Spatial Externalities of Land Use Change: An Ecosystem-Based Approach to Managing Vector-Borne Disease

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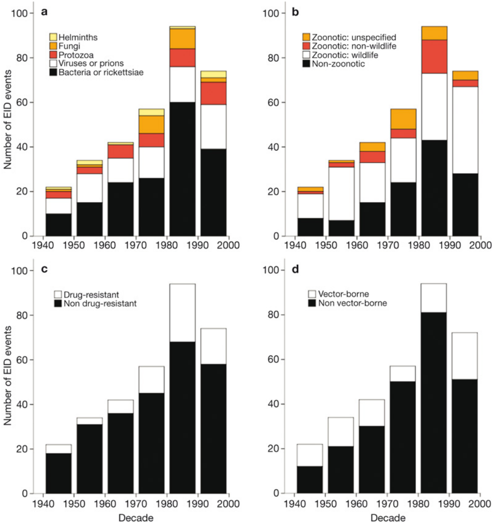
Overview

- *Environmental degradation negatively impacts public health. Land use policy and natural resource management do not account for their influence on infectious disease prevalence.*
- The oversight can be addressed by modeling public health as an environmental feedback of land conversion.
- Modeling approach is applied to land use change policy in the Amazon rainforest using malaria as health risk.

Increasing number of zoonotic disease events



Jones et al., (2008; *Nature*)

Vector-borne disease as a spatial externally

- Transmission dynamics of malaria, a *vector-borne disease*, are well understood.
- Causal relationship between ecosystem disturbance and increased malaria prevalence.
- Malaria affects morbidity, mortality, economic growth and is costly, at local and global scales.

Spatial dependence of landscape value

- Rents vary with proportion of landscape allocated to land use type.
- Ecosystem service production impacted by reduction of area and habitat fragmentation.
- Vector prevalence and disease are affected by land conversion.

Research Question

Do the public health risks arising from land use change alter the value of a landscape enough to impact overall conversion?

Resource manager chooses conversion effort $u(t)$

to maximize landscape value

$$V(u(t)) = \max_{u(t)} \int_{t=0}^{\infty} \left[R(X(t)) + B(X(t)) - D(X(t)) - C(u(t))\right] e^{-\rho t} dt$$

$0 < X(t) < 1$ — proportion of total landscape developed at time t

Resource manager chooses conversion effort $u(t)$

to maximize landscape value

$$V(u(t)) = \max_{u(t)} \int_{t=0}^{\infty} \left[R(X(t)) + B(X(t)) - D(X(t)) - C(u(t)) \right] e^{-\rho t} dt$$

$R(X)$ – rent earned on developed land

$B(X)$ – value derived from undeveloped land

$D(X)$ – disease expenditures

$C(u)$ – land conversion costs

ρ – discount rate

Resource manager chooses conversion effort $u(t)$

to maximize landscape value

$$V(u(t)) = \max_{u(t)} \int_{t=0}^{\infty} \left[R(X(t)) + B(X(t)) - D(X(t)) - C(u(t))\right] e^{-\rho t} dt$$

subject to

$$\dot{X} = \theta u(t)(1 - X(t)) - F(X(t))$$

θ	–	effectiveness of conversion
$F(X(t))$	–	ecosystem regrowth

Characterizing the optimal conversion path

Current value Hamiltonian

$$\mathscr{H} = R(X) + B(X) - D(X) - C(u) + \mu(\theta u(1 - X) - F(X))$$

Optimality conditions

$$C_u = \mu\theta(1 - X)$$

Characterizing the optimal conversion path

Current value Hamiltonian

$$\mathscr{H} = R(X) + B(X) - D(X) - C(u) + \mu(\theta u(1-X) - F(X))$$

Optimality conditions

$$C_u = \mu\theta(1-X)$$

$$\rho = \underbrace{\frac{\theta(1-X)}{C_u}(R_X + B_X - D_X)}_{\text{effective net MB of development}} - \underbrace{F_X - \frac{F(X)}{1-X}}_{\text{lost developed area}}$$

Numerical application: Malaria in the Legal Amazon

Specify of the landscape value function using economic and ecological data

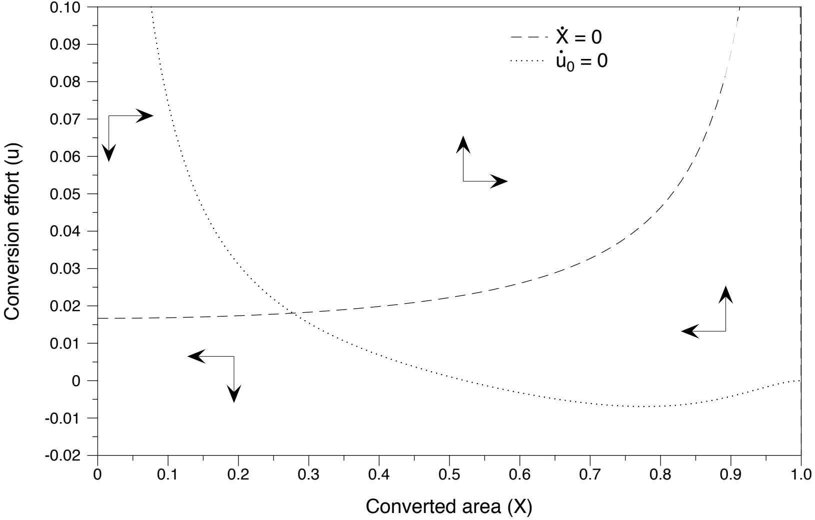
- Spatial deforestation data
- Landscape value
  - Development: industry production revenues and costs
  - Conservation: impacts of land conversion on ecosystem services
- Public health impacts
  - Malaria: prevalence of vector is a function of habitat disturbance

Model dynamics: baseline

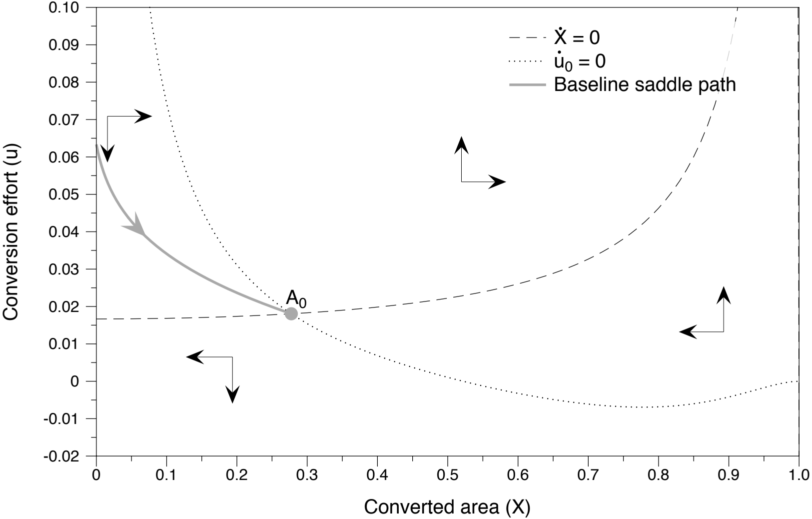
$$V(u(t)) = \max_{u(t)} \int_{t=0}^{\infty} [R(X) + B(X) - D(X) - C(u)]\, e^{-\rho t} dt$$

first, assume $D(X) = 0$

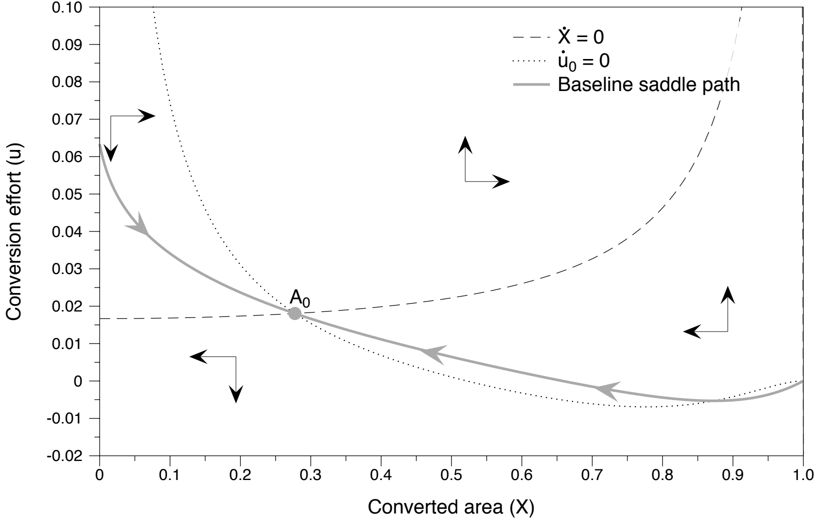
Model dynamics: baseline



Model dynamics: baseline

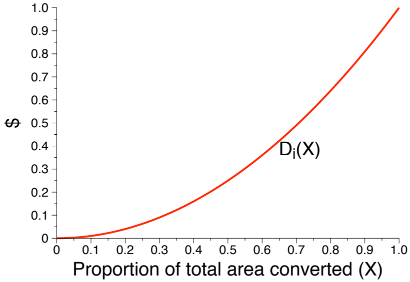


Model dynamics: baseline

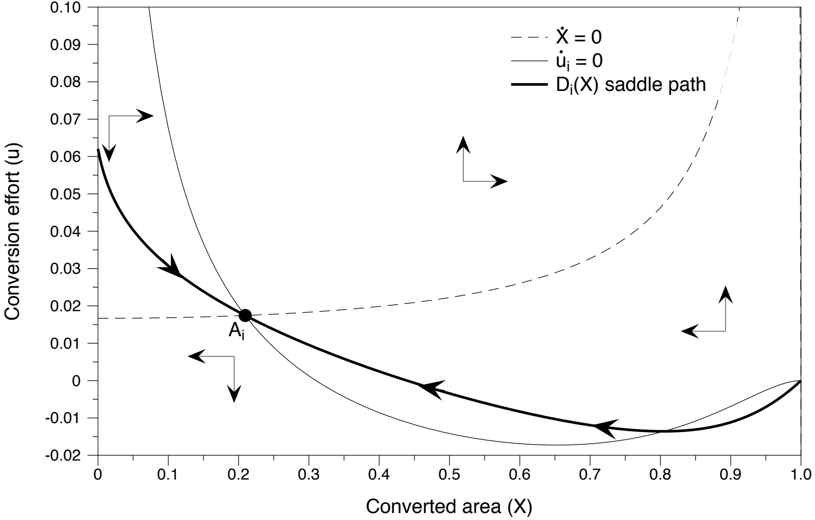


Model dynamics: Increasing damages

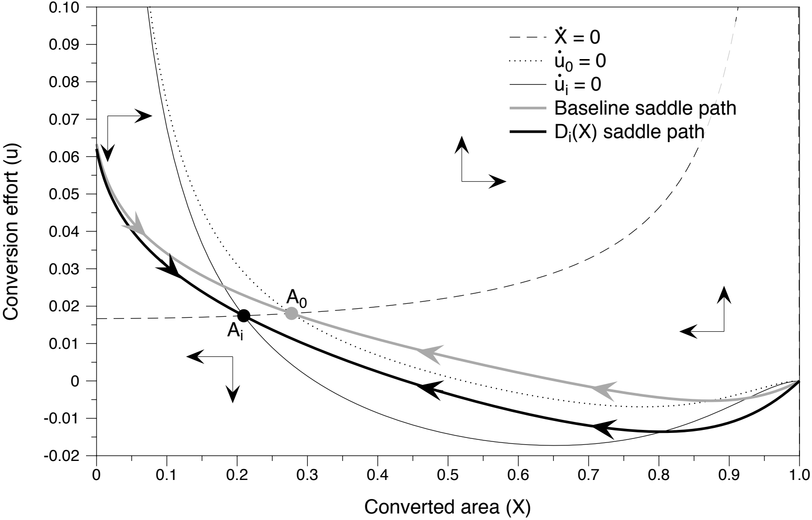
$$V(u(t)) = \max_{u(t)} \int_{t=0}^{\infty} [R(X) + B(X) - D(X) - C(u)]\, e^{-\rho t} dt$$



Model dynamics: Increasing damages

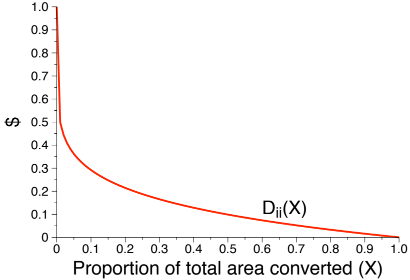


Model dynamics: Increasing damages

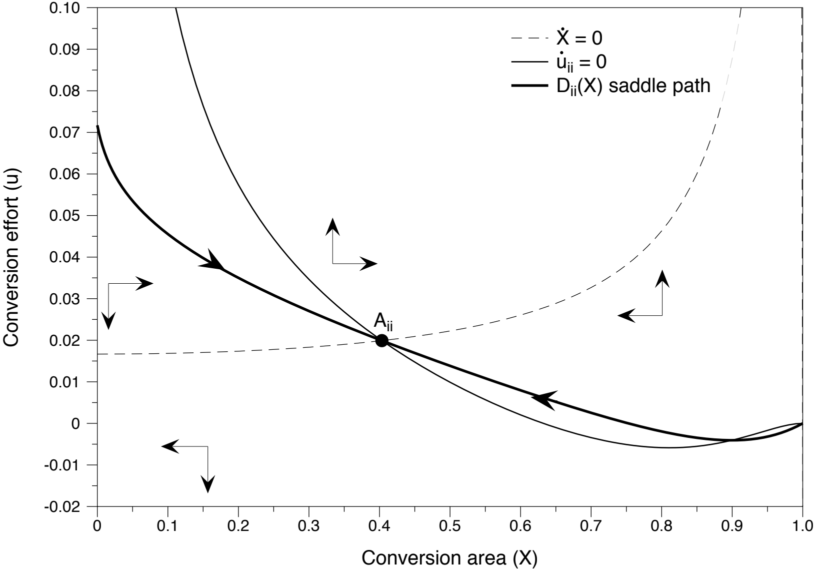


Model dynamics: Decreasing damages

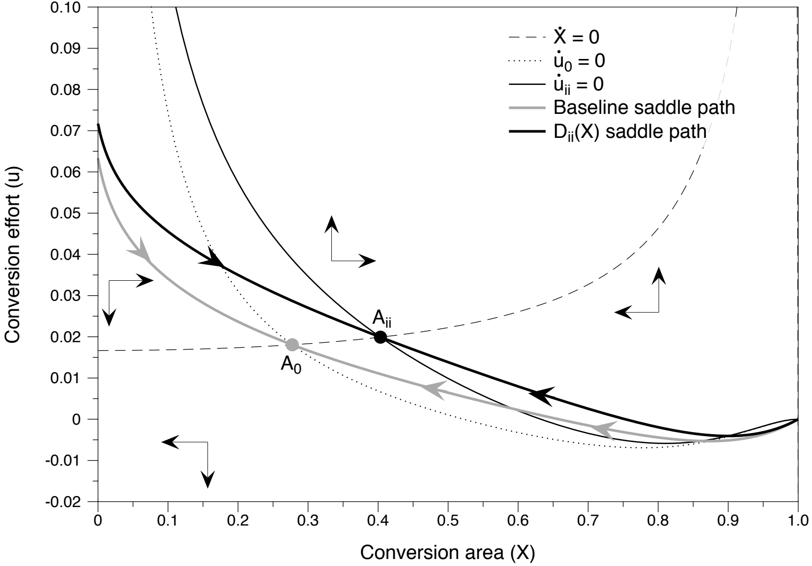
$$V(u(t)) = \max_{u(t)} \int_{t=0}^{\infty} \left[R(X) + B(X) - D(X) - C(u) \right] e^{-\rho t} dt$$



Model dynamics: $D_{ii}(X)$

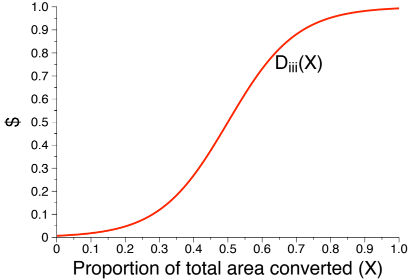


Model dynamics: $D_{ii}(X)$

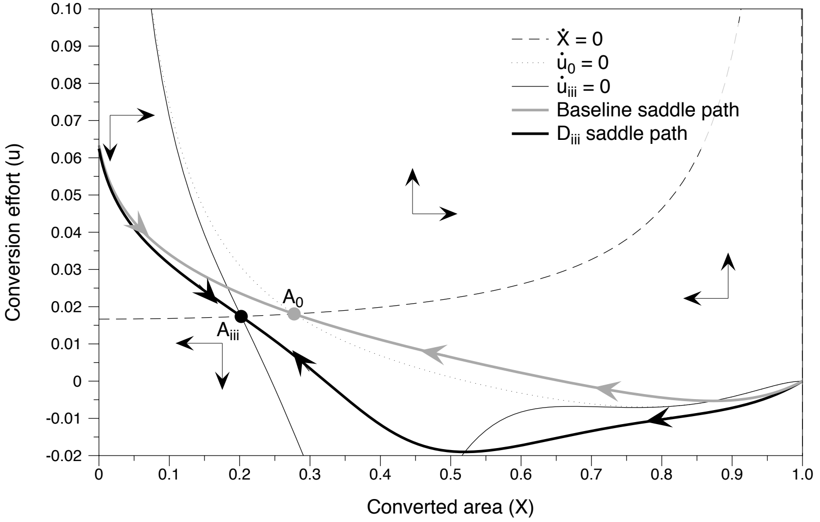


Model dynamics: nonconvex damages

$$V(u(t)) = \max_{u(t)} \int_{t=0}^{\infty} [R(X) + B(X) - D(X) - C(u)]\, e^{-\rho t} dt$$



Model dynamics: $D_{iii}(X)$



Model dynamics: $D_{iii}(X)$, modified

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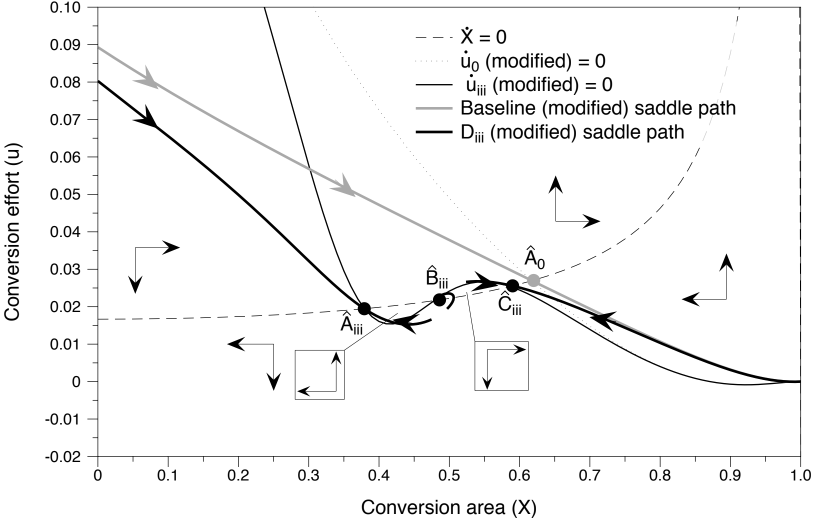
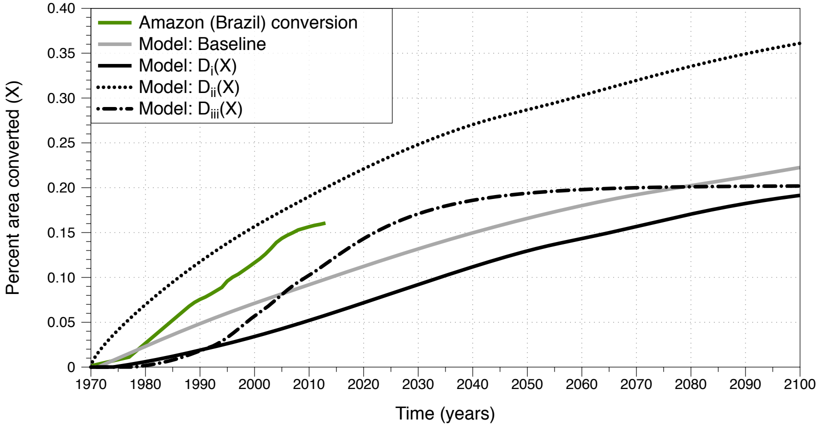


Conversion time paths and Amazon conversion rate



Spatial factors of land use

- Cost of vector-borne malaria decreases the value of converting landscape.
- Managers can anticipate health impacts by modifying converted area over time to account for spatial externalities of land use change.
- Specifying value function using region-specific economic and ecological data allows for tailoring of to a variety of systems.