Dynamic Optimization of Ecosystem Services: A Comparative Analysis of Non-Spatial and Spatially-Explicit Models

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Pest Control Ecosystem Service

- Crop pest control is an important economic issue (Pimentel et al., 2005)
  - In the US, $13.5 billion yearly loss from crop pests
  - Approximately, $120 billion annual pest control expense

- Natural Enemies that prey upon crop pests provide an important Ecosystem Service
  - Mitigates pest control cost
  - Reduces crop yield loss

- Chemical insecticides: a cost effective way
  - Loss of natural enemies exacerbates existing pest problems
  - Potential opportunity cost is huge

Question:
What is the optimal level of pest density & location for investment in habitat for Natural Enemies
⇒ An optimal control program
Crop Pests as an Biological Invasion

- Biological invasion and its management is a main topic in optimal control models of bioeconomics (Fenichel et al., 2010; Horan et al., 2011; Gramig & Horan, 2011)

- Notable recent improvement: SPACE!
  Invasion as a spatial-dynamic process (Wilén, 2007)

- Three sources of complexity:
  Space, Time, and Uncertainty
  - Existing economic models have emphasized one or two components: Tractable models but lack of realism ⇒ simultaneity!
  - Key aspects of biological invasion:
    Predator-Prey system and spatial heterogeneity

- Is the "cost" of modeling this complexity justified?
Example Invader: Soybean Aphid (SBA)

- *Aphis glycines Matsumura*
- A serious invasive crop pest in the Corn Belt
- First reported in 2000 and spread to 21 states within four years.

- **Uncertainty**: initial arrivals by westerlies
- **Space and Time**: biophysical process
- **Predator-Prey**: Lady beetle-SBA
- **Spatial Heterogeneity**: crop fields vs. non-crop habitat

⇒ All at work *simultaneously*.  

Objectives of Study

_construct a dynamic optimization model of biological invasion and its management_

- Empirical study example: SBA
  - Many comparable previous studies
    (Ragsdale et al., 2007; McCarville et al., 2011)
- Numerical experiments using synthetic geography similar to Espanchin-Niell & Wilen (2012)
- Comparison study of spatially-explicit vs. non-spatial models
  - The suggested model has a nested framework;
    Spatially heterogeneous model
    → Spatially homogeneous model
    → Non-spatial model
- Spatial analysis and management implication
  - Synthetic Geography
  - Cropland Data Layer (CDL) of Newton County, IN
Three Important Concepts: EIL, ET, and NEET

- **Economic Injury Level (EIL)**
  the lowest population of pests that will cause economic damage, i.e., yield loss that equals the control cost

- **Economic Threshold (ET)**
  the population density at which control action should be initiated to prevent an increasing pest population from reaching the EIL (Stern et al., 1959)
    - In practice, ET is an operational rule:
      \[ ET_{SBA} = 250 \text{ aphids/plant}. \]

- **Natural Enemy adjusted ET (NEET)** by Zhang and Swinton (2009, 2012)
  the pest population density threshold at which insecticide control becomes optimal in spite of the opportunity cost of injury to natural enemies of the target pest
Extending the NEET model

- The NEET model includes *Time* and *Prey-predator* system.

- A social planner’s problem instead of a single producer’s profit maximization:
  - Accounts for pest control externalities from NE habitat (spatial spillover)

- Two stochastic processes (*Uncertainty*):
  1. Which year is an aphid-year is random
  2. Initial spatial distribution of SBA and natural enemies

- Spatial domain is **heterogeneous**:
  - Crop fields, grassland, forest, and wetland
  - Generate spatially heterogeneous initial distributions of SBA and natural enemies
Model Dynamics

At a soybean field $s$ during $k$-th growing season

<table>
<thead>
<tr>
<th>Plant Stage</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>R0 $(t=0)$</td>
<td>R1 $(t=1)$</td>
</tr>
</tbody>
</table>

Natural Area
Natural Enemies
Control Decision

SBA
Yield Potential

--- Reproduction of $E$ due to SBA consumption
--- Predation of $E$ on SBA
--- Yield damage by SBA
--- Mortality by insecticides
--- Abundance of $E$ due to natural area proportion
--- Stochastic population dynamics

Adopted and modified from Zhang and Swinton (2009, p.1317.)
Nested Modeling Framework

- The previous homogeneous and non-spatial model are special cases of SST-NEET model.

<table>
<thead>
<tr>
<th>Nested Modeling Framework</th>
<th>Heterogeneous Space</th>
<th>Homogenous Space</th>
<th>Non-Spatial Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBA</td>
<td>$A_{k,s,1}$</td>
<td>$A_{k,s,1}$</td>
<td>$A_{k,s,1}$</td>
</tr>
<tr>
<td>Natural Enemies</td>
<td>$E_{k,s,1}$</td>
<td>$E_{k,s,1}$</td>
<td>$E_{k,s,1}$</td>
</tr>
<tr>
<td>Natural Area</td>
<td>Spatial Spillover</td>
<td>Spatial Spillover</td>
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</tr>
<tr>
<td></td>
<td>Parameter ($\gamma \neq 0$)</td>
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<td>Parameter ($\gamma = 0$)</td>
</tr>
<tr>
<td>Maximization</td>
<td>Total Profit</td>
<td>Total Profit</td>
<td>Profit/ha</td>
</tr>
</tbody>
</table>
Stochastic Space-Time NEET: \textbf{SST-NEET}

\begin{equation}
\underset{\text{SST-NEET}}{\arg\max} \sum_{k=1}^{K} \sum_{s=1}^{S} \tau^{k-1} \left( p_0 \cdot y_{T_k,s} - 4c_1 - \sum_{t=1}^{T-2} c_2 x_{k,s,t} \right)
\end{equation}

Subject to:

\begin{align*}
y_{k,s,t+1} &= y_{k,s,t} \left( 1 - \frac{\eta_t \cdot A_{k,s,t}}{1+\eta_t \cdot A_{k,s,t}} \right) & t = 1, \ldots, 5, T \\
A_{k,s,t+1} &= (1 + n g_t) \left( A_{k,s,t} - k \cdot x_{k,s,t} \cdot A_{k,s,t} \right) \\
&\quad - pr_t \left( E_{k,s,t} - k \cdot x_{k,s,t} \cdot E_{k,s,t} \right) & t = 1, 2, 3, 4 \\
E_{k,s,t+1} &= \gamma N_{k,s} + (1 + d) \left( E_{k,s,t} - k \cdot x_{k,s,t} \cdot E_{k,s,t} \right) \\
&\quad + b \left( A_{k,s,t} - k \cdot x_{k,s,t} \cdot A_{k,s,t} \right) \left( E_{k,s,t} - k \cdot x_{k,s,t} \cdot E_{k,s,t} \right) & t = 1, 2, 3 \\
x_{k,s,t} &= I(A_{k,s,t} \geq \text{SST-NEET or } A_{k,s,t+1} \geq \text{SST-NEET}) & t = 1, 2, 3, 4
\end{align*}

Initial Conditions (ICs):

\begin{align*}
A_{k,s,0} &\sim \text{Poisson} (\lambda) & A_{k,s,1} &= \sum_{d_k=1}^{D_k} J(A_{k,s,0}^{d_k}) \\
E_{k,s,1} &\sim \text{DU} (0, C)
\end{align*}
Synthetic Geography

- In total, 1600ha (4,000m × 4,000m)
- 40 × 40 grid cells
- Each cell: 1 ha
- Area composition:
  - Forest (81 cells)
  - River (56 cells)
  - Hedgerows (36 cells)
- 90% of 1,441 cells are soybean fields
- From Newton county, IN data, 0% to 48% natural area proportion is assigned to soybean fields.
Numerical Solution Method: Enumeration

- Integer Program: Impossible to use the gradient based methods such as HJB.
- Programmed in R and run on Hansen A Cluster at Purdue University (running time: about 33h with 96 cores (2.3 GHz)).

```
Generate stochastic daily arrival of SBA at R0 (50 years x 1441 soybean fields)
A_{k,s,0}

Calculate SBA population density at R1
Generate natural enemies population density at R1 (50 years x 1441 soybean fields)
A_{k,s,1}, E_{k,s,1}

Solve SST-NEET

Save NEET
```

Repeat 1,000 times
SST-NEET Results

- Highest SST-NEET: spatially heterogeneous model
- Homogeneous model is similar to non-spatial model
- Non-spatial model shows the ET $250 \pm 2SD$ in Ragsdale et al. (2008)
### Map Analysis: Solution Paths by Spatially Explicit vs. Non-Spatial SST-NEET

<table>
<thead>
<tr>
<th></th>
<th>Heterogeneous SST-NEET (40 aphids/plant)</th>
<th>Homogeneous SST-NEET (28 aphids/plant)</th>
<th>Non-Spatial SST-NEET (25 aphids/plant)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Spray Frequencies</strong></td>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
<td><img src="image3.png" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>Yield (Kg/ha)</strong></td>
<td><img src="image4.png" alt="Diagram" /></td>
<td><img src="image5.png" alt="Diagram" /></td>
<td><img src="image6.png" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>Profit ($/ha)</strong></td>
<td><img src="image7.png" alt="Diagram" /></td>
<td><img src="image8.png" alt="Diagram" /></td>
<td><img src="image9.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>
Map Analysis: Solution Paths by Initial Density of SBA ($A_0$)

<table>
<thead>
<tr>
<th></th>
<th>25 Percentile of $A_0$</th>
<th>50 Percentile of $A_0$</th>
<th>75 Percentile of $A_0$</th>
</tr>
</thead>
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<tr>
<td><strong>Total Spray Frequencies</strong></td>
<td><img src="image1" alt="Graph" /></td>
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<td><img src="image8" alt="Graph" /></td>
<td><img src="image9" alt="Graph" /></td>
</tr>
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</table>
Results of Map Analysis

- Note that the distribution of $A_0$ are random for all three percentiles. The spatial differences are derived from spatial dynamics of the model.

- All maps represent the consistent spatial pattern.
  - Soybean fields near by natural area: lower spray frequencies, higher yield, and higher profit
  - Crop mono-culture areas: the highest spray frequencies, the lowest yield, and the lowest profit
  - Higher $A_0$: more spray frequencies, less yield, and less profit

- Important management implication:
  To take full advantages of ecosystem service, the "proximity" to natural area is more important than the size of natural area proportion: increase heterogeneity of land composition rather than natural area.
Investment on Conservation Planting (CP)

- 2 Grass planting USDA-NRCS conservation practices
- CPs Provide only small natural area proportion, but our study supports that increasing spatial heterogeneity itself is more important than size of natural area.
**Study Area: Spatial Optimization of CP Installation**

- **Cropland Data Layer**
- **Newton County, IN, 2011**
- **5 Candidate Locations**
  - Low Natural Area Proportion
  - Placed along with Water Lines
- **Corn (even year):** 7,132
- **Soybean (odd year):** 6,501
- **Proportion of Natural Area:** 2.5 Km buffers
Spatial Optimization: Optimal Installation of CPs

\[
\text{Argmax}_{CP_{it}} \sum_{k=1}^{K} \left[ \sum_{s=1}^{S} \tau^{k-1} \left( p_0 \cdot y_{Tk,s} - 4c_1 - \sum_{t=1}^{T-2} c_2 x_{k,s,t} \right) \cdot \text{Area}_s \right] - c_3 \cdot l
\]

Subject to:

\[
y_{k,s,t+1} = y_{k,s,t} \left( 1 - \frac{n_t \cdot A_{k,s,t}}{1 + n_t \cdot A_{k,s,t}} \right)
\]

\[
A_{k,s,t+1} = (1 + n g_t)(A_{k,s,t} - k \cdot x_{k,s,t} \cdot A_{k,s,t})
\]

\[
- p r_t(E_{k,s,t} - k \cdot x_{k,s,t} \cdot E_{k,s,t})
\]

\[
E_{k,s,t+1} = \gamma N_{k,s} + (1 + d)(E_{k,s,t} - k \cdot x_{k,s,t} \cdot E_{k,s,t}) + b(A_{k,s,t} - k \cdot x_{k,s,t} \cdot A_{k,s,t})(E_{k,s,t} - k \cdot x_{k,s,t} \cdot E_{k,s,t})
\]

\[t = 1, 2, 3, 4\]

\[x_{k,s,t} = I(A_{k,s,t}^0 \geq SST - NEET \text{ or } A_{k,s,t+1}^0 \geq SST - NEET)\]

\[t = 1, 2, 3, 4\]

Initial Conditions (ICs):

\[A_{k,s,0} \sim \text{Poisson} (\lambda) \text{ and } A_{k,s,1} = \sum_{d_k=1}^{D_k} J(A_{k,s,0}^{d_k})\]

\[E_{k,s,1} \sim DU(0, C)\]
Solution Methods

1,000 Initial Arrival Scenarios of SBA and NE
5 CP candidates: 32 Combinations of Installations
50 years dynamics
Complete Enumeration Approach is applied.
Results of CP Installation

- Up to now, 100 scenarios are simulated (Preliminary Results)
- Top 50 maximum profit supported location combinations are analyzed.
Results Interpretation

- Higher average values with 6-14 and 16-18 combinations of locations
  - CP candidate location 1, 2 and 4 are most frequently chosen

- Means of profits seems similar, but is is more than 10 million dollar differences over whole Newton County for 50 years

- Locations are lower natural area proportion area
  - Installation of CPs is a better than non-installation
  - Installation locations are important (spatial spillover + spatial heterogeneity)

- Complete solution of 1,000 simulations is required
Conclusions

- The optimal control model of biological invasion considers simultaneous complexities in the unified framework that enable to derive new insights of policy implication.
  - Space, Time, Uncertainty, Prey-predator system, and Spatial Heterogeneity

- The suggested SST-NEET model provides a nested framework that enables comparisons of spatially homogeneous model or non-spatial model to spatially heterogeneous model.

- Accounting for spatial heterogeneity and spatial spillovers are important factors to consider pest control decisions with ecosystem services.
Thank you!
Questions or Comments?
NEET Model by Zhang and Swinton (2009, 2012)

- A farmer’s profit maximization for a given year

\[
\text{Max}_{x_t} \left[ p \cdot y_T - \sum_{t=1}^{T-2} c(x_t) \right]
\]

subject to

\[
y_{t+1} = f(y_f, A_t^-) \quad y_1 = y^0 \quad t = 1, \ldots, T - 1
\]
\[
A_{t+1} = g(x_t^-, A_t, E_t^-) \quad t = 1, \ldots, T - 2
\]
\[
E_{t+1} = h(x_t^-, A_t^+, E_t) \quad t = 1, \ldots, T - 3
\]

- \(x_t\): spraying out time
- \(p\): price of soybean
- \(y_t\): potential yield at time \(t\)
- \(A_t\): Soybean Aphid population density at time \(t\)
- \(E_t\): natural enemy population at time \(t\)
### Daily Based SST-NEET: ET Comparable Transformations

<table>
<thead>
<tr>
<th>Days/NEET</th>
<th>Spatially-Explicit Models</th>
<th>Non-spatial Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heterogeneous</td>
<td>Homogenous</td>
</tr>
<tr>
<td>1</td>
<td>40 aphids/plant</td>
<td>28 aphids/plant</td>
</tr>
<tr>
<td></td>
<td>48.17</td>
<td>33.72</td>
</tr>
<tr>
<td>2</td>
<td>69.20</td>
<td>48.44</td>
</tr>
<tr>
<td>3</td>
<td>117.45</td>
<td>82.22</td>
</tr>
<tr>
<td>4</td>
<td>233.34</td>
<td>163.34</td>
</tr>
<tr>
<td>5</td>
<td>537.46</td>
<td>376.22</td>
</tr>
<tr>
<td>6</td>
<td>1421.69</td>
<td>995.18</td>
</tr>
<tr>
<td>7</td>
<td>4278.03</td>
<td>2994.62</td>
</tr>
</tbody>
</table>
Yield and profit are decreasing as $A_0$ is increasing.

No spray only happens at the lower level of $A_0$.

Variable costs of spray make grouped profit structure.