Identifying the Natural Enemy-adjusted Economic Threshold (NEET) for Dynamically Optimal Pest Management in High Tunnels[1]

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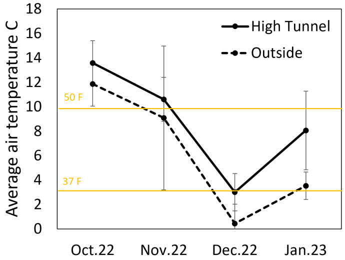
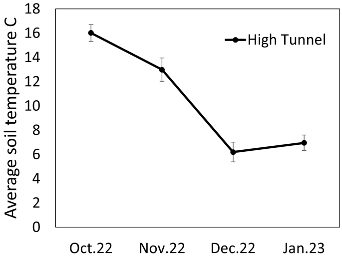
Background-High Tunnel





Background-Pest Management

- Chemical control: applying pesticides
    - The direct cost: Based on the 2023 farm sector income forecast (USDA, 2023), nationwide pesticide expenditures ($25 billion) were around 5.5% of the annual total production expenses.
    - The indirect cost: The use of pesticides can have a variety of negative agricultural, environmental, and health effects, totaling an estimated $12 billion (=$17 billion in 2023 USD terms) for the US alone (Pimental, 2009).
    - To minimize the direct cost, **economic threshold (ET)** was created. To minimize the direct cost plus the loss of ecosystem service provided by the natural enemy of the pest, **naturally enemy-adjusted economic threshold (NEET)** was created.

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- Biological control: relying on the pest's natural enemy
  - Using pesticides that are less toxic to the natural enemy (charging a price premium) or purchasing and releasing the natural enemy directly.

Background-Terminologies

- Economic injury level[a] (EIL): The smallest number of insects (amount of injury) that will cause yield losses equal to the insect management costs.
- Economic threshold[a] (ET): The pest density at which management action should be taken to prevent an increasing pest population from reaching the economic injury level.
- Natural enemy-adjusted economic threshold[b] (NEET): The pest density at which insecticide control becomes optimal in spite of the **opportunity cost** of injury to natural enemies of the target pest.

[a] *Source: Entomological Society of America "Handbok of Soybean Insect Pests" Leon G. Higley and David J. Boethel, eds.*

[b] *A new treatment decision rule came up by Zhang and Swinton (2009).*

Literature

Table 1: Comparison of Pest/Invasive Species Control Models

Study	Control target	Control variable(s)	Pesticides harm predator	Stochasticity
Harper & Zilberman (1989)	Pests	Chemical	Partially yes	No
Zhang & Swinton (2009)	Pests	Chemical	Yes	No
Grogan (2014)	Pests	Chemical & Biological	Yes	No
Marten & Moore (2011)	Invasive species	Chemical & Biological	No	Yes
This research	Pests	Chemical & Biological	Yes	Yes

- Limitations:
- Zhang & Swinton (2009): not including biological control, solving the NEET only for the first stage of a growing cycle, spraying pesticides at most once per stage, and a deterministic setting.
- Grogan (2014): all the analysis are around the steady state, and a deterministic setting.
- Marten & Moore (2011): not a NEET model.

Research questions-all regarding to the winter spinach growing in the high tunnel

- What are the optimal control strategies under different population densities of the pest and the predator? If it is optimal for farmers to adopt either chemical control or biological control, how much should they use?
- What is the natural enemy-adjusted economic threshold (NEET)?
- Are the chemical control and the biological control substitutes or complements? Will this relation change?
- How does the inclusion of stochasticity change the answers to the questions above?

Framework

- We build an infinite, continuous, stochastic dynamic optimization model.
- Three strategies: Waiting without taking any control, taking chemical control (spraying pesticides) and taking biological control (using natural enemy-friendly pesticides or releasing commercial predators).
- The source of uncertainty: the stochasticity from weather, which affects the population dynamics of the pest and predator.
- Objective: Identifying the natural enemy-adjusted economic threshold (NEET) for spraying pesticide and solving the optimal strategies under different values of population densities.

Model - Equations of motions

Stochastic population dynamics (without any control)

(S and P: the pest and the predator, respectively.)

$$dS_t = \left[\alpha S_t(1 - \frac{S_t}{K}) - \beta S_t \cdot P_t\right] dt + \sigma_S S_t dW_t^S$$

$$dP_t = [\gamma\beta P_t \cdot S_t - \tau P_t]\, dt + \sigma_P P_t dW_t^P$$

where

$$E[dW^S dW^P] = \sigma_{SP} dt$$

- For the population dynamics of the pest, we assume a logistic growth part, and a predation part that decreases the pest density.
- For the population dynamics of the predator, we assume a predation part that contributes to its growth, and a death & run off part.
- We use two standardized brownian motions (W_t^S and W_t^P) to account for the stochasticity. They might be correlated (σ_{SP}).

Model - Equations of motions

Stochastic population dynamics (with control strategies)

(S and P: the pest and the predator, respectively. x and A: spraying pesticides and releasing predators/replacing with better pesticides, respectively.)

$$dS_t = \left[\alpha S_t(1 - \frac{S_t}{K}) - \beta S_t \cdot P_t - k_S \cdot x_t \cdot S_t\right] dt + \sigma_S S_t dW_t^S$$

$$dP_t = [\gamma\eta P_t \cdot S_t - \tau P_t - k_P \cdot x_t \cdot P_t + A_t \cdot P_t]\, dt + \sigma_P P_t dW_t^P$$

where

$$E[dW^S dW^P] = \sigma_{SP} dt$$

- Chemical: Farmers can freely choose the amount of pesticides to spray (x_t). Each spraying decreases a fixed rate (k_S) of the current pest density (S_t) and a fixed rate (k_P) of the current predator density (P_t).
- Biological: Farmers can freely choose the rate (A_t) of the current predator density (P_t) to augment. The augmentation can be achieved by either using predator-friendly pesticide or releasing predators.

Model - Cost functions

The costs of control strategies

Chemical:

$$C(x_t) = \theta \cdot x_t$$

Biological:

$$C(A_t) = \omega \cdot A_t$$

- Following Grogan (2014), we assume constant marginal costs for both chemical control and biological control.

Stochastic dynamic optimization model (complete)

Objective: minimize the expected discounted flow of damages plus any cost associated with applying control strategies

$$\min_{x_t, A_t} E\left[\int_0^{\infty} e^{-\rho t}\left(D\frac{S_t}{K} + \theta x_t + \omega A_t\right)\right] dt$$

$$V(S, P) = \max_{x_t, A_t} E\left[-\int_0^{\infty} e^{-\rho t}\left(D\frac{S_t}{K} + \theta x_t + \omega A_t\right)\right] dt$$

Stochastic population dynamics (Equations of motions)

(S and P: the pest and the predator, respectively.)

$$dS_t = \left[\alpha S_t\left(1 - \frac{S_t}{K}\right) - \beta S_t \cdot P_t - k_S \cdot x_t \cdot S_t\right] dt + \sigma_S S_t dW_t^S$$

$$dP_t = \left[\gamma\eta P_t \cdot S_t - \tau P_t - k_P \cdot x_t \cdot P_t + A_t \cdot P_t\right] dt + \sigma_P P_t dW_t^P$$

where

$$E[dW^S dW^P] = \sigma_{SP} dt$$

Stochastic dynamic optimization model - Solution

The optimality conditions

$$\rho V(S_t, P_t) \geq -D\frac{S_t}{K} + \frac{dE(V(S,P))}{dt} \tag{1}$$

$$\theta + V_P \cdot k_P \cdot P_t \geq -V_S \cdot k_S \cdot S_t \tag{2}$$

$$\omega \geq V_P \cdot P_t \tag{3}$$

where

$$\begin{aligned}\frac{dE(V(S,P))}{dt} = &\left[\alpha S_t(1-\frac{S_t}{K}) - \beta S_t \cdot P_t\right] V_S + \left[\gamma\eta P_t \cdot S_t - \tau P_t\right] V_P \\ &+ \frac{1}{2}\sigma_S^2 S_t^2 V_{SS} + \frac{1}{2}\sigma_P^2 P_t^2 V_{PP} + \sigma_{SP}\sigma_S\sigma_P S_t \cdot P_t V_{SP}\end{aligned} \tag{4}$$

- The first condition states that the rate of return obtainable by investing V dollars must be at least as great as the total rate of return generated by the assets, which is the sum of the current return flow and the expected rate of capital appreciation.
- The following two conditions state that the marginal costs of control strategies must be at least as great as their corresponding marginal benefits.

Parametization

Parameter	Definition	Value	Units
D	Damage scale parameter	1	
K	Carrying capacity of pest	100	Pests/plant
α	Intrinsic growth rate of pest	0.15	
β	Predation rate	0.02	Pests/predator
γ	Intrinsic growth rate of predator	0.07	
τ	Death & Run off rate of predators	0.25	
θ	Marginal cost parameter for chemical control	0.5	\$/plant
ω	Marginal cost parameter for biological control	0.06	\$/plant
k_S	Killing efficiency of pesticide on the pest	0.8	
k_P	Killing efficiency of pesticide on predators	0.8	
σ_i	Volatility parameters	0.25	
σ_{XP}	Brownian motion correlation	0.5	

Main result - Optimal control strategies under baseline

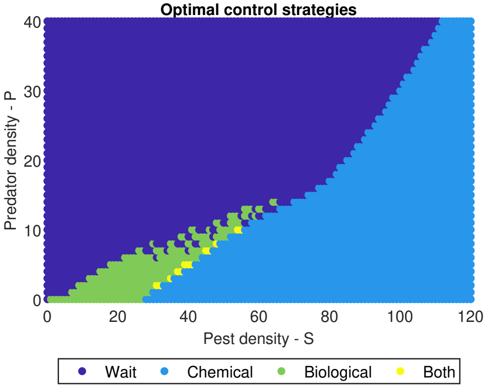
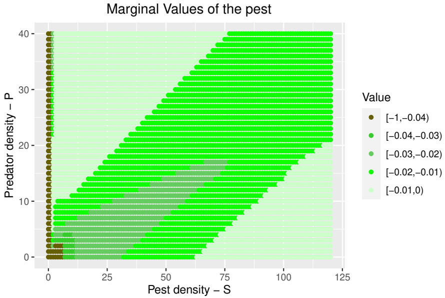
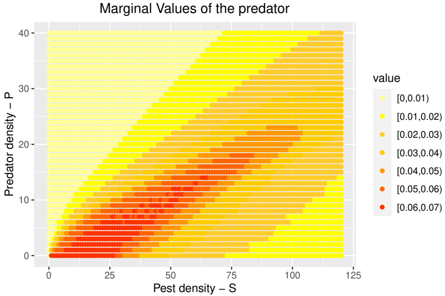


Figure: Simulated optimal control strategies under the baseline

Main result - Estimated values of GPA and LBB


Marginal Values of the pest


Marginal Values of the predator

Optimal control strategies under two other scenarios

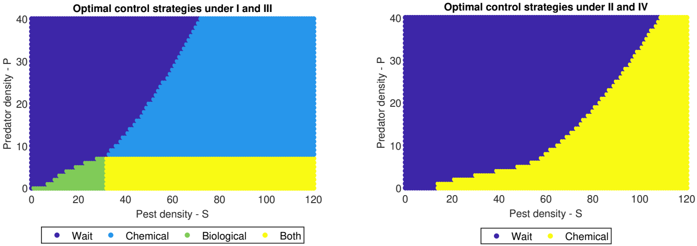


Figure: Simulated optimal control strategies under different scenarios. I: the mortality rate of the pesticide on LBB is k_P; II: the pesticide doesn't harm LBB; III: the farmer is able to purchase and release LBB; and IV: the farmer is unable to purchase and release LBB.

Expected economic gains of the baseline compared to the other two scenarios

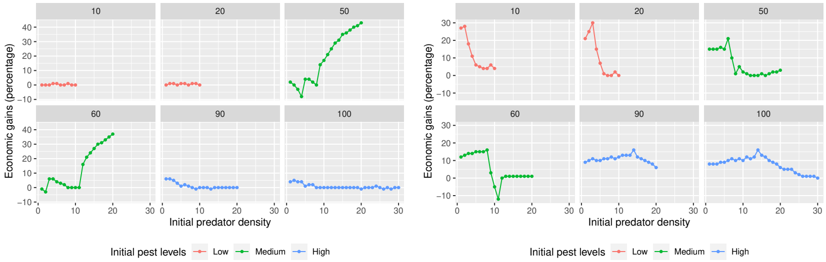


Figure: Expected cumulative economic gains (avoided damages and saved control costs) in the percentage in 50 years of our baseline compared to scenarios (a) and (b). [Top panel: Being able to account for the detrimental effects of the pesticides on LBB. Bottom panel: Being able to purchase and release LBB.][10, 20, 50, 60, 90, and 100 represent the initial pest density.]

Expected economic gains of the baseline compared to the other two scenarios

Table: Cumulative economic gains under different scenarios.

Scenario	Optimal control in Fig.3	Optimal control in Fig.1	Gains
a	Chemical and biological	Chemical only	0-10%
a	Chemical	Biological only or waiting without control	15-45%
b	Waiting without control	Biological	10-35%
b	Chemical	Chemical	0-20%

Notes: Scenario a) represents accounting for the detrimental effect of the pesticide on LBB; scenario b) represents being able to purchase and release LBB. The comparison of the optimal control strategy is in terms of the same state vector in Fig.1 and Fig.3.

Conclusion & Next steps

- The NEET increases as the cost of chemical control increases.
- Both chemical and biological control can become optimal under certain parameter values and population densities of the pest and the predator.
- Throughout a 50-year simulation, we find that accounting for the detrimental impact of pesticides on LBB increases economic gains ranging from 0-45%, and being able to release LBB leads to economic gains ranging from 0-35%.
- Next: Improve the codes to get more consistent results. Improve the parameter values and the bioeconomic model to better account for the reality in high tunnels.

The End & Thank You!

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