# Induced-Innovation and Invasive Species Management

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## Introduction

Public policy for managing invasive species has largely focused on preventive measures ***prior to*** detection (*stage 1*) and on the use of chemical/mechanical or biological control measures ***after*** the establishment and dispersion of the invasive species (*stage 2*). Optimal management policy depends both on the initial stock of the invasive species and on the costs associated with conventional control measures. However, little attention has focused on how an induced technology such as B*t* corn and B*t* cotton is developed and adopted by farmers (*stage 3*), or how it affects the manageability of economic and ecological damages from an invasive species. This analysis evaluates the optimal allocation of management resources between preventive and control measures for invasive species by incorporating induced technology under uncertainty into a conventional dynamic model of invasive species management.

## Objectives

- The study first demonstrates the economic properties of an optimal allocation of management resources for an invasive species across all three stages using a new dynamic modeling framework that accounts for the endogenous technological change under uncertainty (relating to the timings of the pest's *discovery*, of the induced technology's *development*, and of its *adoption* by farmers).
- Second, the study integrates all three risk components within a dynamic economic model of invasive-species management, using hazard functions to measure risks and a logistic growth function to account for the growth rate of an invasive pest.
- Finally, the study conducts comparative dynamic analyses to show how the probabilities of developing an induced technology and its adoption by farmers, as well as species characteristic variables, affect the optimal policies for invasive species management before and after the first discovery of an invasive pest.

**Preventive measures** include establishing screening and monitoring processes; restricting the movement of invasive species; monitoring ship-based pathways; and establishing trade restrictions, border inspections, and pest eradication programs in foreign countries.

**Chemical/mechanical control measures** include the use of pesticide, herbicide, and fungicide applications; as well as mowing, brush-cutting, prescribed burning, girdling of trees or shrubs, mulching, tilling, and flooding to control some plant species.

**Biological control measures** involve the deliberate use of one living organism or natural enemy (for example, insects, mites, or pathogens) to control the target pest.

**Induced technology measures** involve the adoption of new technologies that result from deliberate research by government, academic, and corporate enterprises, aimed at improving an endogenous use of a factor of production such as genetically engineered seed.

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## Tools to measure the economics of invasive species management with induced technology under uncertainty.

**(1) Use a hazard function approach to:**

**(a.) Measure the uncertainty of the timing of discovery of an invasive pest.**

$$\frac{\partial F(t)}{\partial t} = h[E_b(t)][1 - F(t)],$$

where $F(t) = 1 - e^{-h(E_b(t))t}$ is the probability that discovery of an invasive pest has occurred by time $t$ with $F(t=0) = 0$, $h[E_b(t)]$ is the conditional probability that discovery will occur during the next time period with $\partial h/\partial E_b < 0$, $E_b(t)$ = preventive measures adopted before the first discovery of the invasive pest, and where $\partial F(t)/\partial t$ is the probability density function for the time of discovery.

**(b.) Measure the uncertainty of the timing of developing a new technology designed to mitigate increasing costs associated with using chemical/mechanical and biological control measures.**

$$\frac{\partial M(\gamma)}{\partial \gamma} = m(E_a(\gamma), Q(\gamma))[1 - M(\gamma)],$$

where $M(\gamma) = 1 - e^{-m(E_a(\gamma), Q(\gamma))\gamma}$ is the probability of development of a technical innovation occurring by time $\gamma$ where $M(\gamma=0) = 0$, $m(E_a(\gamma), Q(\gamma))$ is the conditional probability that a new technology will be developed during the next time period with $\partial m/\partial E_a > 0$, $\partial m/\partial Q > 0$, and $E_a(\gamma)$ = chemical/mechanical control measures, $Q(\gamma)$ = biological control measures (both considered after an invasive species' discovery/establishment), and where $\partial M(\gamma)/\partial \gamma$ is the probability density function for the time of development of a technical innovation.

**(c.) Measure the uncertainty of the timing of a farmer adopting an innovative technology.**

$$\frac{\partial N(\tau)}{\partial \tau} = n(E_a(\tau), Q(\tau))[1 - N(\tau)],$$

where $N(\tau) = 1 - e^{-n(E_a(\tau), Q(\tau))\tau}$ is the probability of adoption of a technical innovation at time $\tau \geq \gamma$ where $N(\tau=\gamma) = 0$, $n(E_a(\tau), Q(\tau))$ is the conditional probability that a new technology will be adopted during the next time period with $\partial n/\partial E_a > 0$, $\partial n/\partial Q > 0$, and where $\partial N(\tau)/\partial \tau$ is the probability density function for the time of adopting a new technology.

**(2) Use a logistic growth function to measure the rate of change of the invasive species stock.**

$$\frac{\partial z(t)}{\partial t} = g(Q(t))z(t)[1 - k(E_a(t))][1 - \frac{(1 + k(E_a(t)))z(t)}{V}]$$

where $z(t)$ is the stock of an invasive species in year $t$ and $z(t=0) = z_0$, $g$ is the rate of intrinsic growth of the invasive species infestation, where $\partial g/\partial Q < 0$, $V$ represents the maximum possible population of the invasive species that depends on the maximum resources available for species infestation, $k(E_a(t))$ is a fractional coefficient with ( $0 \leq k \leq 1$) representing the removal rate of the invasive species population stock, where $\partial k/\partial E_a > 0$, and $E_a(t)$ and $Q(t)$ are as defined above.

## Dynamic Economic Model of Invasive Species Management with Induced Technology under Uncertainty

The dynamic optimization problem maximizes the expected net social economic benefits (W) over all three invasive species management stages.

$$\text{Max W} = \int_0^T e^{-rt} \Big\{(1 - F(t))\big[NB_b(x) - C_b(E_b(t))\big] + F(t)\big[NB_a(x, z(t)) - C_a(E_a(t), Q(t))\big]$$
$$+ F(t)M(t)N(t)\Big[\big[NB(Y(w)) - C(R)\big] - \big[NB_a(x, z(t)) - C_a(E_a(t), Q(t))\big]\Big]\Big\}\,\delta t$$

**subject to:** the state equations 1a, 1b, 1c, and 2 identified above, and the condition $N(T) = N_T$, where $T$ is the terminal time period, $N_T$ is a known constant, $r$ is the rate of discount, $Y$ is output, $NB$ = net economic benefits of output (excluding the costs of managing the invasive species) in terms of consumer and producer surpluses, and $x$ and $w$ identify conventional and induced technologies, respectively.

$C_b(E_b(t))$ = the costs for preventive measures, $C_a(E_a(t), Q(t))$ = the costs to farmers of managing the invasive species using chemical/mechanical and biological control measures (before adoption of a new technology), and $C(R)$ = investment costs for developing an innovative technology.

Net economic benefits from the adoption of an induced technical innovation, $NB(Y(w))$, increase over time as a function of discounted costs. Adoption of an induced technology requires their net economic benefits, $[NB(Y(w)) - C(R)]$, be greater than or equal to the net economic benefits (less invasive species management costs) of a conventional technology, $[NB_a(Y(x, z(t))) - C_a(E_a(t), Q(t))]$, at any given year.

***Fact***: An induced technology (i.e., $w$) is developed with the probability of $M(t)$, and is adopted with the probability of $N(t)$, while $F(t)\cdot M(t)\cdot(1-N(t))$ is the probability of using a conventional technology even after an induced technology is developed.

# Model Optimality Conditions Reveal That:

## When an induced technology is not considered, i.e., (*M* = *N* = 0):

**(1)**

$$\left(\frac{\partial C_b}{\partial E_b}\right) = \left(\frac{-1}{r+h}\right)\left(\frac{\partial h}{\partial E_b}\right)\Big\{\big[NB_b(x) - C_b(E_b)\big] - \big[NB_a(x,z) - C_a(E_a,Q)\big] - M(t)N(t)\big[\big(NB(Y(w)) - C(R)\big) - \big(NB_a(x,z) - C_a(E_a,Q)\big)\big]\Big\} > 0$$

- marginal costs of adopting preventive measures would be overstated,
- therefore, the recommended management resource allocation for preventive measures would be less than adequate.

**(2)**

$$\left(\frac{\partial C_a}{\partial E_a}\right) = -\left[\frac{\left(\frac{\partial NB_a(x,z)}{\partial z}\right)}{r - g(1-k)\left(1 - \frac{2z(1+k)}{V}\right)}\right] gz\left(1 - \frac{2kz}{V}\right)\left(\frac{\partial k}{\partial E_a}\right)$$

$$+ \left(\frac{1}{r+m}\right)\left(\frac{N(1-M)}{1-MN}\right)\left(\frac{\partial m}{\partial E_a}\right)\big[\big(NB(Y(w)) - C(R)\big) - \big(NB_a(x,z) - C_a(E_a,Q)\big)\big]$$

$$+ \left(\frac{1}{r+n}\right)\left(\frac{M(1-N)}{1-MN}\right)\left(\frac{\partial n}{\partial E_a}\right)\big[\big(NB(Y(w)) - C(R)\big) - \big(NB_a(x,z) - C_a(E_a,Q)\big)\big]$$

- marginal costs from an increase in the removal rate of the invasive species population stock due to species control measures would be understated, leading to a more than adequate management resource allocation.

## Whether an induced technology is considered in the model or not:

**A. When it is not considered:**

- the economically-efficient management resource allocation requires more emphasis on preventive measures before the first discovery of the invasive pest than on control measures after the discovery.

**B. When it is considered:**

- the difference between the marginal benefits of preventive measures and the marginal benefits of control measures increases.

**Why?** Because, when an induced technology is considered, the MCs of preventive measures decline (Eq. 1), while the MCs of control measures increase after discovery (Eq. 2).

**Figure 1 demonstrates graphically results for model optimality conditions on species management resource allocations.**

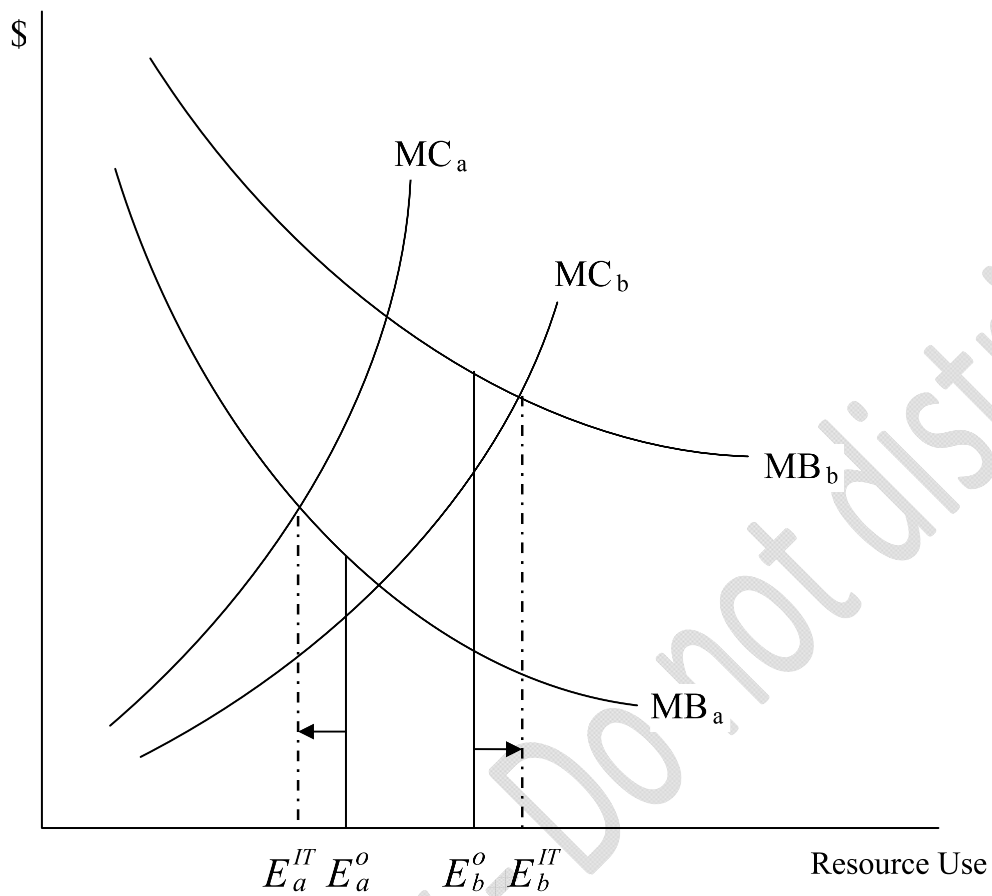


Figure 1. Effects of an induced technology (IT) on the resource allocation for managing invasive species.

**Figure 1 results tell us that:**

- When an induced technology is not considered, then management resources allocated for preventive measures would be *less than adaquate* ($E_b^o$ would be less than $E_b^{IT}$), while resources allocated for control measures would be *more than adequate* ($E_a^o$ would be greater than $E_a^{IT}$).
- However, management resources for preventive measures must be greater than those allocated for control measures after the first discovery, whether or not an induced technology is considered.
- Even so, the difference between the level of management resources allocated for preventive measures and those allocated for control measures increases when an induced technology is accounted for. That is, this difference goes from ($E_b^o - E_a^o$) to ($E_b^{IT} - E_a^{IT}$).

## Policy Relevant Comparative Dynamic Analyses

Comparative dynamic analyses identify qualitatively the potential effects of exogenous changes in policy relevant variables. We conducted comparative dynamic analyses of changes in:

- the rate of intrinsic growth (*g*) of an invasive species.
- the maximum population (*V*) of an invasive species.
- the probabilities of developing and adopting an induced technology (*MN*).
- the rate (*k*) at which control measures reduce the invasive species stock.

**Comparative Dynamic Analyses Results are as Follows**

$\lambda_1 < 0$ is the marginal contribution of the invasive species population stock to the net economic benefits of species management (shadow value).

$\lambda_2 < 0$ is the marginal contribution of the probability of discovering an invasive species to the net economic benefits of species management (shadow value).

$$\text{(1a)} \quad \frac{\partial \lambda_1}{\partial g} > 0; \qquad \text{(1b)} \quad \frac{\partial \lambda_2}{\partial g} < 0;$$

$$\text{(2a)} \quad \frac{\partial \lambda_1}{\partial k} > 0; \qquad \text{(2b)} \quad \frac{\partial \lambda_2}{\partial k} > 0;$$

$$\text{(3a)} \quad \frac{\partial \lambda_1}{\partial V} > 0; \qquad \text{(3b)} \quad \frac{\partial \lambda_2}{\partial V} > 0;$$

$$\text{(4a)} \quad \frac{\partial \lambda_1}{\partial (MN)} > 0; \qquad \text{(4b)} \quad \frac{\partial \lambda_2}{\partial (MN)} > 0;$$

- Equations (1a) and (1b) tell us that for an invasive species with higher rates of intrinsic growth, it is more economical to adopt preventive measures before the first discovery of an invasive species than to adopt control measures after the first discovery.

- Equations (2a) and (2b) tell us that as long as the removal rate of an invasive species population stock increases, by adopting chemical/mechanical control measures, then the shadow values of preventing and controlling an invasive species decline.

- Recognizing that the maximum possible population of an invasive species stock can be represented by the maximum resources available for a species infestation, equations (3a) and (3b) tell us that increases in the supply of resources available for species infestation reduce its shadow price, a straightforward relationship between quantity and its price.

- Equations (4a) and (4b) tell us that the shadow values of both preventing the arrival of an invasive pest and controlling the invasive pest after its first discovery decline (become less negative) as the probabilities of developing an induced technology and its adoption increase.

## Conclusions

When induced technology development and its adoption under uncertainty are accounted for, the allocation of management resources for controlling an invasive species is much more complex than conventional modeling tools would imply.

Applying a conventional invasive species management model would likely result in:

- Allocating less than adequate management resources for preventive measures before the first discovery of the species, but more than adequate resources for conventional control measures after first discovery.

- Not allowing management decisions to reflect potential resource savings from development of an induced technology.

Accounting for the effects of induced technology development and its adoption under uncertainty can improve upon analyses of invasive species management policies by providing decision-makers with a broader policy information base covering all three invasive species management phases.

**Use the following pictures ONLY IF SPACE ALLOWS.**

## Examples of Invasive Species that Affect U.S. Agriculture

**The Mediterranean Fruit Fly (Medfly).**

The Medfly has been recorded infesting a wide range of commercial and garden fruits, nuts and vegetables, including apple, avocado, bell pepper, citrus, melon, peach, plum and tomato. [Source: The California HungryPests Coalition at: http://www.hungrypests.com/medFly.html.

*Symptoms in non-tolerant (left) and tolerant (right) soybean infected with soybean rust.*

### Soybean Rust

Two fungal species, *Phakopsora pachyrhizi* and *P. meibomiae*, cause soybean rust and are spread primarily by windborne spores that can be transported over long distances. *P. pachyrhizi*'s rapid spread and severe damage with yield losses from 10 to 80% have been reported in Argentina, Asia, Brazil, Paraguay, South Africa, and Zimbabwe. In November, 2004, the presence of *P. pachyrhizi* was confirmed in the continental United States. [Source: http://www.ncipmc.org/alerts/soybeanrust/soybeanrust_alert_hires.pdf .]

**The Soybean Aphid**

***Soybean aphids*** (Aphis glycines Matsamura) are plump, oval and soft bodied, and usually less than 1/16" long (when mature) and pale yellow. It is a native pest of soybean in eastern Asia. It's the only aphid that forms colonies on soybean in the U.S. Soybean aphids pierce the soybean plant's "plumbing system" and suck sap (photosynthates). They cause yield loss via stunting; reduced photosynthesis; and by transmitting viral diseases, such as soybean mosaic virus, alfalfa mosaic virus and cucumber mosaic virus.