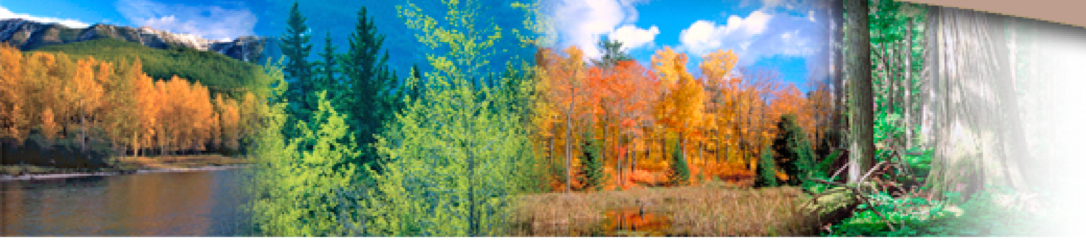

NATURAL RESOURCES CANADA - INVENTIVE BY NATURE

OPTIMAL STRATEGIES IN SURVEILLANCE PROGRAMS FOR INVASIVE PESTS: DETECT EARLY OR DELIMIT?

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Early detection of novel invasive pests

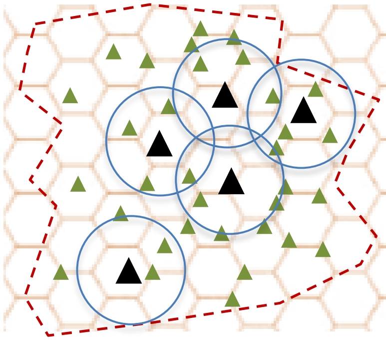
Questions to consider:

- What is the optimal strategy in early pest detection?
- What is the appropriate detection success metric?
- How does an early detection strategy differ from other survey types?
- How may a decision-maker’s aversion to risk change the survey strategy?

This study:

- Proposes an early detection model that minimizes expected **time to first detection**
- Compares early detection and delimiting survey strategies
- Compares strategies that minimize the **expected** vs. **expected worst** outcomes
- Applies the approach to ALB detection surveys in Greater Toronto Area, ON

Early detection vs. delimiting surveys



- ▲ Trees that are likely infested
- ▲ Uninfested trees
- - - Managed area
- ⬡ Potential survey sites
- ◯ Safety zone around the infested trees

Early detection survey :

- Aims to find first signs of infestation in shortest time
- Implemented at low densities
- Like a fire alarm system -
  first detection triggers regulatory response

Delimiting survey:

- Aims to uncover full spatial extent of invasion
- Continues regardless of the number of detections

Key assumptions:

- Depict the uncertain pest entries with stochastic scenarios
- When detection is successful, all infested + healthy trees in a safety radius are removed
- When detection fails, the pest continues to spread until it is detected by public
- The number of trees to remove at the time of detection defines the damage value

Conceptual problem formulation

Delimiting survey problem 1:

Damage if detected | Damage if not detected | Damage if not surveyed

$$\min \frac{1}{S}\sum_{s=1}^{S}\sum_{j=1}^{J}\left([p_{js}d_{1js} + (1-p_{js})d_{0js}]x_j + d_{0js}(1-x_j)\right)$$

- **Minimize the expected damage to host over area *J* in *S* invasion scenarios**

s.t.:

$$\sum_{j=1}^{J}(c_j\ x_j) \le B$$

- **Total survey cost is limited by budget**

d_{1js}, d_{0js} – damages when detection is successful and when it fails (or the site is not surveyed)

p_{js} – probability of detecting one or more infested trees at a site *j* in a scenario *s*

Early detection survey problem 2:

Time to 1st detection

$$\min \frac{1}{S}\sum_{s=1}^{S}\sum_{j=1}^{J}(R_{js}t_{js})$$

- **Minimize expected time to 1st detection, t_{js} in area *J* in *S* invasion scenarios**

s.t.:

$$\sum_{j=1}^{J}(c_j\ x_j) \le B$$

- **Total survey cost is limited by budget**

$$R_{js} \le x_j \quad \forall\ s \in S,\ j \in J$$

- **Detections occur at the sites that are surveyed**

$$\sum_{j=1}^{J} R_{js} = 1 \quad \forall\ s \in S$$

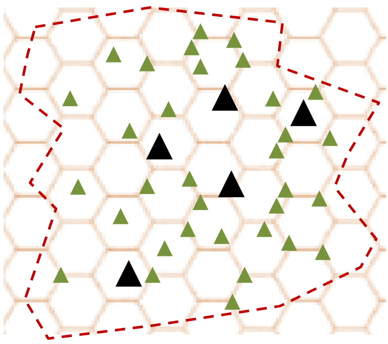
- **Only one site (with the shortest detection time) is credited with the detection in area *J* in scenario *s***

$$R_{js} \in [0;1] \quad \forall\ s \in S,\ j \in J$$

$$x_j \in \{0,1\} \quad \forall\ j \in J$$

- **Bounds on survey selection and first detection variables**

Time to first detection



- ▲ Trees that are likely infested
- ▲ Uninfested trees
- Managed area
- Potential survey sites

Inspect trees, $k = 1,\ldots,K$ at a site j in a scenario s …

The probability that an inspected tree is infested:	$\theta_{js\,k}$
Time to inspect the k^{th} tree in a sample K_m	$v_{j\,k}$
The detection probability after inspecting a tree:	$\gamma_{js\,k}$
Time when the infestation is detected by public:	T ($T = 1000$)

The probability of detecting infestation in a sample of K trees:

$$p_{js} = 1 - \prod_{k=1}^{K}(1-\theta_{js_k}\gamma_{js_k})$$

Expected time to first detection :

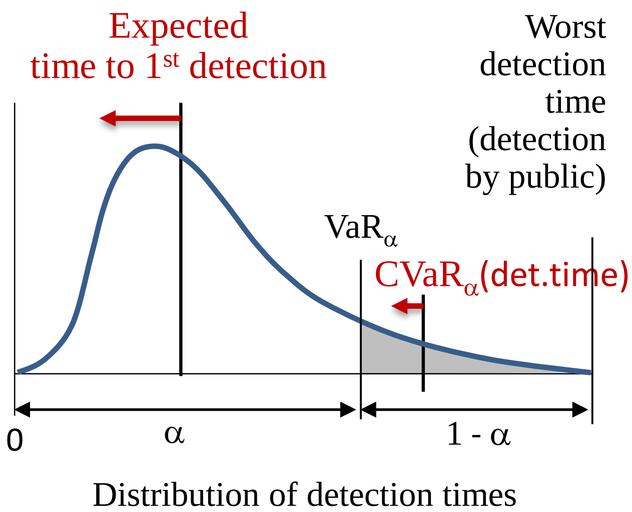
$$t_{js} = \sum_{k=1}^{K}\left[\left(\sum_{n=1}^{k} v_{j_n}\right)\theta_{js_k}\gamma_{js_k}\prod_{n=1}^{k-1}(1-\theta_{js_n}\gamma_{js_n})\right] + T\prod_{k=1}^{K}(1-\theta_{js_k}\gamma_{js_k})$$

Time until first detection is made in a sample of K trees

Portion of detection time that exceeds time required to sample K trees

Sub-index n denotes individual trees that are inspected in sequence from 1st to k^{th} tree in a sample of K trees at a site j in a scenario s

Minimizing the expected outcome vs. worst outcome



Minimizing expected detection time does not guarantee successful detections in worst cases –

In this case, worst detection times need to be minimized

Conditional Value-at-Risk (CVaR)*

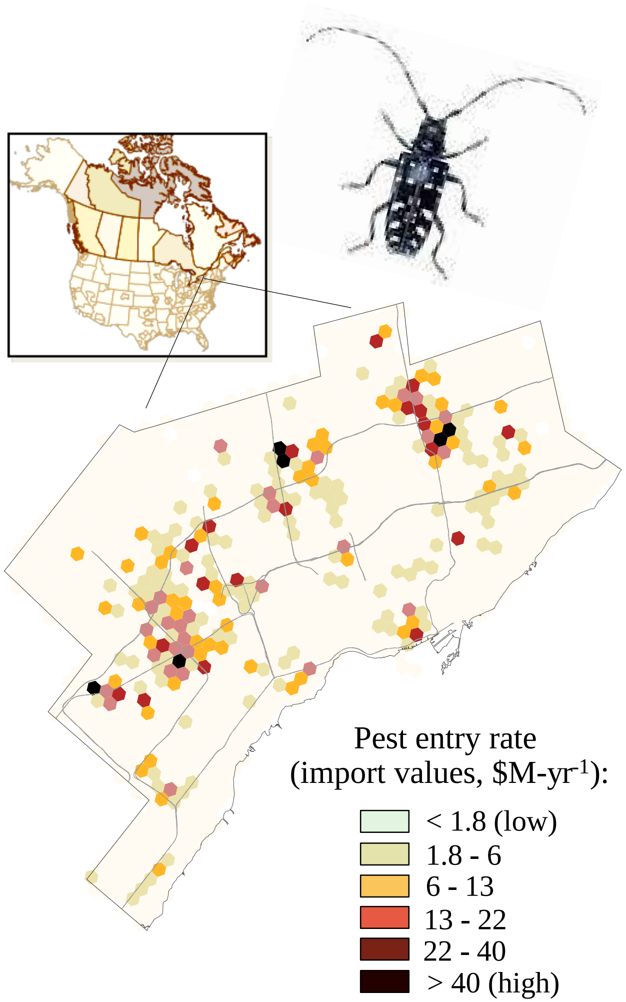
- Enable controlling worst detection times
- For a confidence level α, $CVaR_{\alpha}$ is the expected value of the distribution over $(1 - \alpha) \times 100\%$ of worst scenarios
- Minimizing CVaR controls the outcomes in worst cases
- CVaR can be incorporated into an optimization framework if the objective is linear with respect to decision variables

Risk-averse survey strategy in problems 1 and 2 :

Delimiting survey problem 1 - Minimize expected worst damage : **$\min[CVaR_{\alpha}(\text{damage})]$**
Early detection problem 2 - Minimize expected worst time to 1st detection :
$\min[CVaR_{\alpha}(\text{time to } 1^{st} \text{ detection})]$

* Acerbi and Tasche 2002; Rockafellar and Uryasev 2000, 2002

Case study: Finding optimal strategies for early detection of ALB in Canada



Asian longhorned beetle (ALB)

Major pest of maple (*Acer* spp.), birch (*Betula* spp.), poplars (*Populus* spp.) and willows (*Salix* spp.); one of the most harmful pests in North America

ALB's biological spread is slow (<300 m/yr.).* Known introductions are attributed to imports from China, Hong Kong and Korea

Tree removal is the only viable eradication method

Early detection surveys aim to find the pest in shortest possible time with minimum damage to host resource

Information about the future pest entries is **uncertain**

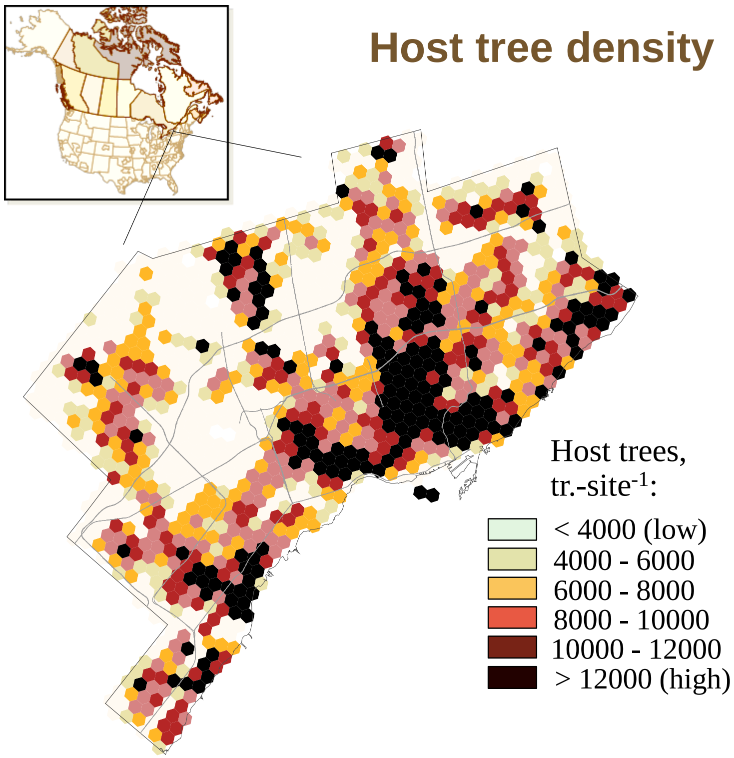
Two optimal survey strategies:

- **Detect early**: Minimizes expected time to **first detection**
- **Delimit**: Minimizes the expected damage to host in the managed area

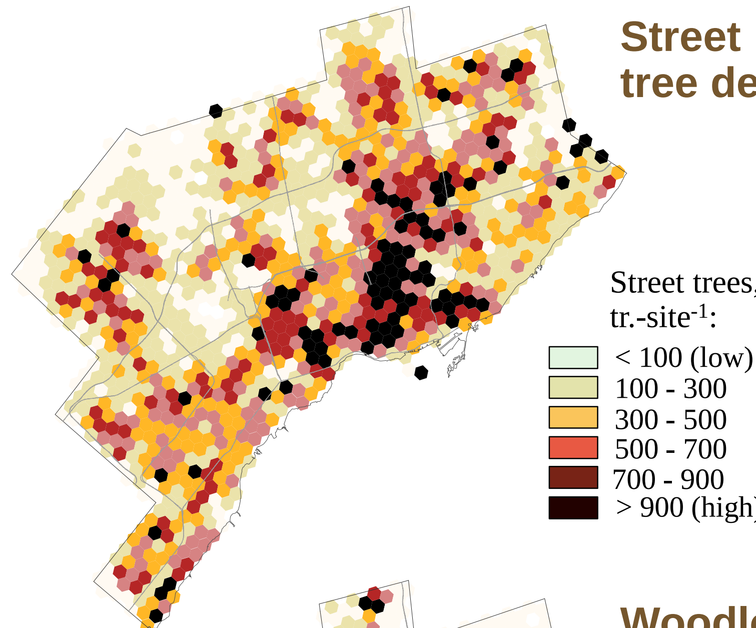
* Favaro et al. 2015; Trotter and Hull-Sanders 2015

Susceptible host resource

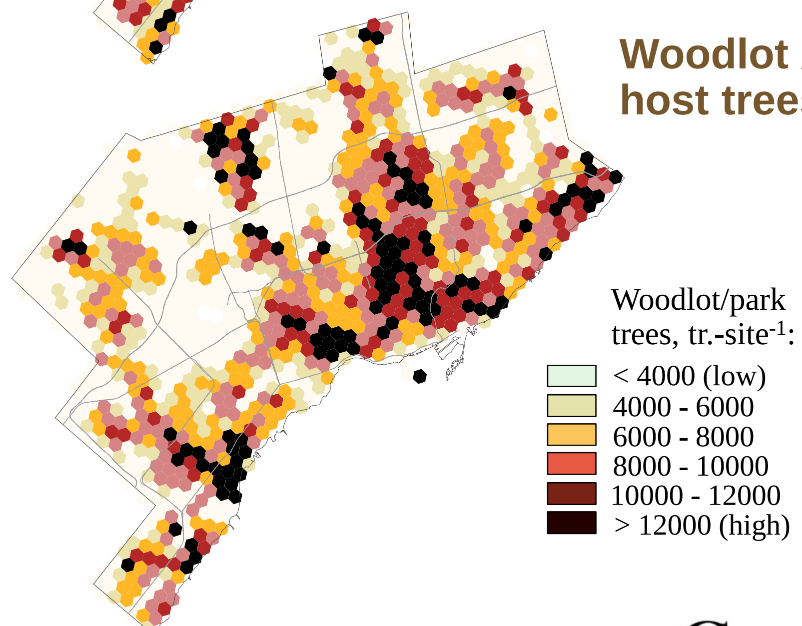
Host tree density



Street host tree density



Woodlot / park host trees



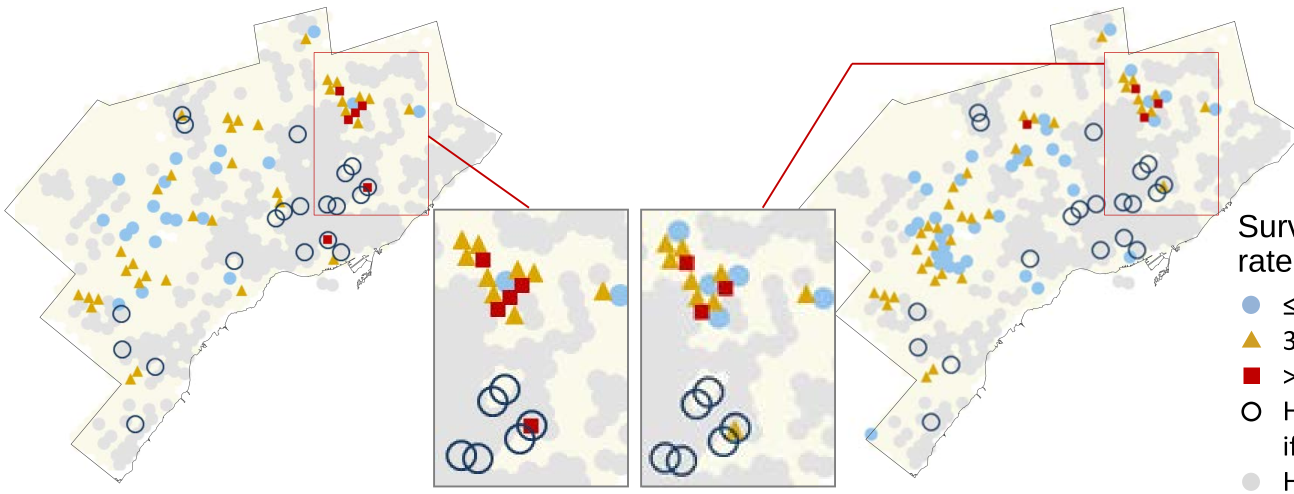
Search times and detection rates:

	Street trees	Backyard trees	Woodlot trees
Detection rate	0.7	0.7	0.4
Inspection time	1x	2.5x	6x
Invasion likelihood	5.6x	5.9x	1x

Optimal survey strategies

Delimiting survey problem 1:
Minimize expected damage

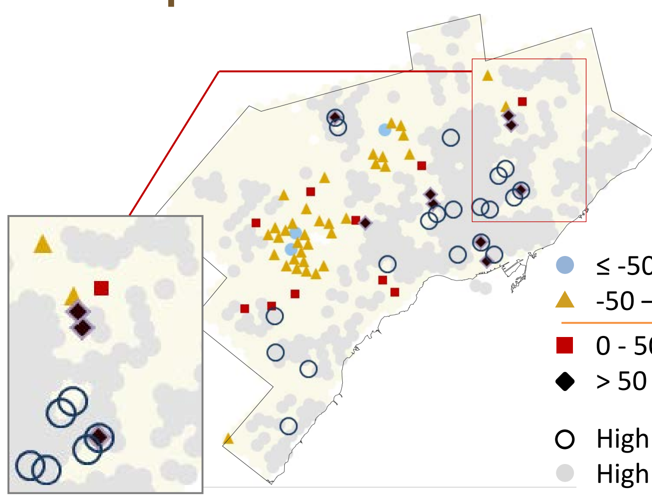
Early detection survey problem 2:
Minimize expected time to 1st detection



Budget = $30k

Survey inspection rate, trees per site
- ≤30
- 30-100
- >100
- High host damage if detection fails
- High host density

Difference between problem 1 and 2 solutions



- ≤ -50
- -50 – 0

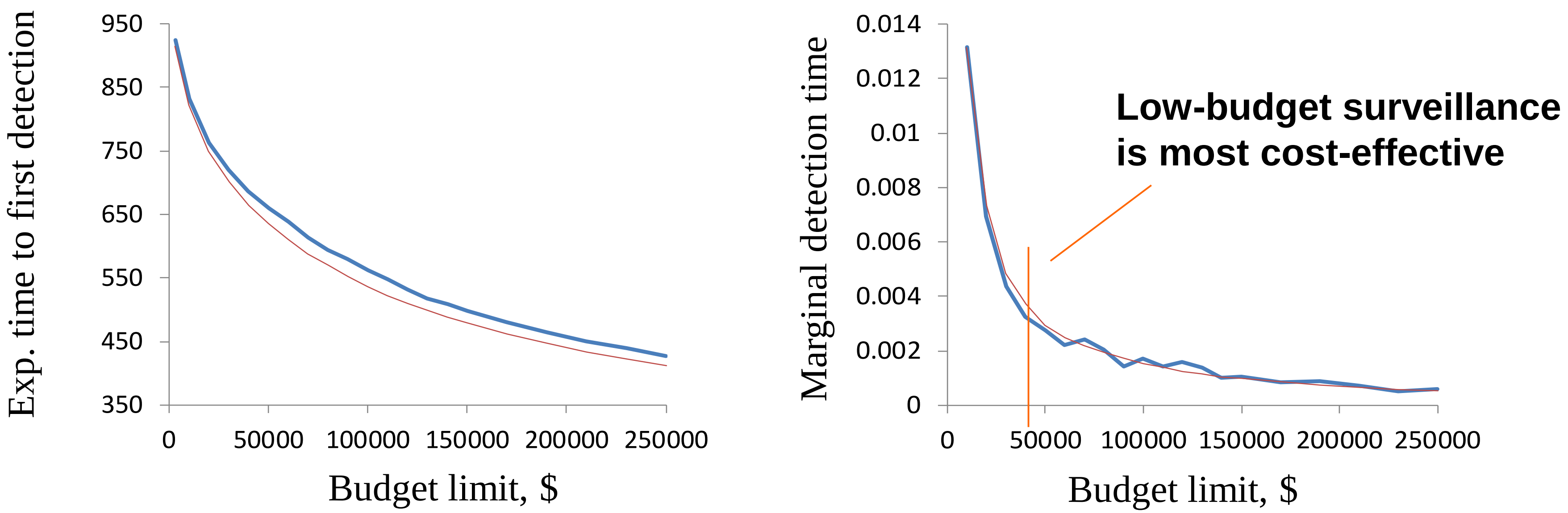
Problem 2 solution surveys more sites

- 0 - 50
- > 50

Problem 1 solution surveys more sites

- High damage
- High host density

Cost-effectiveness of the survey efforts



Problem 1: delimiting survey
Problem 2: early detection survey

Sensitivity analysis

Problem 1 – min [exp. Damage]:
Response of the expected damage value to a +/-20% parameter change

Budget level	N (street host trees)	N (backyard host trees)	N(all host trees)	Detection probability	Pest entry likelihood	Survey cost	Damage when detected	Damage if not detected	Spatial smoothing of P(entry)	Square root transform of P(entry)
Sensitivity of the expected damage value to the +/- 20% change in the parameter value										
10000	0.02	0.02	0.05	0.09	0.09	0.09	0.00	**1.00**	0.07	0.21
30000	0.04	0.04	0.09	0.17	0.17	0.16	0.01	**0.99**	0.13	0.28
90000	0.04	0.09	0.16	0.29	0.29	0.28	0.02	**0.98**	0.23	0.41

Problem 2 – min [exp. time to 1st detection]:
Response of the expected time to 1st detection to a +/-20% parameter change

Budget level	N (street host trees)	N (backyard host trees)	N(all host trees)	Detection probability	Pest entry likelihood	Survey cost	Spatial smoothing of P(entry)	Square root transform of P(entry)
Sensitivity of the expected time to first detection to the +/- 20% change in the parameter value								
10000	0.03	0.03	0.06	**0.12**	**0.12**	0.12	0.09	0.11
30000	0.04	0.05	0.10	**0.21**	**0.21**	0.18	0.15	0.18
90000	0.04	0.09	0.16	**0.34**	**0.34**	0.27	0.21	0.27

Optimal vs. rule-based strategies

Simple rule-based survey strategy:

- Order the sites in the area by pest entry risk
- Start surveying from the site with highest risk rank
- Once the highest-risk site is surveyed inspect the site with 2nd, 3rd highest rank, etc.
- Continue the survey until the budget is exhausted

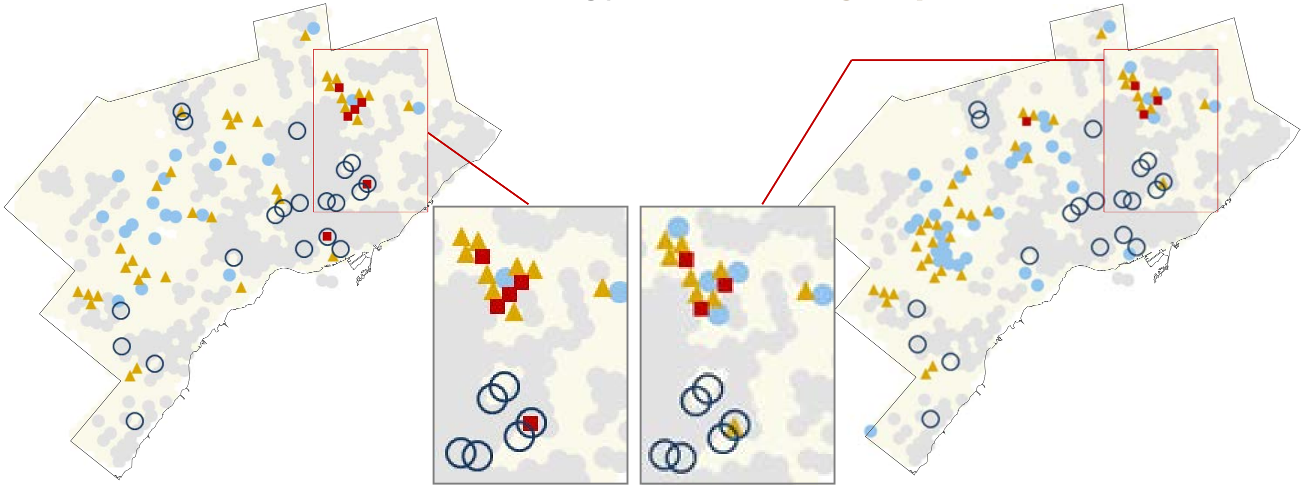
	Budget $60000		Budget $90000	
Scenario	Total sites surveyed	Expected time to 1st detection	Total sites surveyed	Expected time to 1st detection
Rule 1, survey all host trees at a site	1	944.1	6	935.8
Rule 2, survey all street host trees at a site	42	677.4	56	631.1
Rule 3, survey 90 street host trees at a site	93	649.4	137	603.1
Rule 4, survey 30 street host trees at a site	282	772.6	316	772.2
Optimal solution	108	**601.2**	138	**552.1**

Risk-averse survey strategies

Delimiting survey problem 1:
MIN [damage]

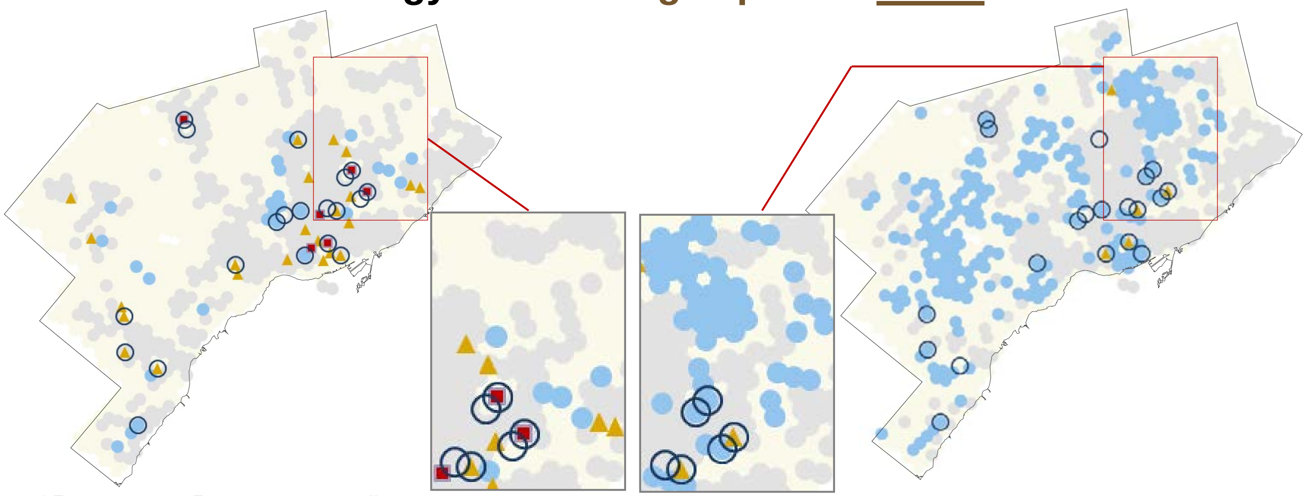
Early detection problem 2:
MIN [time to 1st detection]

Risk-neutral strategy: minimizing expected outcome

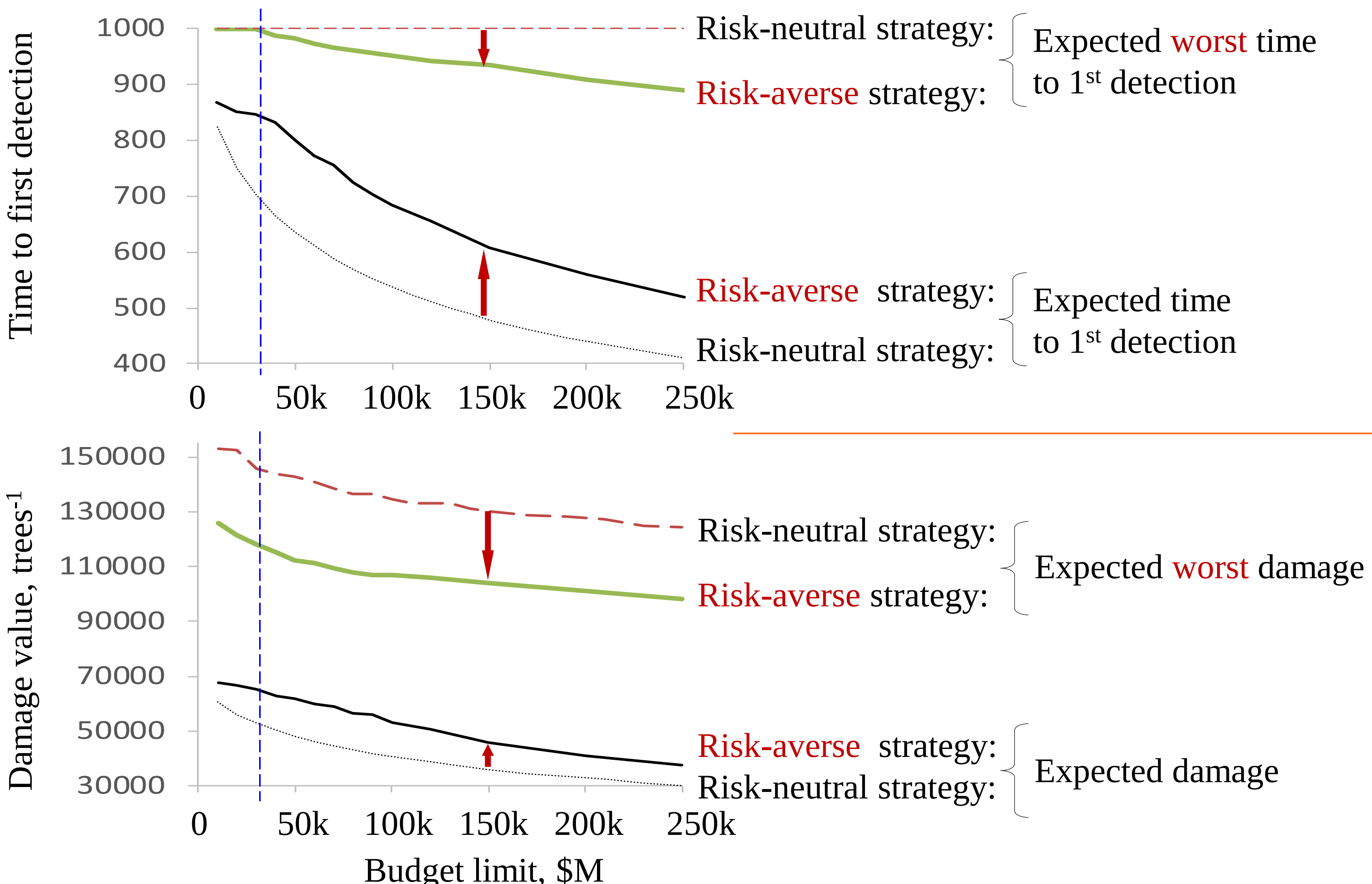


Budget = $30k

Risk-averse strategy: minimizing expected worst outcome



Trade-off between risk-neutral and risk-averse survey strategies



Insights for decision-making

Planning early detection emphasizes the importance of handling the uncertainty about pest arrivals and damage

Risk-neutral survey strategy :

- Most cost-effective at small budget levels
- When the budget is small the optimal strategy is to inspect street trees in major industrial commercial areas
- Does not guarantee that worst detection time is minimized
- Trade-off between minimizing expected damage and time to 1st detection is small

Risk-averse strategy :

- Adds penalty to the expected detection time value
- Only effective when the budget is sufficient to inspect large number of sites
- The optimal strategy is to survey as many sites as possible at low sampling rates
- Trade-off between minimizing worst damage and worst detection time is significant

Rule-based strategies may achieve acceptable results but do not approach the detection times in optimal solutions

The approach helps understand key differences between time- and damage-minimizing survey strategies and is applicable to other pest species and geographic areas

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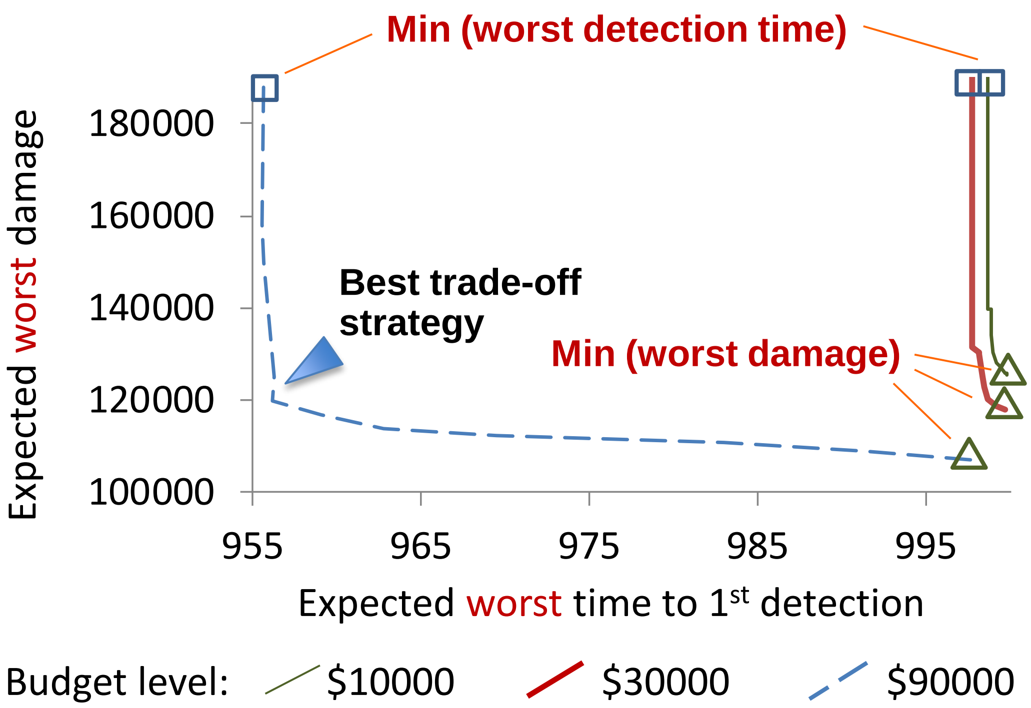
Can we minimize both, worst damage and worst detection time?



Different spatial survey strategies:

- Survey sites with high host densities to minimize worst damage
- Survey as many sites with positive pest entry rates as possible to minimize worst time to 1st detection

Best trade-off: moderate reduction of the expected worst damage while minimizing worst detection time but not both

Need large budget to minimize worst detection times