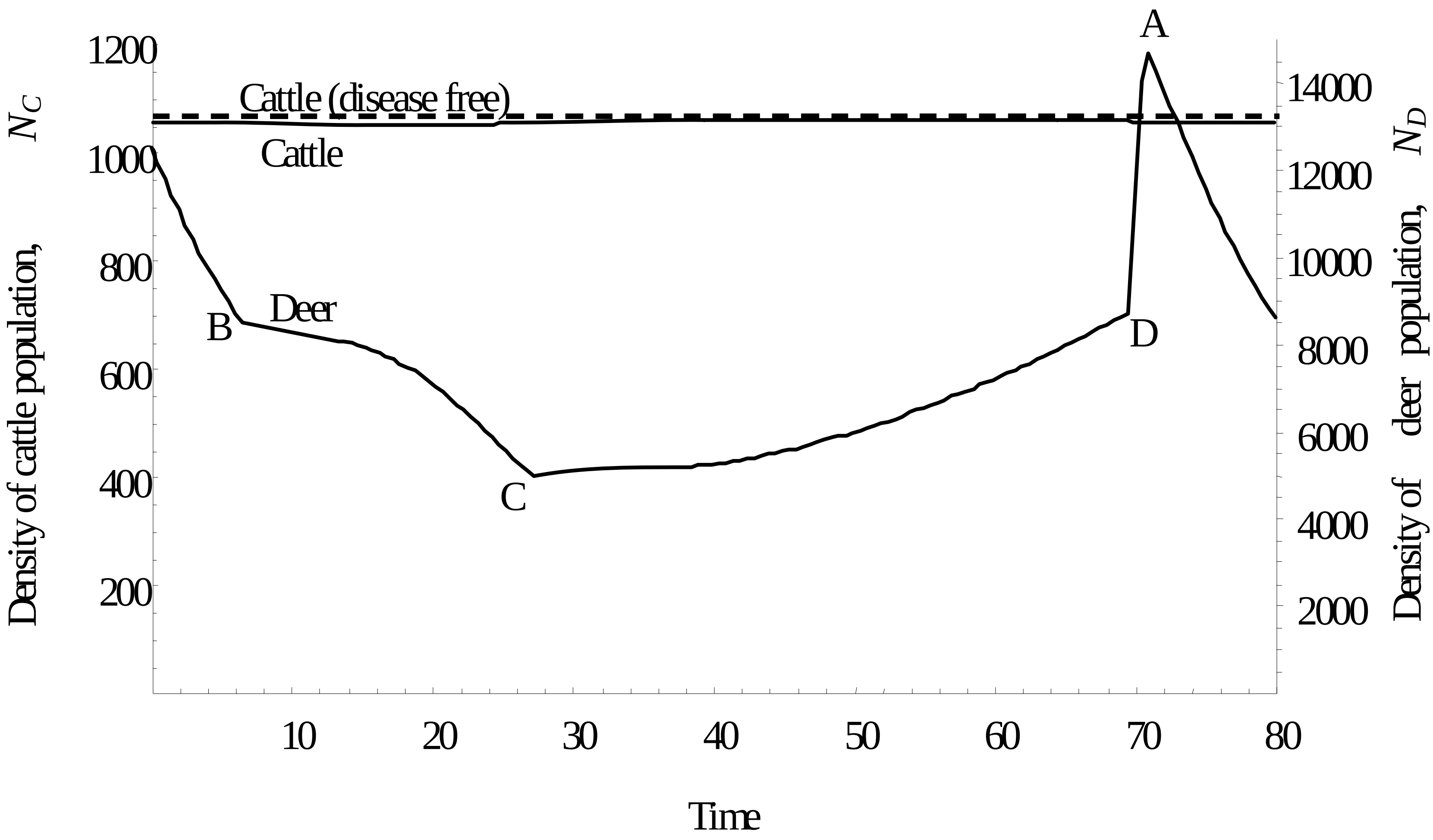
Invest heavily in biosecurity

- Deer and cattle managed as almost separate systems (but not quite)

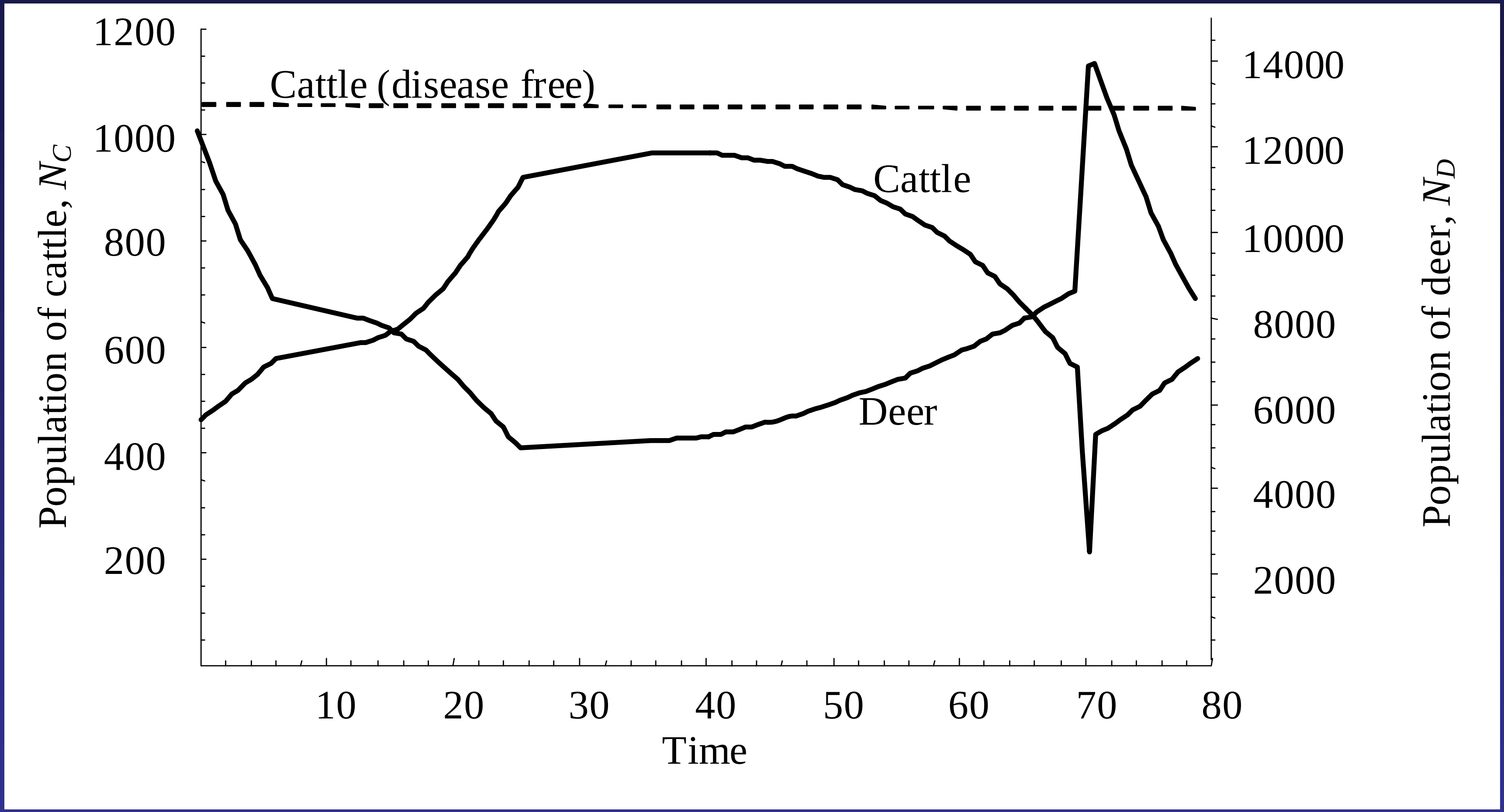
- Reduces the reservoir status of deer
  - Reservoir status is endogenous



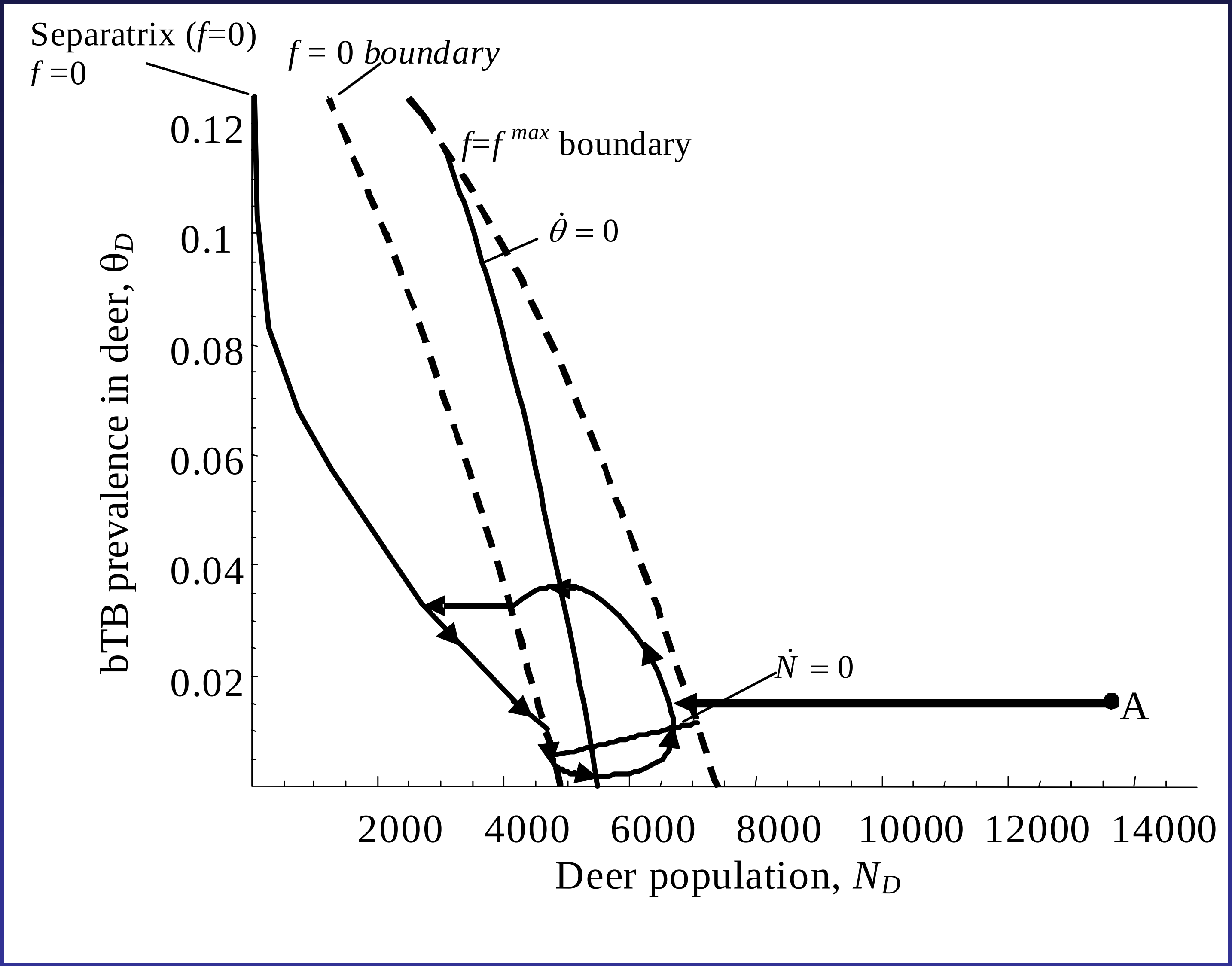
f = 0 boundary
Separatrix (f=0)
θ̇ = 0
f = f^max boundary
C
B
A
D
Ṅ = 0
Separatrix (f = f^max)
0.25
0.2
0.15
0.1
0.05
2000
4000
6000
8000
10000
12000
14000
bTB prevalence in deer, θ_D
Deer population, N_D



A
1200
1000
800
600
400
200
Cattle (disease free)
Cattle
Deer
B
C
D
14000
12000
10000
8000
6000
4000
2000
10
20
30
40
50
60
70
80
Time
Density of cattle population, N_C
Density of deer population, N_D



Time paths of deer and cattle for the base case model with no biosecurity



Deer-prevalence dynamics when cattle are ten times more valuable

Conclusions

- "Rule of thumb" in ecological lit is to manage reservoir populations relative to a fixed host-density threshold
- This paper contributes to the economics of wildlife disease management
- Two themes
  - Economic and ecological systems jointly determined
    - Thresholds endogenous
    - Reservoir status endogenous
  - How to target resources
    - Non-selective wildlife controls reduce relative efficiency of these controls
    - Primarily direct controls towards reducing reservoir status of wildlife
      - Reduces incentives to target wildlife – opposite of prior economic and ecological work
- Eradication is not optimal