A Model of Inspection, Detection and Control for Invasive Species

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Introduction

• Motivation (1):
  – Working on a project with colleagues involving a complicated model of invasive species with continuous population growth, spatial elements…
  – Model was so difficult that we eliminated many aspects that I thought were important
  – For example: assumed a known date of introduction
Introduction

• Wanted: simple model capable of incorporating
  – Uncertain dates of introduction
  – (Imperfect) Learning about the state of the system
  – Ability to control tied to size of population at time of detection

• Model with multiple policies but with limited states
  – Non-spatial
  – Extremely simple population growth
Introduction

• Several potential interventions to reduce damage from invasive species
  – Inspection: inspection of cargo & treatment that lowers the rate of introduction of invasive species
  – Detection: search for invasive species that allows for early detection while population is small and control is less costly
  – Control: efforts to eradicate, reduce population numbers, contain spread, to limit damage
• These interventions interact: the optimal choice for one depends on the level of others
Introduction

• Motivation (2): I’ve always liked the song Alice’s Restaurant
• Model of important components of the song…
• “…you walk in, you get injected, inspected, detected, infected, neglected and selected.”
Arlo Guthrie, Alice’s Restaurant*

* This song is called Alice's Restaurant, and it's about Alice, and the restaurant, but Alice's Restaurant is not the name of the restaurant, that's just the name of the song, and that's why I called the song Alice's Restaurant
An economic approach to the management of invasive species

• An "invasive species" is defined as a species that is:
  – non-native (or alien) to the ecosystem
  – whose introduction causes or is likely to cause economic or environmental harm or harm to human health

• In this model, will assume that introduction and spread of invasive species causes losses
An economic approach to the management of invasive species

• Builds from ecological foundation: knowledge of underlying biology is essential
  – What is the rate of arrival of propagules?
  – How likely will introduced species survive?
  – What is population growth potential?
  – How does invasive species change ecosystem dynamics?

• Specify possible management strategies: what are possible interventions that might prevent introductions or control invasives that are introduced?

• What are the benefits of management strategies?
  – How would strategy affect the introduction, population size or geographic extent of invasive species?
  – What are the damages associated with invasive species?

• What are the costs of management strategies?
An economic approach to the management of invasive species

- Optimal strategy maximizes the net benefits: weigh benefits and costs of strategies
- Optimal invasion rate may not be zero
  - Costs of tighter controls over introductions include trade restrictions and inspection costs
  - Benefits: lower damages from invasive species
- Similarly, optimal control strategy may not be eradication (which may not even be feasible)
- Approach is similar to that in environmental economics: optimal pollution level is where marginal benefits of environmental improvement equal marginal costs of abatement
An aside: invasive control vs. conservation

• Invasive species are the opposite of my typical research problem involving the conservation of biodiversity
• Conservation: objective is to maintain viable populations of species threatened by anthropogenic or natural changes
• Invasives: prevent introduction, eradicate, or at least control, invasive species
• “Conservation with a minus sign in front”
• Invasive species management more similar to public health: how to prevent or control the spread of disease
Three State Invasive Species Model

- Discrete time model
- At any given time, there are three possible states of the system
  - Not present: invasive species is not in the system
  - Introduced: invasive species is in the system but at a low population level
  - Spread: invasive species is extensive

- NIS model for NIS problem
Information

• Species arrival is stochastic – probability of arrival in each period
• Can search for species to detect if it is present
• Not finding the species could mean that it is not present or that it is present but just not found
• Assume that once the invasive species has spread then detection is no longer an issue
• From the manager’s point of view the states of the system are:
  – Undetected (not present or introduced)
  – Detected (introduced)
  – Spread
Difference between introduction and detection

  - San Francisco Bay and Delta may be the most invaded estuary and possibly the most invaded aquatic ecosystem in the world
  - 234 new species discovered
  - Majority of these species discovered after 1960
  - Even after correcting for taxonomic effort, the rate of introductions to the San Francisco estuary has steadily increased over the past 150 years
Difference between introduction and detection

• Costello and Solow (2003) *PNAS* 100(6): 3321-3323:
  – Observed rate of introductions depends on true rate of introductions, collection effort, and the observability of newly introduced species
  – Factoring in observability it can appear as though species are arriving at an increasing rate, even if in fact the rate were constant or even zero
Difference between introduction and detection

  - Statistical model of the discovery record that includes both the introduction and discovery processes
  - For San Francisco estuary the estimated mean rate of introductions increases from 0.3 introductions in 1850 to 2.3 introductions in 1995
Policy Interventions

• Inspection effort: $q$
  – $\lambda(q)$ is the probability that the invasive species will not be introduced into the system, $\lambda'(q) > 0$
  – $c(q)$ is the cost of inspection

• Detection (search) effort: $s$
  – $\gamma(s)$ probability of finding the invasive species if it is present, $\gamma'(s) > 0$
  – $d(s)$ is the cost of detection

• Control effort: $r$
  – $\varphi(r)$ is the probability of eradication, $\varphi'(r) > 0$
  – $e(r)$ is the cost of eradication
Policy interventions

• Reducing the probability of introductions
  – Inspections
  – Chemical controls (insecticide application, fumigation)
  – Trade restrictions
  – Ballast water exchange

• Once species has been introduced the management strategies change
  – Detection
  – Control
Policy interventions

• Introduction stage: detection and control
  – Species may die out on its own (ignore this possibility here)
  – Without control it may become established and spread
  – Detection at the introduction stage is difficult due to small population
  – Control at the introduction stage, including possibly eradication, is highly effective due to small population
A simple framework for invasive species management

• Spread stage:
  – Population is growing and spreading to new areas
  – Detection and control issues become spatial problems
    • What is the geographic spread of the species?
    • What can be done to halt, or at least delay, the spread of the species?
  – Simple model considered here ignores the spatial problems of halting or delaying spread
Interactions among stages

- Much of the literature to date analyzes one or two stages independently
- But optimal choice of strategy at each stage will depend on choices at other stages
## Transition matrix between states from period $t$ to $t+1$

<table>
<thead>
<tr>
<th></th>
<th>Not present</th>
<th>Introduced</th>
<th>Spread</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not present</td>
<td>$\lambda(q_t)$</td>
<td>$1 - \lambda(q_t)$</td>
<td>0</td>
</tr>
<tr>
<td>Introduced</td>
<td>$\gamma(s_t)\varphi(r_t)$</td>
<td>0</td>
<td>$1 - \gamma(s_t)\varphi(r_t)$</td>
</tr>
<tr>
<td>Spread</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
Completing the model

• Flow of ecosystem services:
  – $W$ per period if invasive species is not present or introduced
  – 0 if invasive species has spread

• Let $\delta$ be the discount factor between periods
Dynamic programming problem

\[ V(U) = \text{Max}_{\{q,r,s\}} \left[ W - c(q) - d(S) - \gamma(s)e(r) \right] \\
+ \delta [\lambda(q) + (1 - \lambda(q)\gamma(s)\varphi(r))]V(U) \]
Analysis

• Steady-state results relatively easy to find and characterize (set of necessary and sufficient conditions for optimal choice of $q$, $r$ & $s$)

• Complete optimal dynamic path is messier

• On dynamics: relationship between strategy from one period to the next:
  – If probability of introduction in last period was low then marginal value of detection in this period will be low
Results

• Inspection is a substitute with Detection & Control
  – High levels of inspection lead to lower chance of species being introduced so the marginal value of detection and control is lower
  – Easy detection and control lead to lower marginal value of inspection (why prevent when cure is easy?)

• Detection and Control are complements
  – Higher ability to control increases the marginal value of search
  – And, only control if the species is detected
Numerical example

- **Quadratic costs**
  - \( c(q) = cq^2 \)
  - \( d(s) = ds^2 \)
  - \( e(r) = er^2 \)
  - Set \( c = d = e = 1 \)

- **Probability functions**
  - \( \lambda(q) = 1 - e^{-(a+bq)} \)
  - \( \gamma(s) = 1 - e^{-as} \)
  - \( \varphi(r) = 1 - e^{-\beta s} \)
  - Set \( a = 0, \ b = \alpha = \beta = 1 \)

- **Other parameters:**
  - \( W = 10 \)
  - \( \delta = 0.9 \)
Numerical results

• Steady-state values
  – $q = 1.74$
  – $s = 0.63$
  – $r = 0.73$

• Probabilities:
  – No introduction ($\lambda$): 0.824
  – Detection ($\gamma$) = 0.467
  – Control ($\varphi$) = 0.518

• With equal costs and equal success probabilities
  – prevention is more valuable than cure
Numerical results

- Suppose we change the rate of introduction: $a = 1$ (even with no inspection there is a 63% change of no introduction)

- Steady-state values
  - $q = 1.46$
  - $s = 0.49$
  - $r = 0.60$

- Probabilities:
  - No introduction ($\lambda$): 0.915
  - Detection ($\gamma$) = 0.387
  - Control ($\varphi$) = 0.451
Numerical results

• Changes in cost: increase detection costs \( d = 10 \)
• Steady-state values
  \( q = 1.87 \)
  \( s = 0.04 \)
  \( r = 0.21 \)
• Probabilities:
  - No introduction (\( \lambda \)): 0.846
  - Detection (\( \gamma \)) = 0.039
  - Control (\( \phi \)) = 0.189
Numerical results: other results

- Effort levels increase with increases in:
  - $W$
  - $\delta$
A random picture to break up the monotony of blue slides
Yachats, Oregon
Parameterizing the model

• Model to date has been a “data free” exercise

• Important pieces of information:
  – Damages from introduction and spread ($W$)
  – Cost and probability functions: what is the likely cost of achieving a given likelihood of success
    • Inspection
    • Detection
    • Control
Empirical evidence

• Brief foray into the literature – evidence is pretty sparse
• Estimates that exist do not appear very reliable
Estimates of total damage in the U.S. from invasive species

- U.S. Office of Technology Assessment (1993): approximately $5 billion annually
- My advice: treat this number with healthy dose of skepticism
- Example – annual damage from feral cats annually: 17 billion
  - Method:
    - Assume 8 birds killed per feral cat per year
    - 30 million feral cats
    - 240 million birds are killed per year
    - Each adult bird is valued at $30
    - Multiply 30 x 240 million = 7.2 billion
  - When Pimentel et al. do the multiplication they get 17 billion
- Pigeons – damages of over $1 billion per year (control costs of $9 per pigeon) – who knew??
- If feral cats kill pigeons is that a benefit?
Other damages

• Wilcove et al. (1998) *Bioscience*: 400 of the 958 species on the Endangered Species Act list are considered to be at risk primarily because of competition with or predation by nonindigenous species.

• Changes to ecosystem function and processes that may be difficult to quantify or monetize:
  – A problem for ecologists – quantifying ecosystem changes
  – A problem for economists – what are the changes in value associated with ecosystem change?
Other issues and extensions

• Include more states (stages)
  – Include establishment phase
    • Introduction may die out or become established
    • Once established easier to detect but harder to detect than at introduction
  – Multiple population levels: as population level rises detection becomes easier but control becomes harder

• Include spatial analysis: spread of invasive species where damage is related to area infected
Example of strategies at the spread stage

- Gypsy moth
- Oak wilt
Slow the Spread of the Gypsy Moth Project
http://www.gmsts.org/operations/maps/
Oak Wilt

- Attacks red and white oaks in eastern USA
- Caused by fungus Ceratocystis fagacearum
- Leads to rapid wilting
- Is often fatal to red oaks
- Spreads quickly
Oak Wilt

OAK WILT DISTRIBUTION 2002
Oak Wilt Treatment

- Remove infected trees and healthy trees within 500 meters
- Plow perimeter to break root grafts
Other issues and extensions

• Multiple pathways of introduction: analysis of which methods of reducing introduction are most cost-effective
Non-native species found in Lake Superior since 1883

<table>
<thead>
<tr>
<th>Introduction</th>
<th>Number of Species</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unintentional</td>
<td>47</td>
<td>55</td>
</tr>
<tr>
<td>Unknown</td>
<td>19</td>
<td>22</td>
</tr>
<tr>
<td>Intentional</td>
<td>21</td>
<td>24</td>
</tr>
</tbody>
</table>

Source: Minnesota Sea Grant
# How are they getting here?

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Number of Species</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballast Water Discharge</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>Cultivation</td>
<td>19</td>
<td>22</td>
</tr>
<tr>
<td>Stocked Fish</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>Unknown</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Diseases and Parasites with Fish</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Canals and Diversions</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Aquarium Releases</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Live Bait Releases by Anglers</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Recreational Boaters</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Railroads and Highways</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Packaging Hitchhiker</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Other Release</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Other issues and extensions: why are alien species bad and biodiversity conservation good?

• Consequentialist approach: judge states by their consequences on human welfare
• No clear results on alien species or conservation
  – Invasives are bad by definition
• Eradicating small pox or other diseases (even though natural) improves welfare (good)
• Introducing certain alien species improves welfare (good): wheat, rice, cattle, pigs to the new world (though not Hawaii?); corn, potatoes to the old world
• Zebra mussel case
  – Costs from increase maintenance and negative affects on native species
  – Benefits: improved water quality
  – Filtration plants: pay good money to improve water quality…
  – Overall net benefits of zebra mussels likely to be highly negative
• Consequentialist approach: must judge on a case-by-case basis. What are net benefits?)
Other issues and extensions

• Value of information:
  – We currently don’t know a lot of information about ecological and economic parameters that would help us ferret out the benefits and costs of alternative policies
  – Use the model to find the value of information:
    • What parameters really matter for net benefits?
    • For which parameters are policy choices sensitive?
Summary

• Range of potential strategies to use
• Reduce the probability of introductions
  – Inspections
  – Trade restrictions
  – Ballast water exchange
• Reduce the effect of invasive species once they have been introduced
  – Early detection
  – Eradication
  – Reduce population size and/or limit damage
  – Contain the spread of invasive species
• Interactions of strategies: best to have systematic approach that considers all potential strategies in combination