Catch Me if You Can: An Optimal Pest Survey Strategy to Delimit Biological Invasions

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- We mathematically formulate and solve the problem of allocating survey effort to delimit the invasion frontier under uncertainty, with general applications to delimiting surveys of biological invasions

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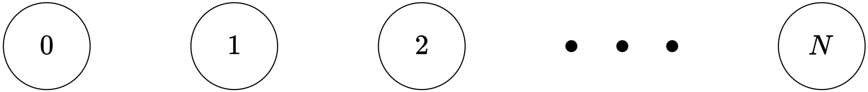

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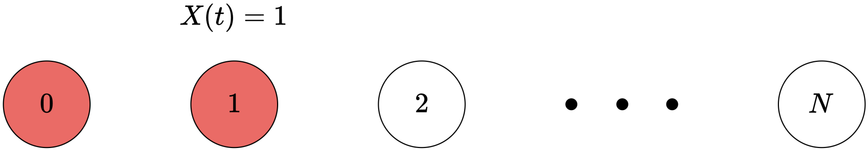

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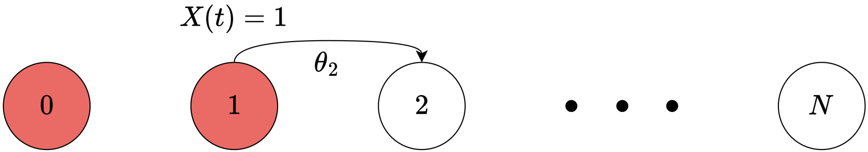

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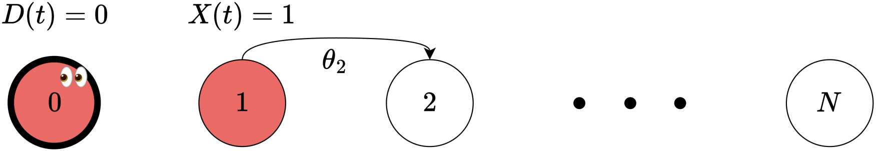

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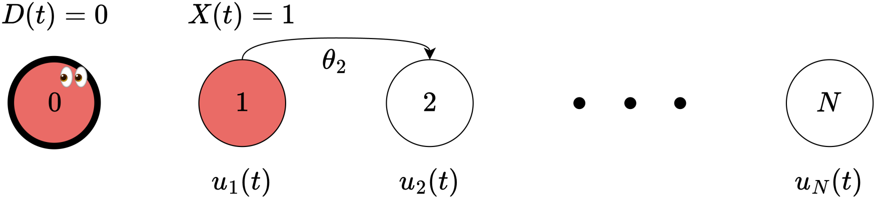

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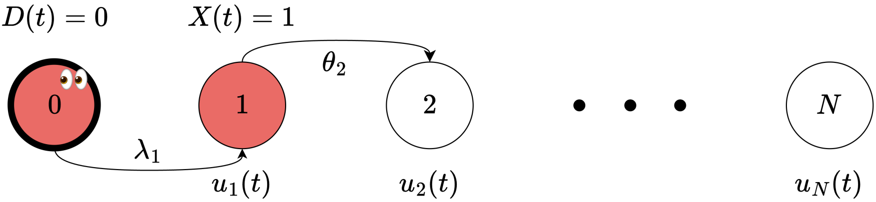

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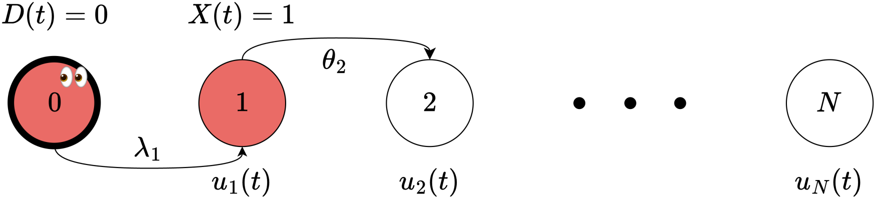

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- Detections occur with Poisson rate $\lambda_i u_i(t)$ if the region is infested
- Objective: minimize the area of undetected infestation, $\mathbb{E}_\pi \left[\int_{t=0}^{T} X(t) - D(t) \mathrm{d}t \right]$

POMDP Approach

Standard approach:

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Computing (even approximately) the optimal policy is infeasible

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Question: How do we specify the cost-to-go of a detection conditional on the detection time, region, and belief?

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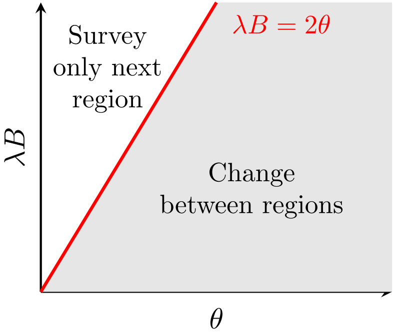
- Impact of budget: as budget increases, the optimal suvery policy concentrates on the *closest* region to the current furthest detection.



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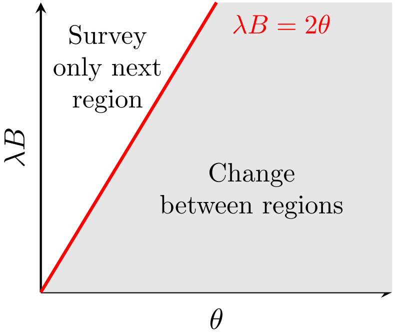
Theoretical insights into the optimal survey policy:

- Impact of budget: as budget increases, the optimal suvery policy concentrates on the *closest* region to the current furthest detection.
- Surveying near vs. far regions: if we believe the frontier is close, we should survey close.



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- We estimate *cost-to-go* of a detection at site i as a linear function of the distance to the current furthest detection point.

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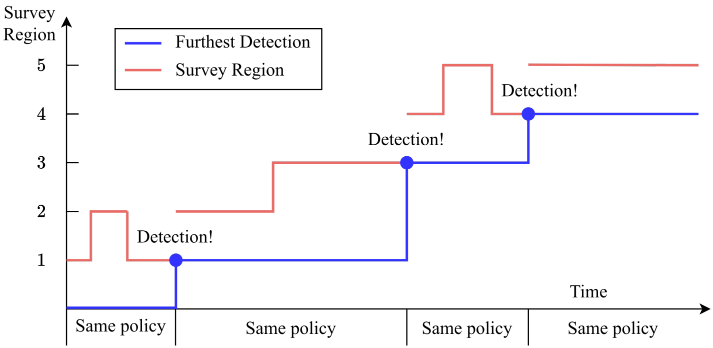
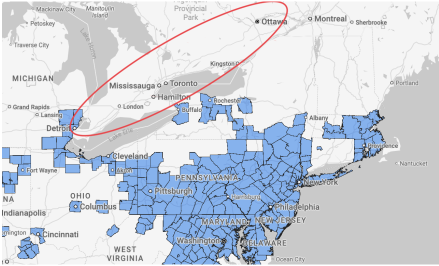
- For an entire invasion, after each detection we compute the approximate survey policy and apply it until the next detection.



Case Study: Spotted Lanternfly

(a) The spotted lanternfly



(b) Infestation region as of July 2025[1]

[1]Image credit Cornell Integrated Pest Management

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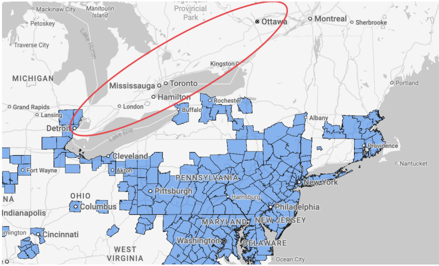
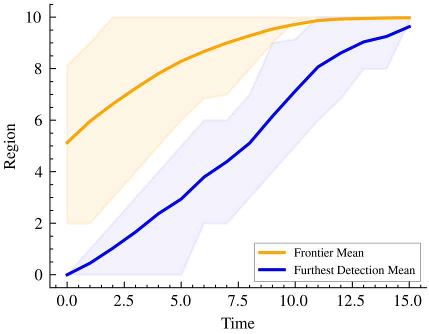


(b) Infestation region as of July 2025[1]

- $N = 10$ to divide Ontario into 50km regions; $T = 15$ years
- Uniform prior π on infestation frontier, $\pi_i = \mathbb{P}(X(0) = i) = \frac{1}{N}$
- From historical data, spread rate $\theta = 0.8$
- Visual survey detection rate is $\lambda = 0.36$
- Budget level B is the total number of surveys available

[1] Image credit Cornell Integrated Pest Management

Results (Catch Me If You Can!)



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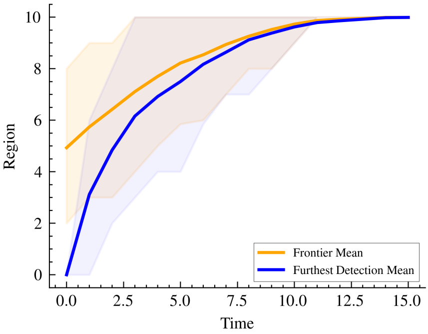
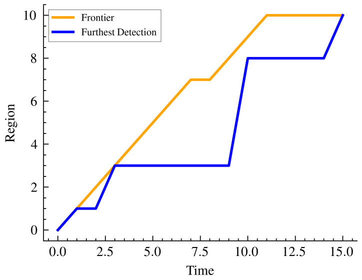


(b) Budget = 50

Figure: Comparison of the frontier and furthest detection (averaged over 100 simulated invasions). Shaded area represents the 15/85th percentile runs.

Single Run Results



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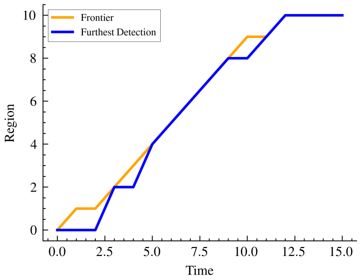

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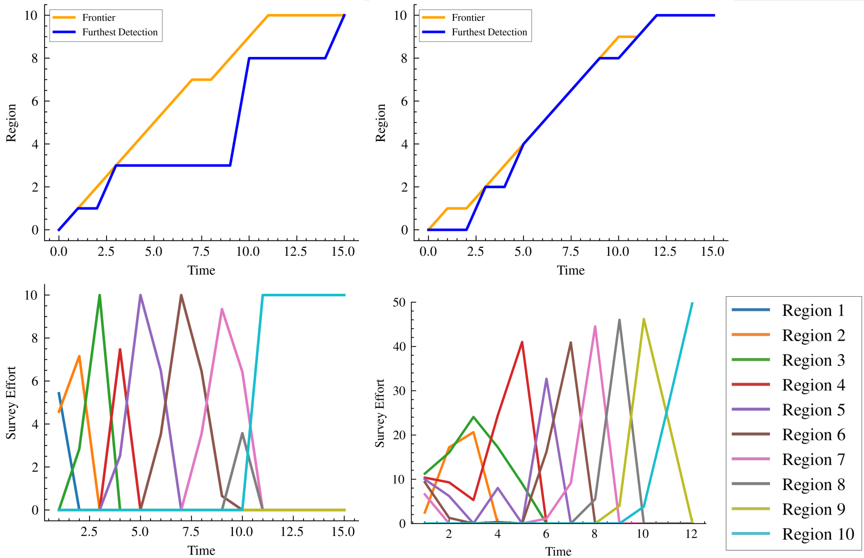

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- Our model is applicable to a variety of biological invasions and is simple in the input parameters
- Estimating the *cost-to-go* of detection allows the intractable POMDP to be solved efficiently as an optimal control problem
- The resulting optimal control problem can be analytically studied, leading to counterintuitive managerial insights