A Bioeconomic Model of Invasive Species Control: The Case of Spotted Wing Drosophila in the United States

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Selected Poster prepared for presentation at the 2015 Agricultural & Applied Economics Association and Western Agricultural Economics Association Joint Annual Meeting, San Francisco, CA, July 26-28

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Introduction

Background

Spotted Wing Drosophila (SWD) (Figure 1), native to eastern Asia, is an insect pest presently having a devastating effect on high value, high nutrient berry and stone fruit such as blueberries, blackberries, raspberries, strawberries, and cherries in much of the United States.

Figure 1 Male SWD (2–3 mm)

Damages

SWD is causing significant damage, more than any other vinegar (fruit) fly; it attacks **healthy ripening** fruit while other flies only lay eggs on past ripe or rotting fruit.

- The female penetrate the fruit skin with her ovipositor and lay eggs just under the skin, creating a small puncture, or "sting," on the fruit surface (Figure 2)
- Most damage occurs at the next stage, when eggs hatch and maggots develop and feed inside the fruit, causing the fruit skin wrinkle, the flesh to turn brown and soft, making the fruit susceptible to decay and rots (Figure 3)

Figure 2 Small "stings" on this cherry are SWD oviposition scars

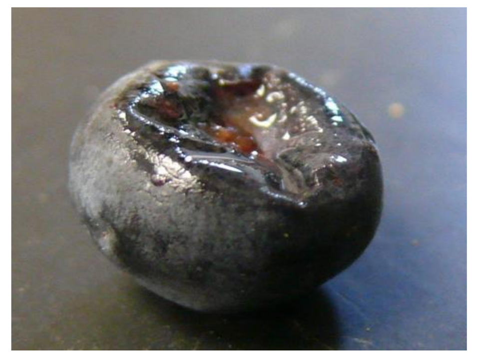


Figure 3 SWD damage to blueberry showing soft spot

Economic Costs

U.S. crop losses due to SWD are estimated at $718 million annually, and increases in labor and input costs associated with SWD management are estimated to range from $129 to 172 million annually. High crop losses are due to:

- **Zero tolerance** for SWD infested fruit for either fresh market or whole frozen products
- Detection of even a single larva in a shipment can result in **complete rejection**

Management

- To meet the zero tolerance threshold, the main to treat for SWD is calendar-based broad-spectrum insecticide sprays.
- To better control SWD, it is very important to monitor for SWD activity. A common way to do this is using traps (Figure 4).

Figure 4 Example of a trap to monitor SWD

Objectives

Although research has been conducted to study the pathogens of SWD, there is lack of economic analyses to identify optimal SWD control strategies.

The **objective** here is to develop a field-level bioeconomic model and apply it to the case of a blueberry farmer making decisions to control for SWD infestation and its subsequent damages.

The bioeconomic model incorporates a Partially Observable Markov Decision Process (**POMDP**) framework to take into account the specific characteristics of SWD monitoring activity, given that:

- SWD reproduces very quickly (Figure 5). To take appropriate actions to control SWD, it is important we employ monitoring efforts to know **the population size**.

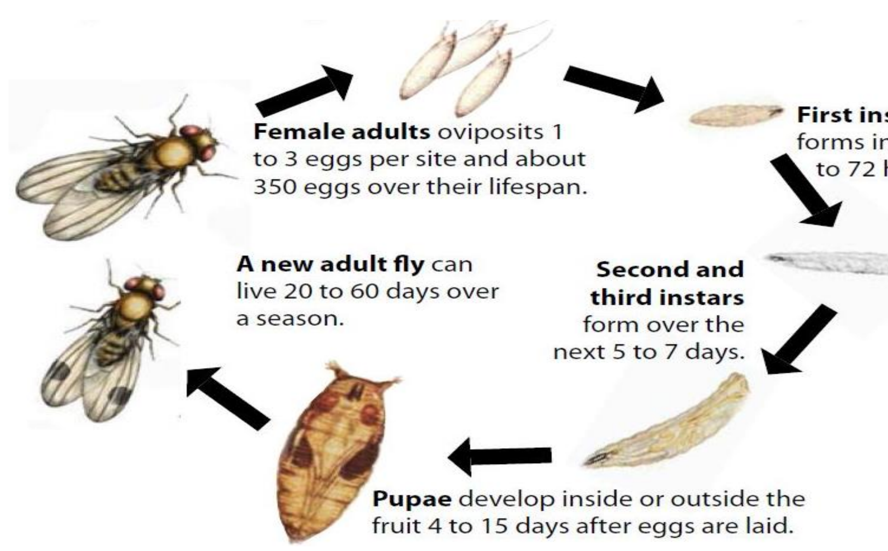


Figure 5 SWD Life Cycle

- Monitoring is **costly**. For example, the farmer needs to train workers to be able to identify SWD, and the monitoring process is time-consuming and costly.
- **Imperfect observation.** In reality, it is difficult to perfectly monitor SWD population density. (Costello and Solow 2003; Haight and Polasky 2010).

Literature

Spotted Wing Drosophila

Since the detection of SWD in the U.S., significant research and efforts have been undertaken to study the pathogens (Cini et al. 2012; Pfeiffer et al. 2012; Burrack et al 2013)

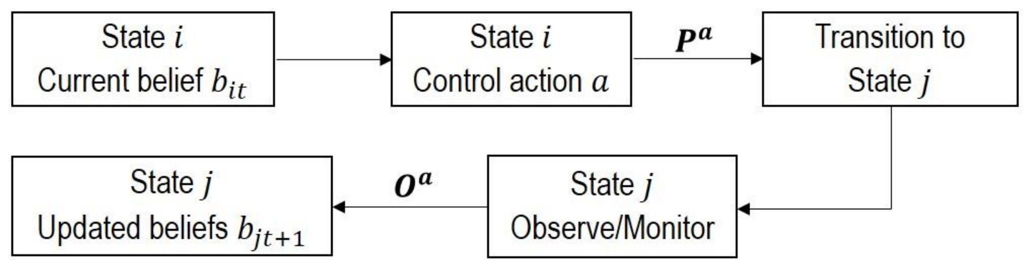
Less emphasis on economic impact and optimal control of SWD (Bolda et al. 2010; Goodhue et al. 2011; Farnsworth 2013)

POMDP

Researchers have used the POMDP framework to address partial observability in invasive species control problem (Regan et al. 2006, 2011; Moore 2008; Haight and Polasky 2010; Williams 2011; Fackler and Haight 2014)

Model

SWD infestation and control process:



Manager's problem: at each period $t = 1, \dots, T-1$, given the set of beliefs about the infestation states, choose a sequence of actions to control for SWD that minimizes the expected total costs. Mathematically:

$$V_t(b_{1t}, \dots, b_{nt}) = \min_{a \in A} \left[\sum_{i=1}^{n} b_{it}(d_i^a + m_i^a) + \delta \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{\theta=1}^{n} b_{it} p_{ij}^a o_{j\theta}^a V_{t+1}\big((b_{1t+1}|\theta, a), \dots, (b_{nt+1}|\theta, a)\big) \right]$$

with terminal condition:

$$V_t(b_{1T}, \dots, b_{nT}) = \min_{a \in A} \left[\sum_{i=1}^{n} b_{iT}(d_i^a + m_i^a) \right]$$

- $t = 1, 2, \dots, T$: time period index
- $i = 1, 2, \dots, n$: infestation states index
- b_{it}: manager's belief (probability) of being in state s at the start of period t. $0 \le b_{it} \le 1, \sum_i b_{it} = 1$.
- a: possible control action from the set A, based on current belief probabilities.
- $\boldsymbol{P^a}$: a state-transition matrix where each element p_{ij}^a equals the conditional probability of transitioning from state i in period t to state j in period $t+1$ after taking action a.
- $\theta = 1, \dots, n$: index for states that the manager may observe in period $t+1$.
- $\boldsymbol{O^a}$: an observation matrix, where each element $o_{j\theta}^a$ equals the conditional probability of observing an infestation state θ given an actual infestation state j in period $t+1$ and that the decision maker took action a in period t. $0 \le o_{j\theta}^a \le 1, \sum_\theta o_{j\theta}^a = 1$.
- Belief update by Bayes rule:

$$b_{jt+1}|a, \theta = \frac{o_{j\theta}^a \sum_{i=1}^n p_{ij}^a b_{it}}{\sum_{k=1}^n o_{k\theta}^a \sum_{k=1}^n p_{ik}^a b_{it}}$$

- d_i^a: damage costs in state i associated to management action a
- m_i^a: costs of action a at the start of state i

Calibration Parameters (One-acre blueberry farm):

- *T*=15; Timeline is a 15-week horizon (one crop season, from fruit coloring to harvest) and time interval is one week.
- 3 infestation states: no infestation state ($i = 1$), moderate infestation state ($i = 2$), and high infestation state ($i = 3$).
- 4 possible actions: no action ($a = 1$), only monitor ($a = 2$), only treat (pesticide application) ($a = 3$), monitor and treat ($a = 4$).
- δ =1 (discount rate)
- $d_i^1 = d_i^2 = d_i^3 = d_i^4 = [0 \quad 59 \quad 118]'$: assume damage cost depends on the level of infestation but not the action taken.
- Monitoring costs are $5.15 and pesticide application costs are $31.5: $m_i^1 = 0, m_i^2 = 5.15, m_i^3 = 31.5, m_i^4 = 36.65$ for all i.

Results and Discussion

The manager's problem is solved using MDPSolve in MATLAB (Fackler and Haight 2014). The optimal solution is shown in Figure 6, which displays the optimal action as a function of the current manager's belief vector b. Figure 7 displays the optimized total cost (the value of the objective function) under different belief states.

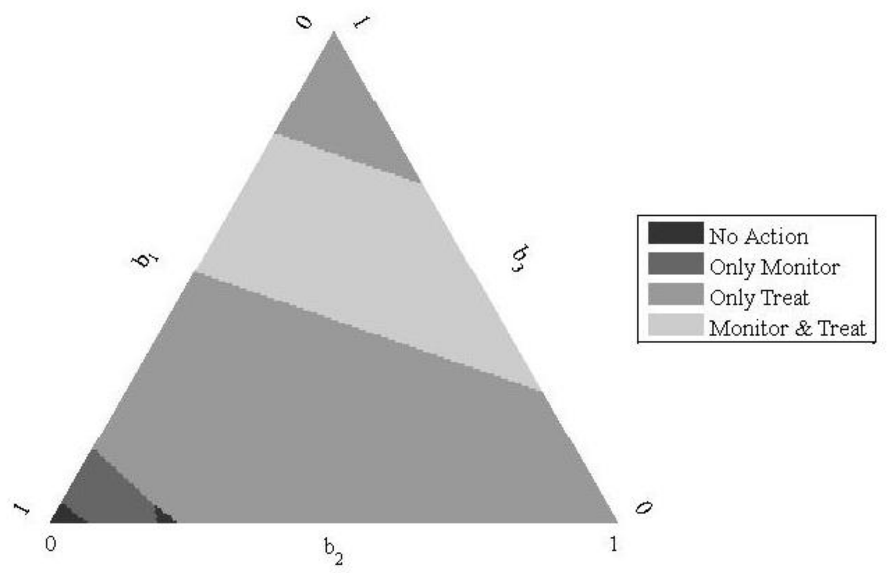


Figure 6. Optimal SWD treatment and monitoring decisions as a function of manager's belief state

Figure 6 show tenary plots in which each corner represents certainty in one the three alternative states with the lower left corner representing certainty in state 1 (no infestation), the lower right certainty in state 2 (moderate infestation) and the upper corner in state 3 (high infestation). Certainty in a given alternative diminishes as one moves toward the boundary opposite (diagonally to the right for state 1, diagonally left for state 2 and down for state 3) of the certainly corner.

Based on the parameters of the model:

- It is optimal to take **no action** or **only monitoring** when it is fairly certain that the infestation is low (lower left corner).
- **Treatment** is optimal either when the manager believes the infestation is high (upper corner) or when s/he believes the infestation is moderate or relatively low (lower middle region)
- It is optimal to both **monitor and treat** when the manger believe the infestation is moderate or relatively high (upper middle region)

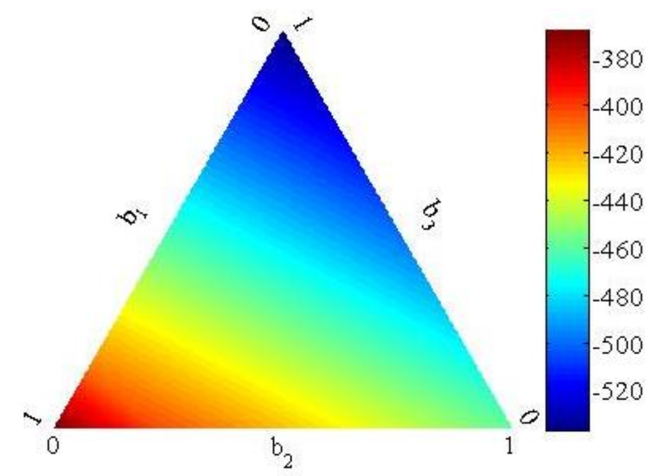


Figure 7. Optimized total cost as a function of manager's belief state

Conclusion

- In this paper, we develop a bioeconomic model for decision-makers to optimally treating and monitoring invasive species such as SWD, taking into account the imperfect monitoring problem.
- The application of these bioeconomic techniques to SWD control will provide a useful framework for addressing the economics underlying other invasive species affecting U.S.