Invasive Species Management: Border Enforcement, Location Theory, and Risk

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Previous Research on Economics of Invasive Species

- Research on prevention (and control) does not model the specifics of border enforcement (e.g., Horan et al. 2002; Jensen 2002; Olson & Roy 2005).
- No consideration of heterogeneity of importers or ports.
- No agent-based models (which are able to incorporate this heterogeneity).
- Though spatial analyses are becoming more common (Brown, Lynch, & Zilberman 2002, Barbier & Shogren 2002), they do not address border enforcement.
McAusland and Costello (2004):
- analyze the optimal mix of tariffs (rather than penalties) and inspection to control invasive species introductions,
- find that at low levels of infectedness, optimal inspection increases as infectedness increases, while at high levels, this relationship is reversed,
- consider one enforcement scenario only - infected goods barred from entry - which drives their findings on optimal inspections, and
- do not consider multiple, heterogeneous ports.
Research Components

1. **Theoretical Model**: evaluates both intended & unintended importer response to different border enforcement regimes with a focus on firm-specific and port-specific attributes.

2. **Data**: APHIS import, inspection, & enforcement data.

3. **Agent Based Model (ABM)**: based on theoretical model, spatial explicit, incorporates firm and port heterogeneity.

4. **Simulation Analysis**: will evaluate the welfare impacts of enforcement regimes for representative commodities.
## Project Schedule

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Data and Selection of Representative Commodities

- Data were retrieved from APHIS administered databases, our primary sources of data on shipments, country of origin, commodity, port-of-entry, interceptions, violations and disposition (action taken, e.g., entered, prohibited, fumigated, destroyed).

- Representative commodities and pests were selected based on preliminary data on disposition, pest interceptions, and interviews:
  - **Broccoli from Mexico**: flea beetle, *Copitarsia* worm
  - **Tomatoes & peppers, Netherlands**: *Agromyzidae* (Diptera).
Theoretical Model

Assume:

- $i=1, \ldots, I$ importing firms of a single commodity,
- Pest risk increases with $i$,
- Firms ship through $k=1, \ldots, K$ ports of entry.

The model has four stages.
**Model of Pest Populations & Movement, Importer Decisions, & Enforcement**

1. **Pest populations at origin**
2. **Output shipped to ports**
3. **Movement through ports**
4. **Border inspections**
   - **Scenario 1**: Output destroyed, penalties levied
   - **Scenario 2**: Output treated, penalties levied
5. **Pests move with goods through country to final market**
6. **Pest establishment & infestations**
7. **Environmental damages**
8. **Response**

**Stage 1**: Firms choose # of units of output to export, pre-entry treatment, and port-of-entry

**Stage 2**: Pest not detected or pests detected

**Stage 3**: Pests move with goods through country to final market

**Stage 4**: Pest establishment & infestations and environmental damages
Stage 1: Production, Initial Pest Exposure, Treatment & Shipment to Border

- An initial pest population, \( n_{ik}^0 \), increases with \( i \).
- Firms choose:
  - \( k \), to which port to ship,
  - \( y_{ik} \), output, and
  - \( e_{ik}^0 \), per unit pre-entry treatment.
- After initial treatment, pest populations decline to
  \( n_{ik}^1 = n_{ik}^0 g(e_{ik}^0) \) where \( g \) is a kill function.
- Transportation costs from origin to border, \( \tau_{ik} \).
- Initial cost of production, \( c_i(y_{ik}) \).
Stage 2: Border Inspections, Enforcement & Treatment

- Port entry fees, $\phi_k$, per unit of output.
- Inspection leads to discovery of $h(n_{ik}^1, w_k)y_{ik}$, where $h(n_{ik}^1, w_k)$ is a discovery function with per unit cost of inspection, $w_k$.

Scenario 1. Shipments are destroyed
The $i$th firm:
- supplies $s_{ik}^1 = (1 - h(n_{ik}^1, w_k))y_{ik}$, and
- pays a penalty of $t_k^1 h(n_{ik}^1, w_k)y_{ik}$. 
Stage 2: Border Inspections, Enforcement, & Treatment (con’t)

Scenario 2. Shipments are treated

The $i$th firm:

- supplies $s_{ik}^2 = y_{ik}$,
- pays a penalty of $t_k^2 h(n_{ik}^1, w_k) y_{ik}$, and
- pays treatment costs, $x_k h(n_{ik}^1, w_k) y_{ik}$.

Pest populations decline to $n_{ik}^2 = n_{ik}^1 g^2(x_k)$. 
Stage 3: Shipment to Final Market

- $l_k$ – per unit transportation cost from port to final market (analytically the same as a tariff).
- Import supply is sum of firms’ output.
- Total supply = imported + domestic supply.
- Market equilibrium $\wp$ output price.
- Consumer surplus, domestic consumer surplus.
Stage 4: Environmental Damages

- $E(N,R)$
- $N$, pest population arriving on imported goods
- $R$, post-border, responsive treatment
- where: $\frac{\partial E}{\partial N} > 0, \frac{\partial E}{\partial R} < 0$. 
Firm’s Decision

Under scenario 1, for each port, the firm first solves:

\[ \pi_{ik}^1 = \max_{y_{ik}, e_{ik}} \left\{ (pq_i - l_k)(1 - h(n_{ik}^1, w_k)) - t_k^1 h(n_{ik}^1, w_k) - \phi_k - \tau_{ik} - e_{ik}^0 \right\} y_{ik} - c_i(y_{ik}) \]

Alternatively, under scenario 2:

\[ \pi_{ik}^2 = \max_{y_{ik}, e_{ik}} \left\{ pq_i - (x_k + t_k^2) h(n_{ik}^1, w_k) - \phi_k - l_k - \tau_{ik} - e_{ik}^0 \right\} y_{ik} - c_i(y_{ik}) \]

The firm then chooses optimal port:

\[ \Pi^1(i) = \max_k \{ \pi_{ik}^1 \} \quad \text{or} \quad \Pi^2(i) = \max_k \{ \pi_{ik}^2 \} \]
Social Welfare

\[ sw_{\text{scenario}} = CS + PS_D + Envir. Damages + Inspection + Response \]

The social planner chooses optimal inspection, penalties and post border response for each scenario:

\[
\max sw_{\text{scenario}}(y_{ik}^*, e_{ik}^{0*}, p^*; \square) = \\
\max \int_0^{S_T(p^*)} [D(p) - p^*] ds + \int_0^{S_D(p^*)} [p^* - S_D(p)] ds - E(N, R) - \sum_{k=1}^{K} \sum_{i=1}^{I} w_k - R
\]

then chooses optimal enforcement scenario:

\[
\max SW = \max_{\text{enforcement scenario}} \left\{ sw^1, sw^2 \right\}.
\]
An increase in per unit inspection levels will lead to:

- an increase in pre-entry treatment if

\[ \frac{\partial^2 h}{\partial n_{ik} \partial w_k} \geq 0 \]

meaning the discovery function is either more responsive to changes in pest populations as inspection levels increase or unaffected by changes in inspection levels.
Preliminary Theoretical Results: Firm Response to Inspection (cont.)

An increase in inspection will also lead to:

- a reduction in output – an unintended response – if:

\[ (pq_i - l_k + t_k) \left( \frac{\partial h}{\partial n_{ik}} \frac{\partial n_{ik}^1}{\partial e_{ik}^0} \right) \leq 1 \]

meaning:

- price of output & penalties are relatively low,
- transportation costs high, or
- pre-entry treatment is relatively ineffective.
Preliminary Theoretical Results: Firm Response to Penalties v. Tariffs

Under both scenarios, an increase in penalties will lead to:
- an increase pre-entry treatment, and
- a reduction in output if:

$$ (pq_i - l_k + t_k) \left( \frac{\partial h}{\partial n_{ik}} \frac{\partial n_{ik}^1}{\partial e_{ik}^0} \right) \leq 1 $$

An increase in the tariff will lead to:
- an ambiguous change in pre-entry treatment under scenario 1 with no change under scenario 2, and
- reduced output under scenario 2, and also under scenario 1 if:

$$ (pq_i - l_k + t_k) \left( \frac{\partial h}{\partial n_{ik}} \frac{\partial n_{ik}^1}{\partial e_{ik}^0} \right) \geq 1 $$
Preliminary Theoretical Results: Firm Heterogeneity in Pest Populations

An increase in initial pest population will lead to:

- increased levels of pre-entry treatment if:
  \[
  \frac{\partial^2 n_{ik}^1}{\partial e_{ik}^0 \partial n_i^0} < 0
  \]
  (the kill function gets more efficient as pest populations increase), and

- an increase or decrease in output depending on specific conditions.
Preliminary Theoretical Results: Port Choice

Obvious effects:

- A uniform increase in costs (e.g., tariffs, transport, port entry fees, treatment costs) across ports will not lead to port switching.
- An increase in costs at a single port will encourage importers to shift away from that port.
Non-obvious effects:

- A firm-specific change, such as a change in initial pest populations, can cause a shift between ports if:

\[
\frac{\partial h}{\partial n_i^1} \frac{\partial n_i^1}{\partial n_i^0} \neq \frac{\partial h}{\partial n_{i2}^1} \frac{\partial n_{i2}^1}{\partial n_i^0} \quad \text{or} \quad \frac{\partial h}{\partial n_{i1}^1} \neq \frac{\partial h}{\partial n_{i2}^1}
\]

- Similarly, a change in inspection levels can cause a shift between ports if:

\[
\frac{\partial h}{\partial w_1} \neq \frac{\partial h}{\partial w_2}
\]
Preliminary Theoretical Results: Preliminary Theoretical Results:
Scenario 1 (destroy) vs. Scenario 2 (treat)

- Under scenario 1, changes in inspection or initial pest populations lead to a greater output and pre-entry treatment response than under scenario 2 if:

\[(pq_i - l + t_k^1) > (x_k + t_k^2)\]

- It is likely that under scenario 2, changes price, quality, transportation costs, tariffs, and port entry fees lead to a greater output response and lesser pre-entry treatment response than under scenario 1.
**Scenario 3:**
- 3a. The unit where pests are discovered are destroyed,
- 3b. The remaining units are treated.

**Scenario 4:**
- 4a. Penalties are based on the number of discovered units,
- 4b. All units are treated
Implications

- Firms consider the tradeoffs associated with costs and benefits associated with location - inspection intensity or port entry fees versus distance to port-of-entry and final market.
- Different types of firms will weigh these tradeoffs differently.
- High risk firms are likely to select ports that are perceived to be low-enforcement ports, perhaps forfeiting distance.
- High risk firms are likely to choose low-enforcement ports rather than pre-entry treatment.
Implications (cont.)

- Low risk firms are likely to value transportation cost savings versus enforcement.
- Increased enforcement (higher inspection intensity) may not result in reduced pest risk.
- Scenario 1 (destroy) is likely to be optimal when response costs and potential damages are high, and consumer surplus impacts are low.
- Scenario 2 (treat) is likely to be optimal when response costs are low, potential damages are low, and consumer surplus impacts are high.
Further Questions to Address with Theoretical Analysis

- What are the specific conditions under which scenario 1 (destroy) is an optimal choice over scenario 2 (treat)?
- How do socially optimal enforcement and response change with changes in model parameters?
- What are the implications of different assumptions concerning risk (e.g., uncertain pest populations, prices)?
- Given importer response, how should gov’t decision makers allocate inspection effort across different types of ports?
- What are options for firm-specific enforcement?
Agent Based Modeling

- Computational simulation of individual classes written in object-oriented programming.
- Model of complex systems of interactions between autonomous agents.
- Tracks system level dynamics emergent from autonomous individual actions.
Spatially Explicit Agent Based Models

Agents
- Importers
- Regulators
- Pests, etc.

Landscape
- Roads, cities, boundaries
- Natural features
- Native animal populations
- Locations of affected industries (ag, fisheries, etc.)

Dynamic
- Event sequencing
- Interaction rules
- Stochastic events
Agent Based Modeling

- U. of Alberta personnel working collaboratively with Berkeley researchers on analytical model design and Texas A&M researchers on spatial modeling of invasive damage on key crops.
- APHIS data will provide benchmark values to calibrate the port-specific and commodity/country of origin-specific parameters.
The ABM will evaluate and rank inspection and enforcement schemes for imports of a single commodity across different types of importers and ports-of-entry.

Policy Instruments/Regulator Behavior

Importer Behavior (type, port-specific)

Probability of Detecting Infected Shipments

Frequency of Infected Shipments

Range of Damages (given a landscape)