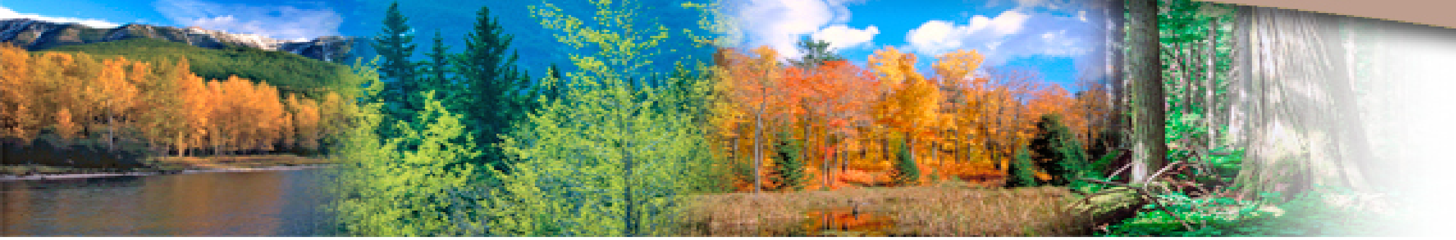

# OPTIMAL SURVEILLANCE OF BIOLOGICAL INVASIONS: COMPARING RISK-BASED AND ACCEPTANCE SAMPLING APPROACHES

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# Delimiting pest surveys

- Aim to uncover full spatial extent of invasion
- Continue regardless of the number of detections

**Common strategy:**

- Maximize the expected area (or number of sites) with successful detections

**Known issues:**

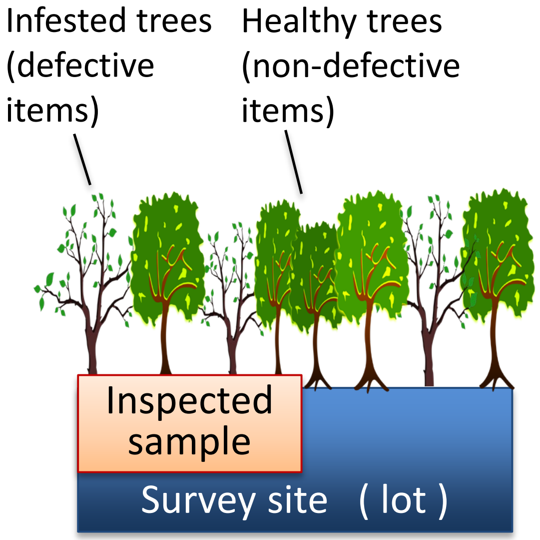
- **Uncertainty** – uncertain estimates of spread do not guarantee a proper account for damages from the outcomes of survey actions
- **False negatives** – infested trees at sites that have been inspected and no infestation was found

**Better approach: Statistical quality control methods (acceptance sampling)**

- Widely used for quality control in manufacturing, food safety and disease control
- Helps address the issue of false negatives
- Works with uncertain data
- Can be designed to minimize inspection costs (Baker et al. 1993; Lattimore et al. 1996) or achieve an acceptable level of risk of overlooking a defective item (Starbird 2005; Whiting et al. 2006; Yamamura et al. 2016; Chen et al. 2018)

Images: Florida Dept of Ag and Consumer Services; New York Dept of Environmental Conservation; Iowa Dept of Natural Resources; USDA-FS, R9, Allegheny NF; USDA

# Acceptance sampling



- Helps inspectors accept or reject a lot based on inspections of a sample of items in the lot
- The inspection plan selects the lots, the sample size and the inspection method
- The lot is accepted only if the number of defective items in the sample does not exceed the acceptance threshold

**Spatial pest survey problem** = Acceptance sampling plan for multiple lots, subject to a budget constraint

| Pest survey | | Acceptance sampling |
|---|---|---|
| Potential survey sites | = | Multiple lots |
| Host trees at a survey site | = | Items in a lot |
| A set of trees surveyed | = | Sample of items inspected in a lot |
| Detection rate after inspecting a tree | = | 1 - inspection error |
| If one or more trees is found infested the site is declared as infested | = | If one or more items are found defective the lot is rejected |

# Problem formulation

**Problem 1:**

P(not detecting one or more infested trees at a site)

$$\min \frac{1}{S}\sum_{s=1}^{S}\sum_{j=1}^{J}\sum_{m=1}^{M}\left(x_{jm}\left[(1-\gamma_{js}e)^{n_{jm}}\right]\right)$$

**Minimize the expected area (number of sites) with undetected infestations**

**Problem 2:**

Expected slippage

$$\min\left[\frac{1}{S}\sum_{s=1}^{S}\sum_{j=1}^{J}\sum_{m=1}^{M} x_{jm}E_{jms}\right]$$

**Minimize the expected number of infested trees in the sites that are inspected and declared uninfested or not surveyed (expected slippage)**

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**s.t:**

$$\sum_{j=1}^{J}\sum_{m=1}^{M} x_{jm}n_{jm}g_j \le B$$

**- Budget constraint on sampling cost, *B***

$$\sum_{m=1}^{M} x_{jm} = 1 \quad \forall \quad j \in J \quad x_{jm} \in \{0,1\}$$

**- A site can only be inspected at one sampling rate, *m***

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**Sets:**

$J$ – potential survey sites, $j$

$S$ – infestation scenarios, $s$

$M$ – potential sampling rates, $m$

**Parameters:**

$g_j$ – sampling unit cost at a site $j$

$\gamma_{js}$ – infestation rate at a site $j$ in a scenario $s$

$e$ – detection rate after inspecting a tree

**Decision variables:**

$x_{jm}$ – binary decision variable to survey a site $j$ at a sampling rate $n_{jm}$

# Expected slippage

- The expected number of infested trees in the sites that are inspected and declared uninfested or not surveyed
- Helps address the issue of **false negatives**
- We apply the expected slippage formula for the acceptance sampling problem from Chen et al. (2018):

$$E_{jms} = (1-\gamma_{js}e_j)^{n_{jm}}\left[\gamma_{js}(N_j - n_{jm}) + \frac{1-e_j}{1-\gamma_{js}e_j}\gamma_{js}n_{jm}\right]$$

Probability that the survey fails to detect the infestation * [ Expected number of infested trees in an unsampled population + Expected number of infested trees in a sampled population ]

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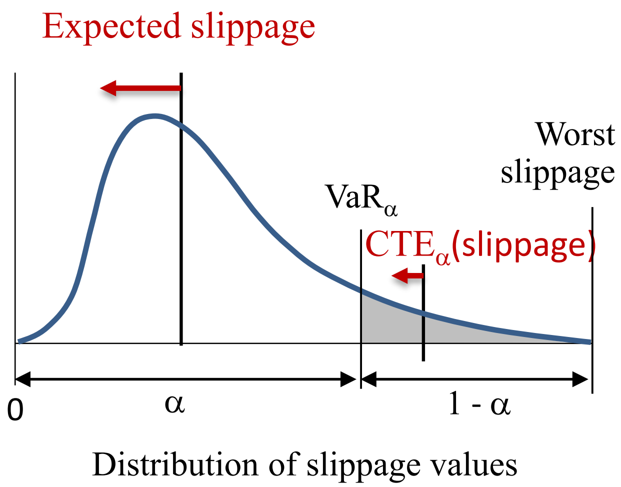
$N_j$ – number of host trees at a survey site $j$
$\gamma_{js}$ – infestation rate at a site $j$ in a scenario $s$
$e_j$ – detection rate after inspecting a tree at a site $j$
$n_{jm}$ – sample size rate at the sampling rate level $m$ at a site $j$
$x_{jm}$ – binary decision variable to survey a site $j$ at a sampling rate $n_{jm}$

# Incorporating decision-maker’s risk aversion: Minimizing the expected worst outcome



Distribution of slippage values

Minimizing expected slippage does not guarantee avoiding the worst-case outcomes of the survey actions

In this case, expected worst slippage need to be minimized

**Conditional Tail Expectation (CTE)**

(Acerbi and Tasche 2002; Rockafellar and Uryasev 2000, 2002)

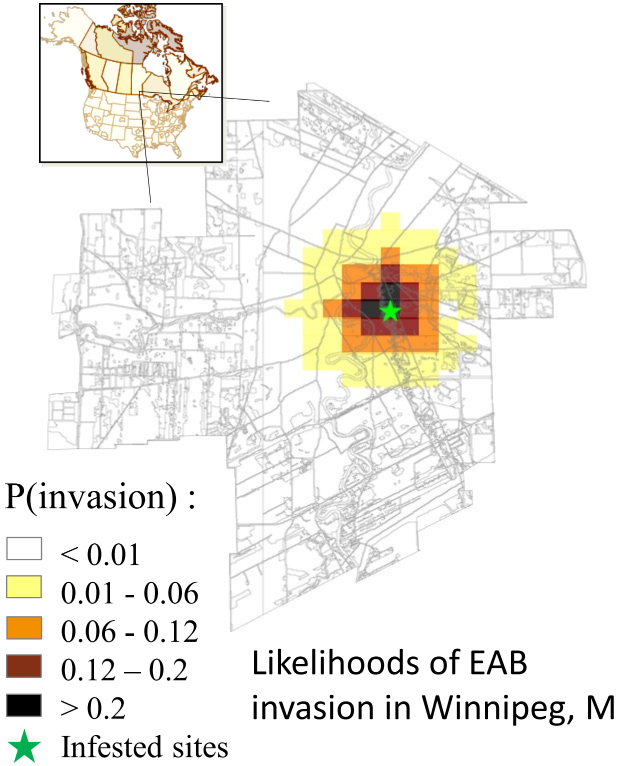
- For a confidence level $\alpha$, $CTE_\alpha$ is the expected value of the distribution over $(1 – \alpha)\times100\%$ of worst scenarios
- Minimizing CTE controls the worst survey outcomes
- CTE can be minimized if the objective is linear with respect to decision variables (see Rockafellar and Uryasev, 2000, 2002)

**Incorporating risk-averse decision-making perceptions into a pest survey problem:**

**Problem 1** - Minimize expected largest area of undetected infestations

**Problem 2** - Minimize expected worst slippage

# Case study: Developing optimal survey strategies for EAB outbreak in Winnipeg, MB, Canada



Likelihoods of EAB invasion in Winnipeg, MB

**Emerald Ash Borer (EAB)**

- Major threat to ash (*Fraxinus* spp.)
- Causes major damage to urban and forest trees
- Detected in Winnipeg, MB in December 2017
- Fast spread rates (>20 km/yr.)[*] - eradication is problematic
- Spread is associated with human activities, primarily with vehicles that could move infested materials (Buck and Marshall 2008)
- Two common detection methods:

| | |
|---|---|
| - Branch sampling | – reliable but expensive |
| - Trapping | – cheaper but less reliable |

- Poor capacity to detect EAB at early stages due to lack of effective pheromone - branch sampling is the only choice
- Local spread rates are uncertain - can only be guessed from the records of previous infestations in other regions

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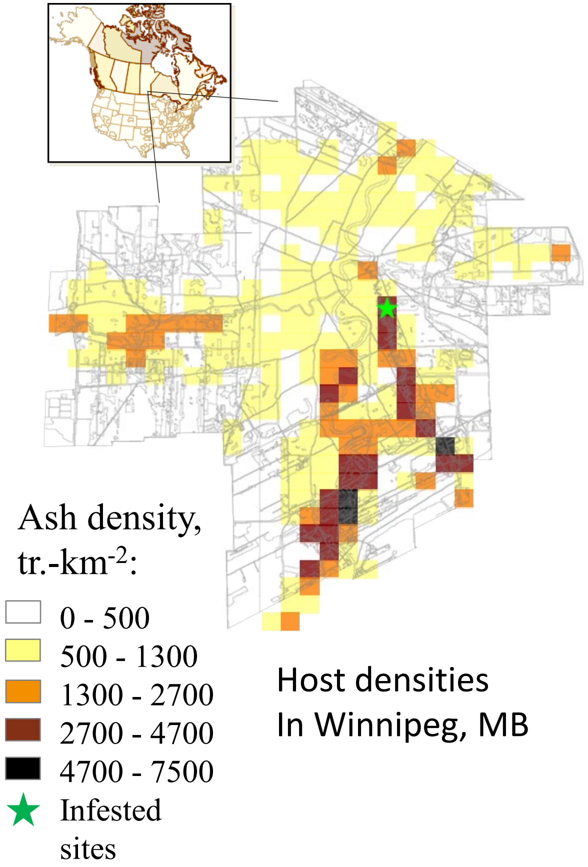
[*] Kovacs et al. 2010

Images: CFIA – www.inspection.gc.ca/pests
New York Dept of Environmental Conservation; USDA-FS, R9, Allegheny NF;

# Planning EAB delimiting surveys strategies in Winnipeg, MB



Host densities
In Winnipeg, MB

- Grid of potential 1x1-km survey sites
- Survey costs and detection rates – from recent survey campaigns (Ryall et al. 2011, 2013; Turgeon et al. 2015):

| | Detection rate | Tree survey cost, $-tr$^{-1}$ | |
|---|---|---|---|
| | | 20-60cm dbh | >60cm dbh |
| Trapping | 0.5 | $89.2 | $124.4 |
| Branch sampling | 0.7 | $128.9 | $249.6 |

- Host densities – from municipal tree inventory
- Surveys are limited to public trees above 20-cm dbh
- Distance-dependent likelihoods of EAB spread – from 6-year historical records of EAB spread in Minneapolis-St. Paul, MN, USA (Fahrner et al. 2017; Osthus 2017)
- Tested two decision-making strategies:
  - Risk-neutral - minimizes the expected outcome from the survey actions
  - Risk-averse - minimizes the expected worst outcome

# Survey allocation examples - $25000 budget

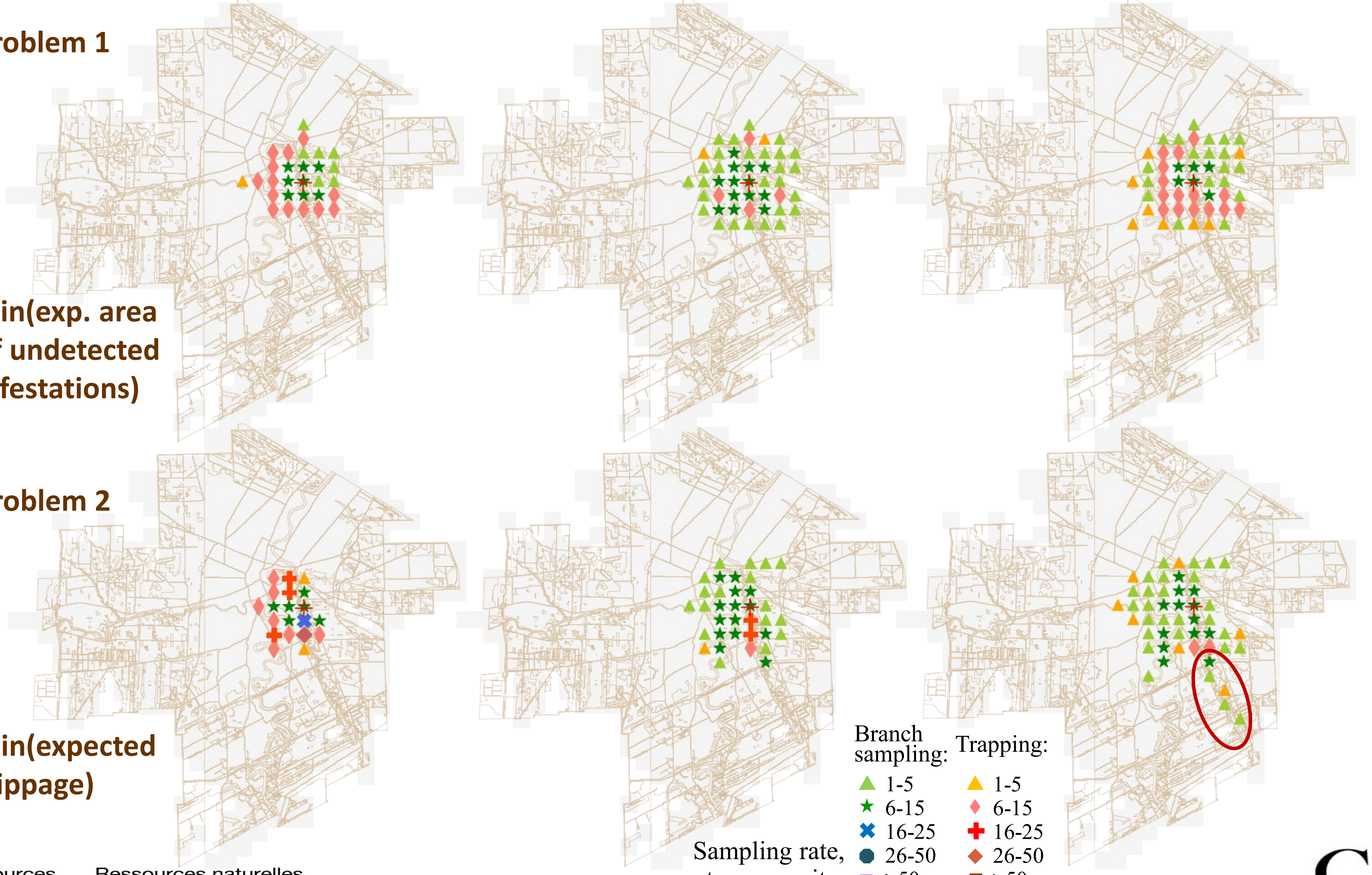
No uncertainty | Uncertainty | Uncertainty, risk aversion

**Problem 1**

**min(exp. area of undetected infestations)**

**Problem 2**

**min(expected slippage)**



# Survey allocation examples - $100000 budget

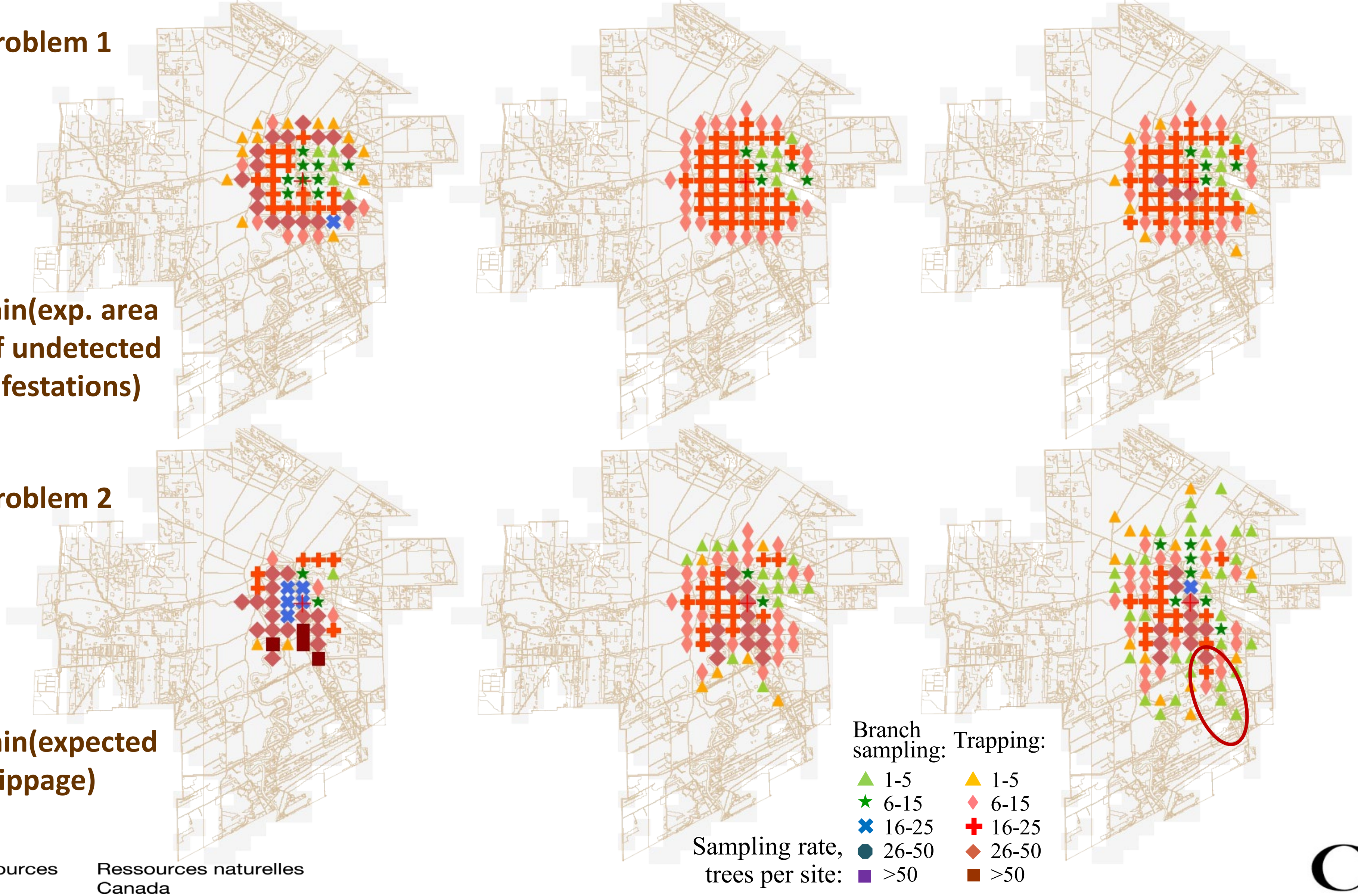
No uncertainty | Uncertainty | Uncertainty, risk aversion

**Problem 1**

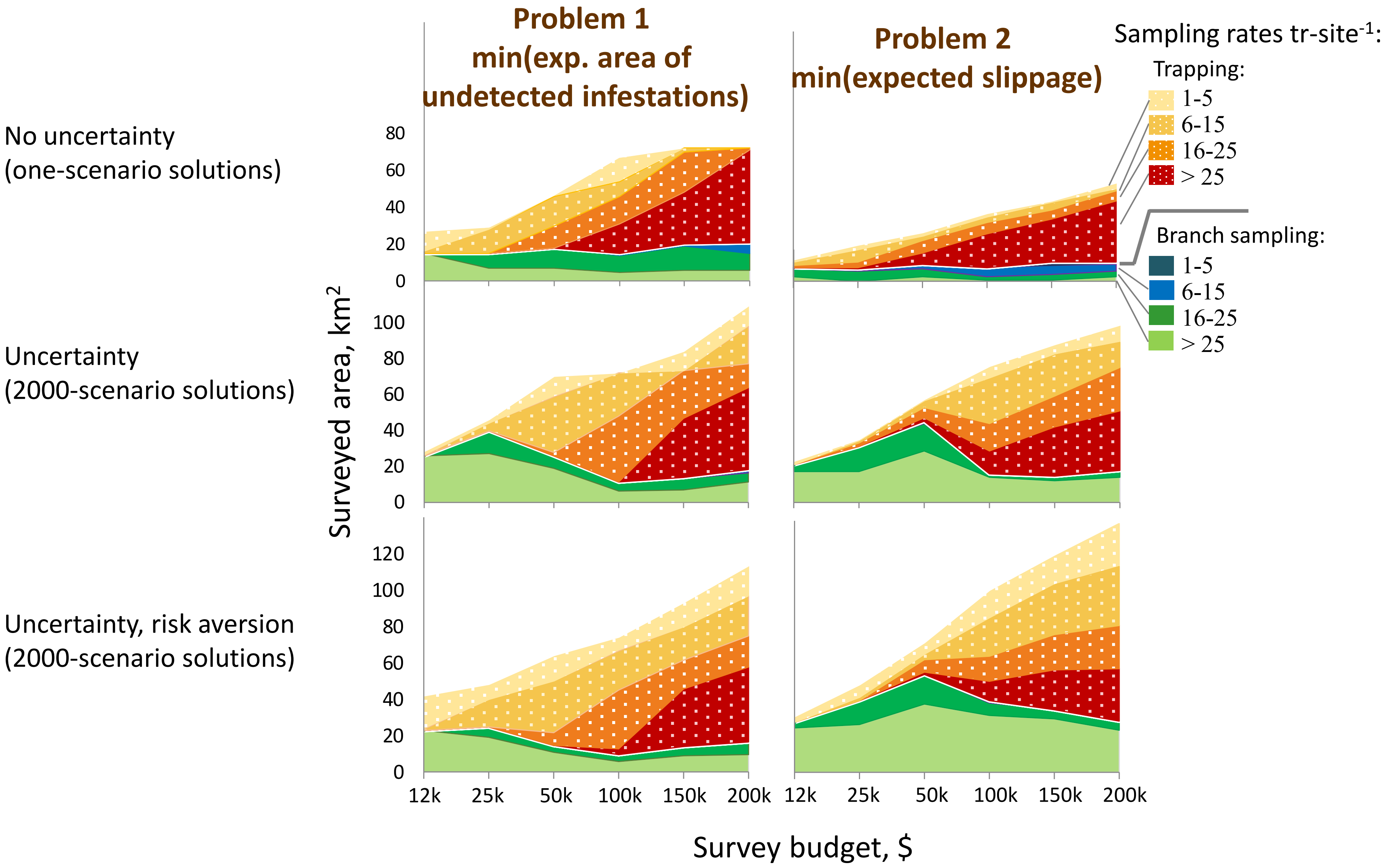
**min(exp. area of undetected infestations)**

**Problem 2**

**min(expected slippage)**



# Surveyed area vs. sampling rate and detection method



# Impact of changing the trap detection rate

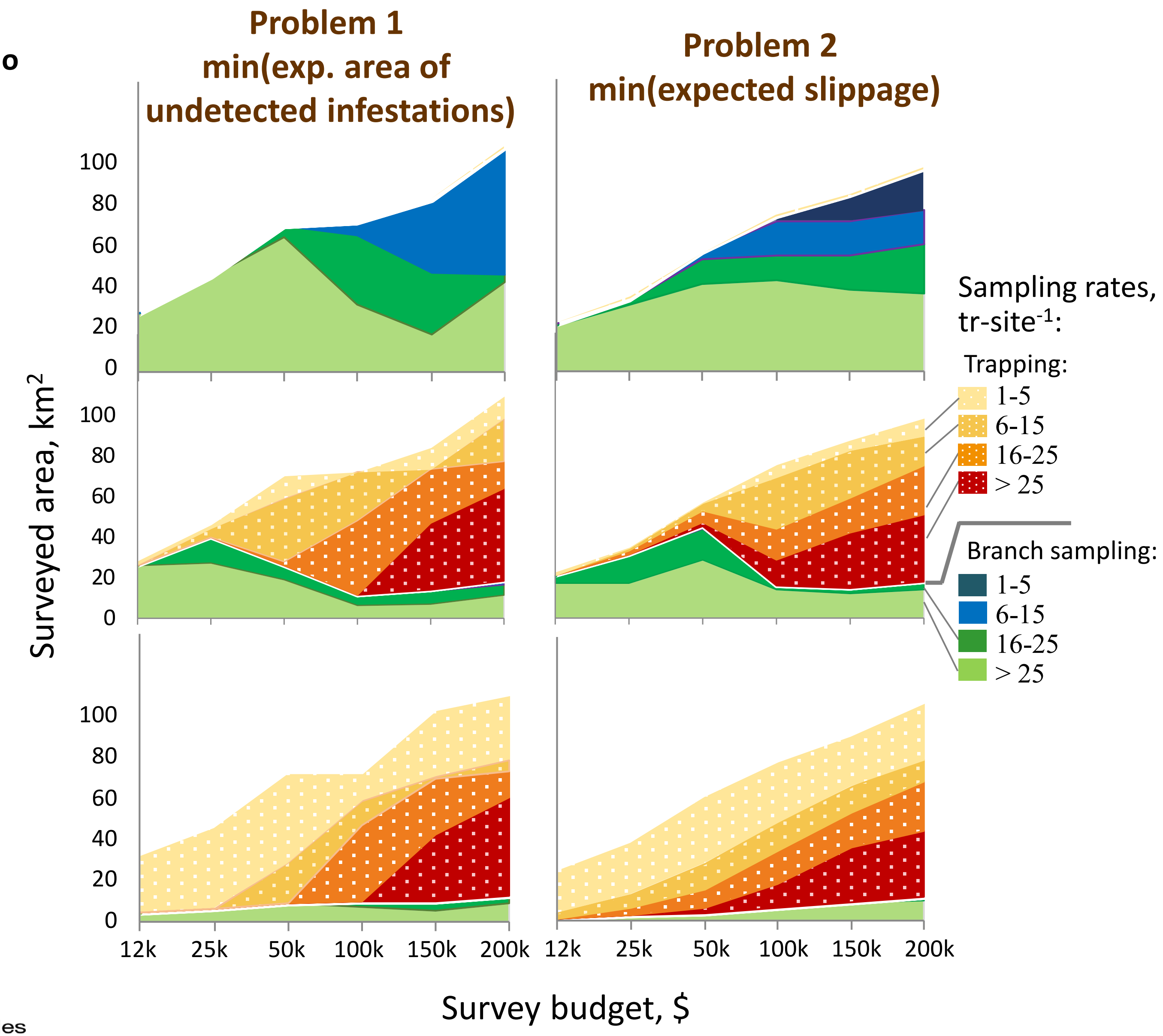
**Examples of 2000-scenario solutions (uncertainty)**

Trap detection rate:

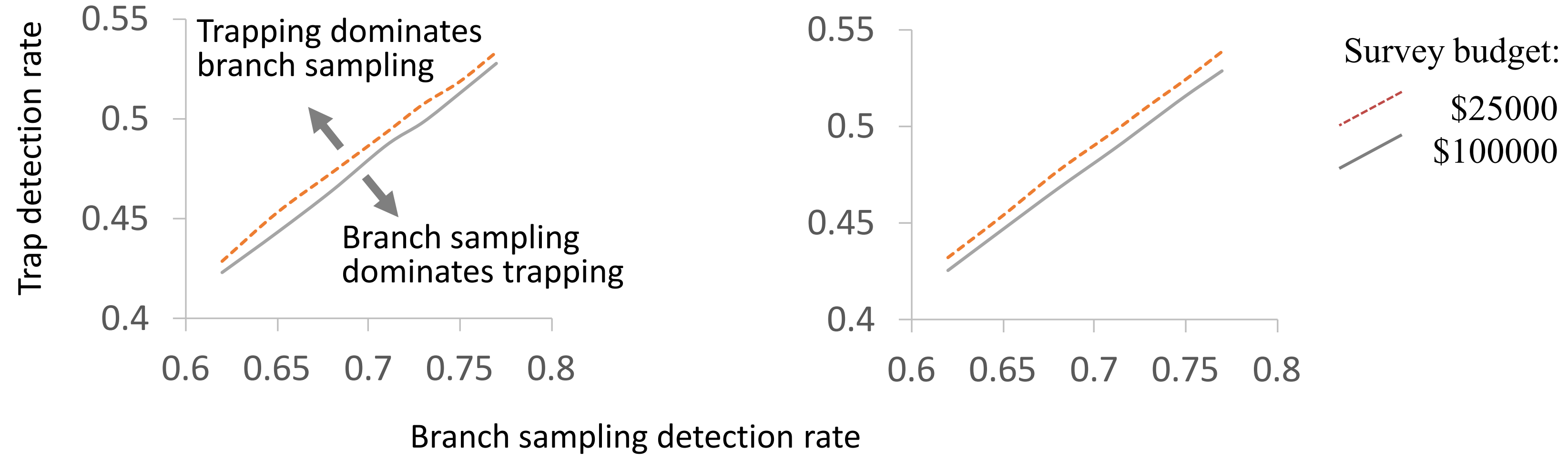
0.45

0.5 (baseline)

0.55



# Survey method preference vs. the detection rate

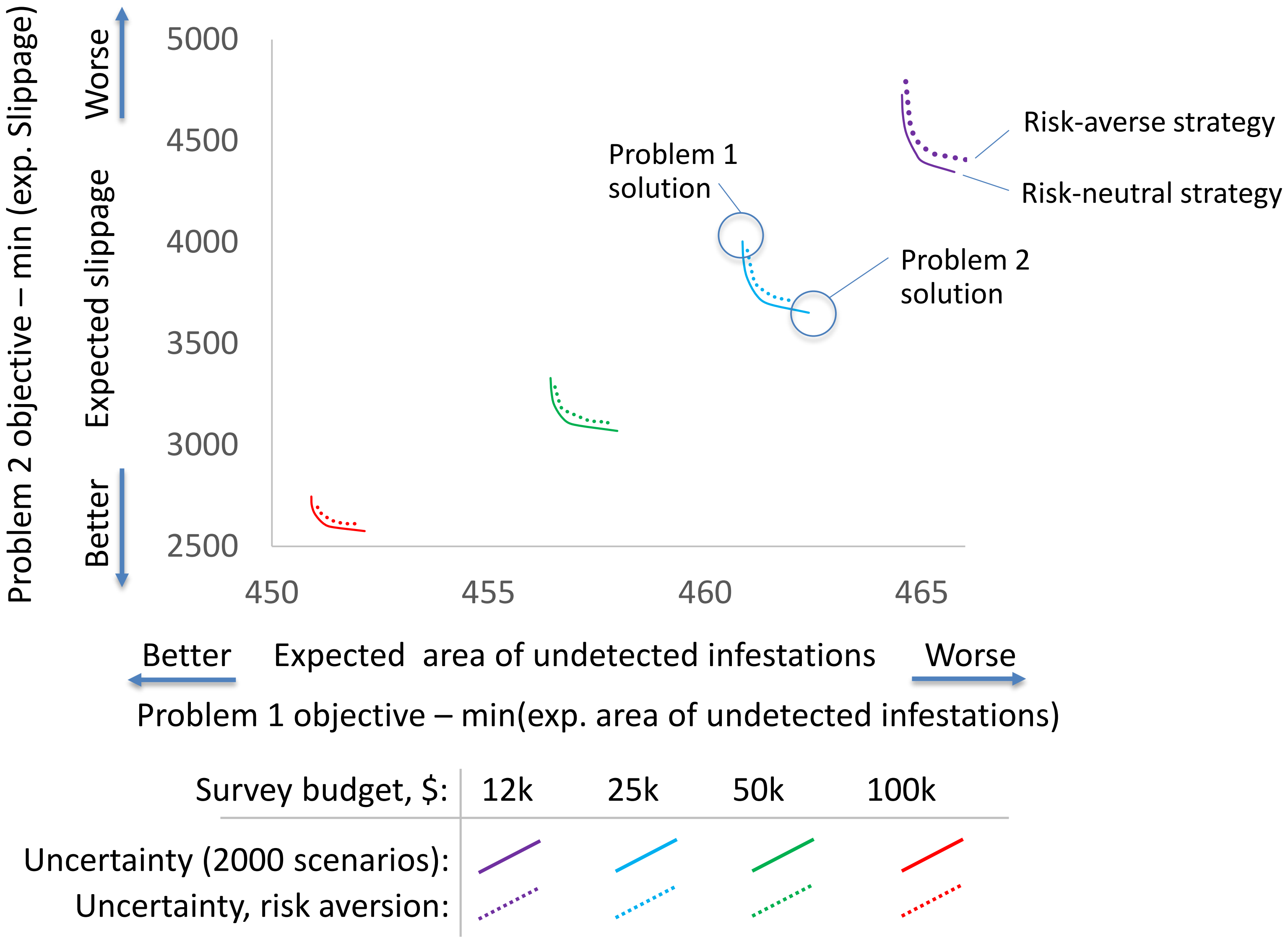


**Problem 1**
**min(exp. area of undetected infestations)**

**Problem 2**
**min(expected slippage)**

Branch sampling is preferred
if its detection rate, on average,
is **1.45 times** greater than the
trap detection rate

# Minimizing the area of undetected infestations vs. minimizing the expected slippage



# Insights for decision-making

- The acceptance sampling approach helps address the issue of false negatives in pest surveys
- The choice of trapping vs. branch sampling is influenced by the survey budget and the uncertainty of EAB spread
- In small-budget solutions, branch sampling is preferred
- In large-budget solutions, trapping is preferred but branch sampling is limited to sites with both high infestation rates and low host densities
- The impact of uncertainty:
  - Larger portion of budget is spent on branch sampling (especially in low-budget solutions)
  - Larger area is surveyed at lower sampling rates to compensate for uncertainty
  - More sites are inspected at further distances from the infested area
- The impact of risk-averse perceptions:
  - The surveys cover even greater area to detect low-probability long-distance infestations
  - Inspections target more sites with high host densities at far distances from the infested area where EAB entries could cause significant host damage
- The penalty of risk-averse perceptions on the expected survey outcomes is small
- Work in progress to optimize the delimiting survey programs with optional tree removal

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