Optimal control and Spatial conservation planning

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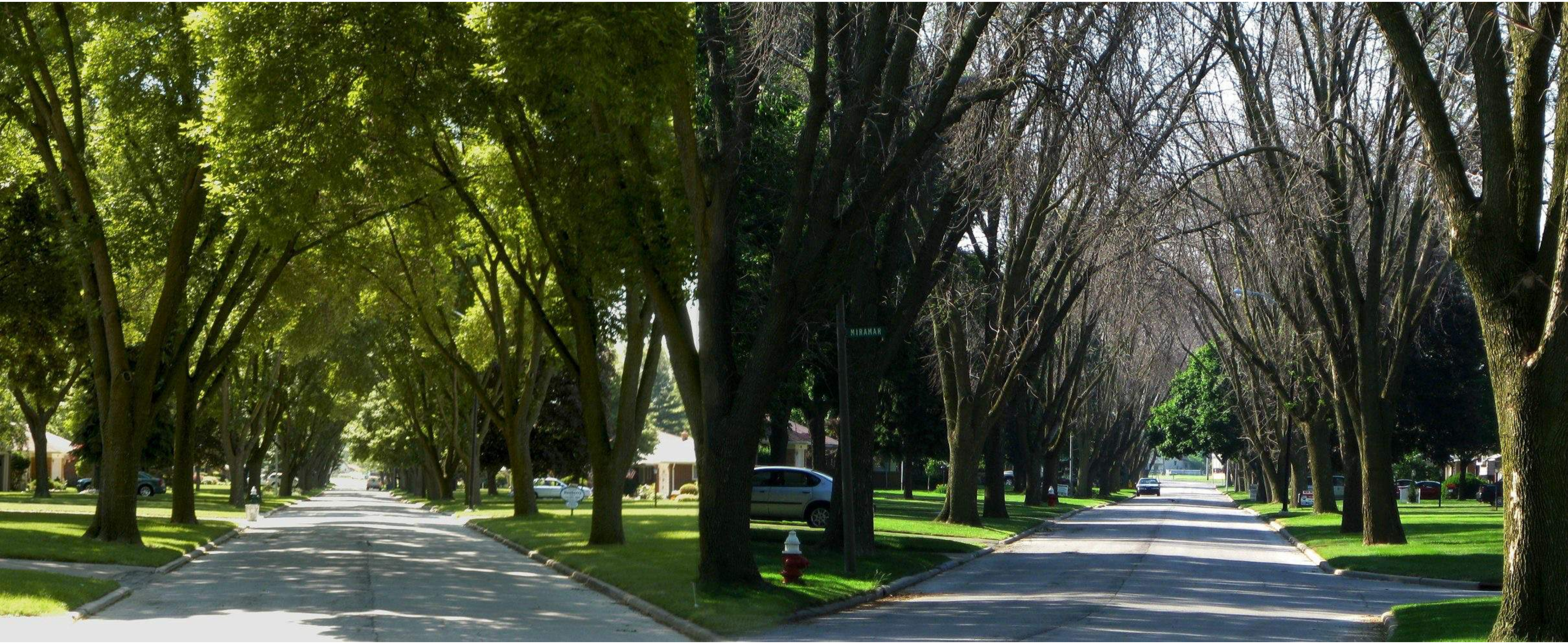
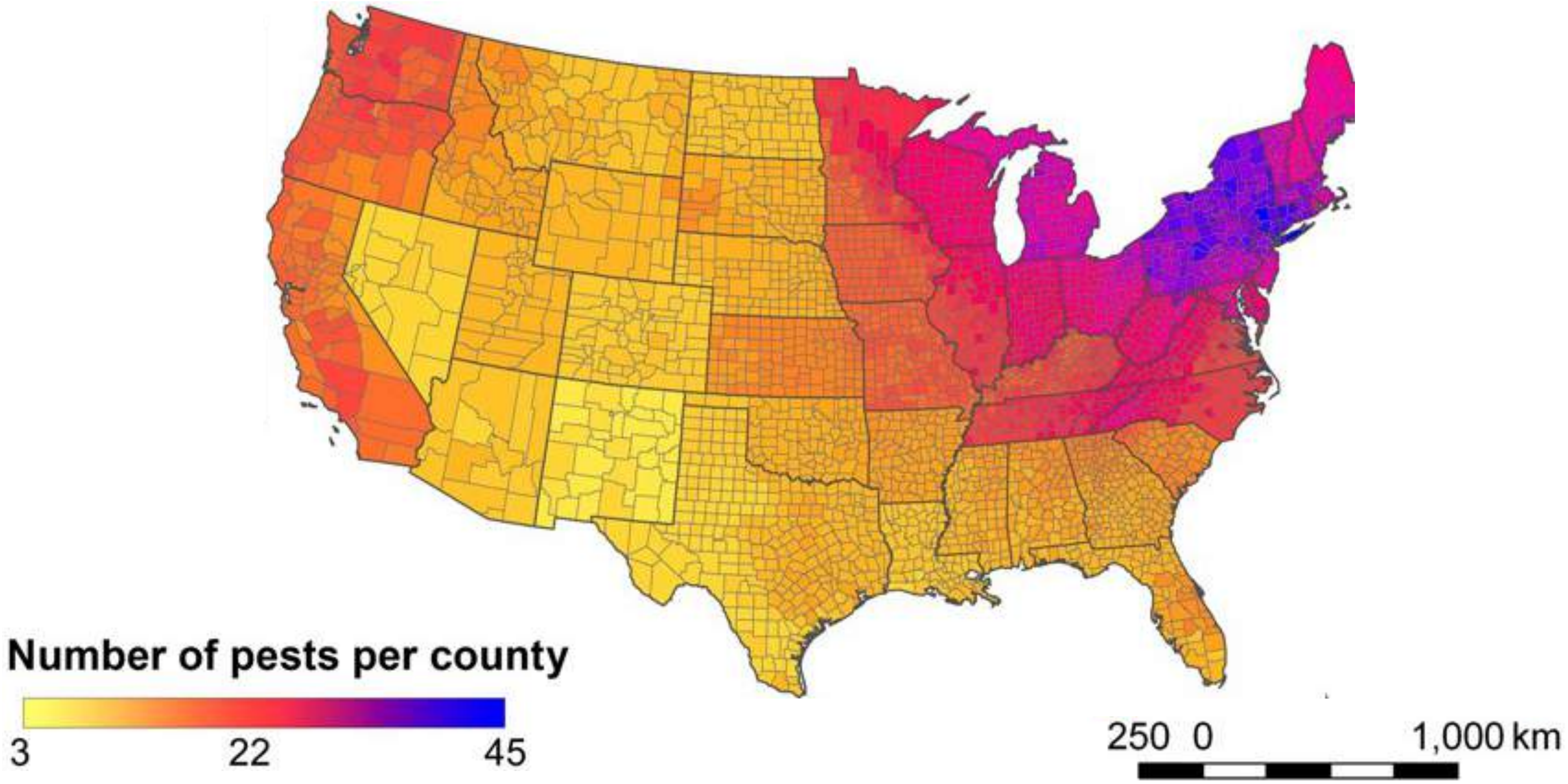


Treehuggerswinnipeg.com

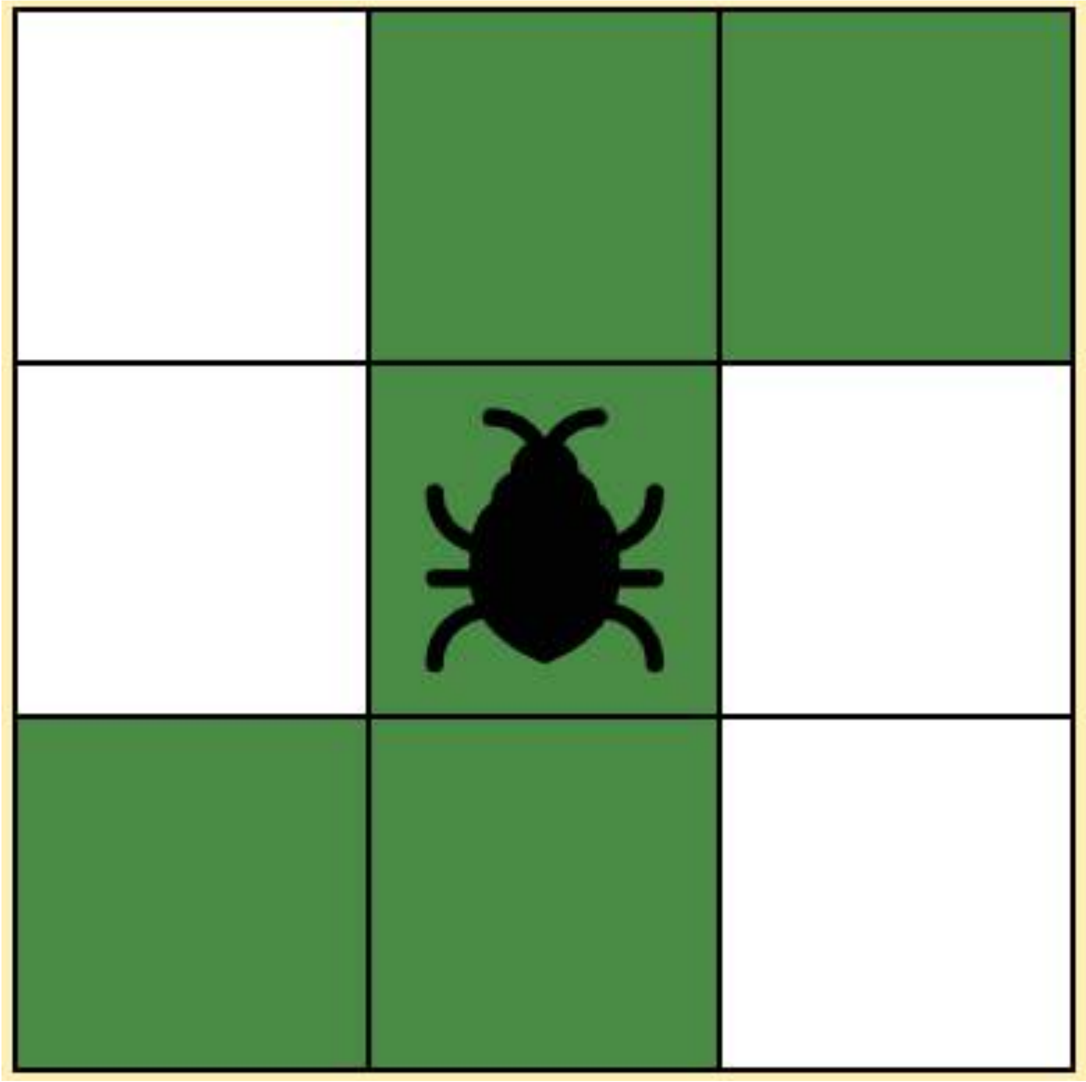


Liebhold et al. 2013 *Divers. Distrib.*

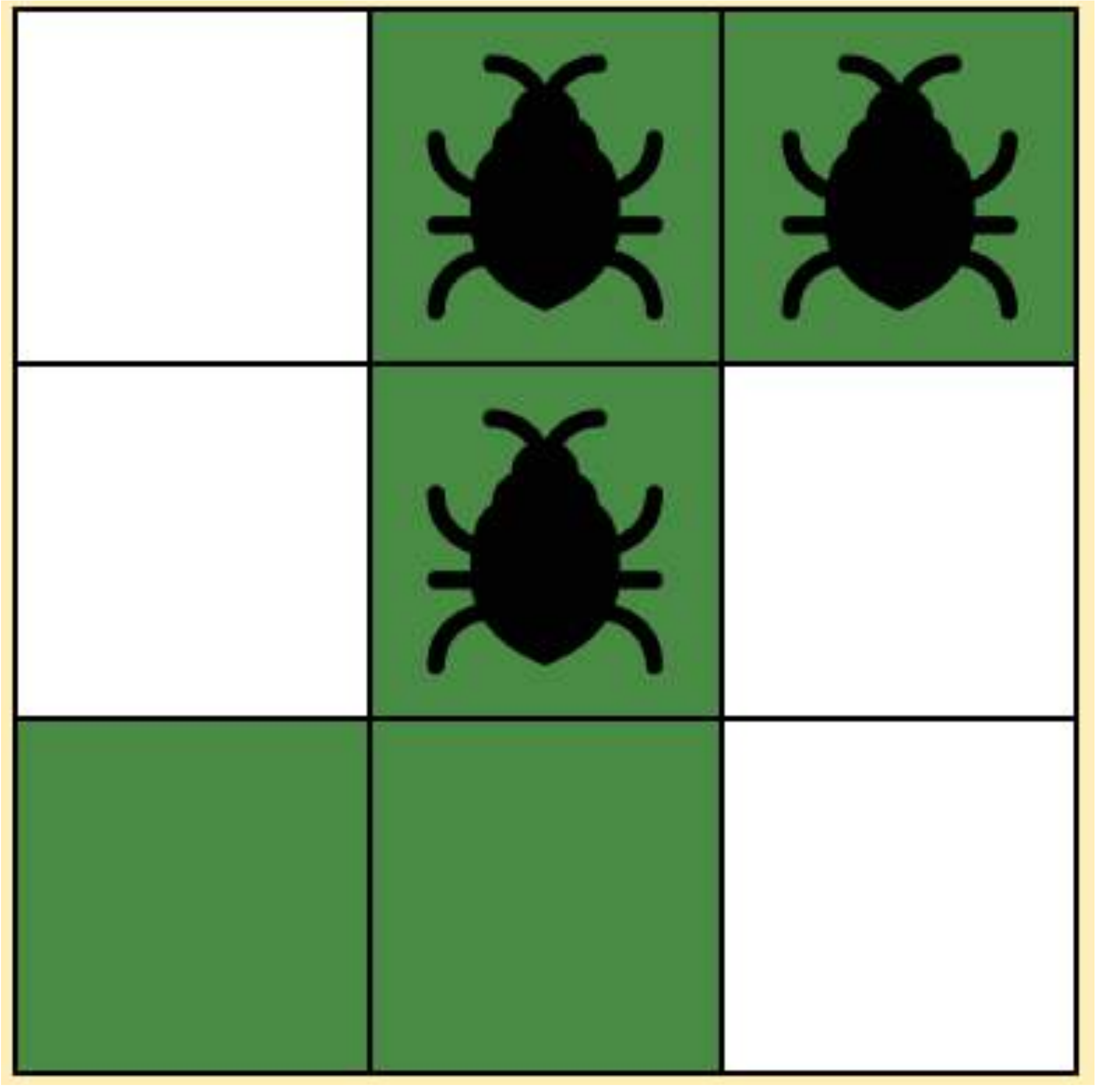



1. Simulation-based dispersal models

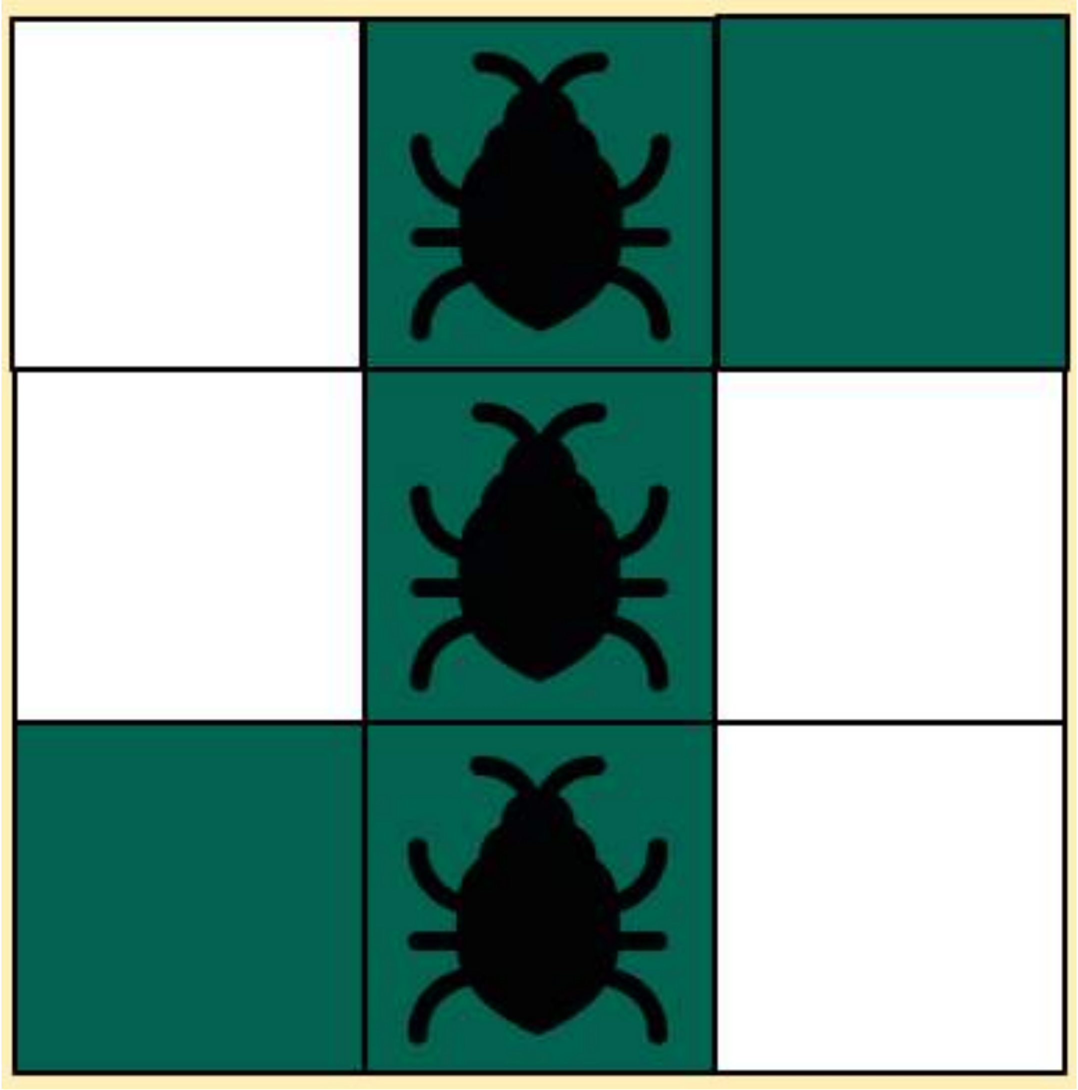
Simulated Invasion Dynamics



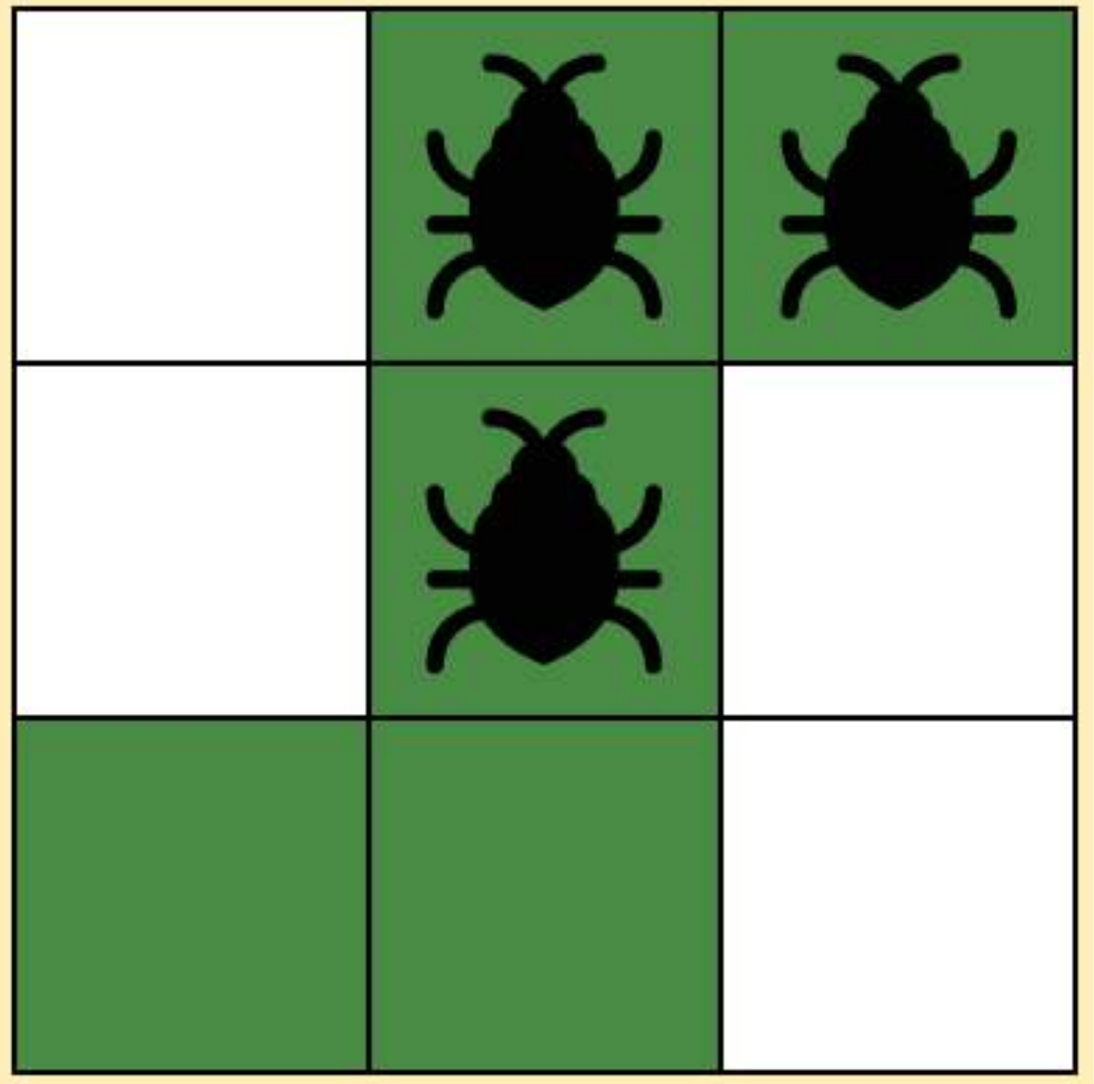
Simulated Invasion Dynamics



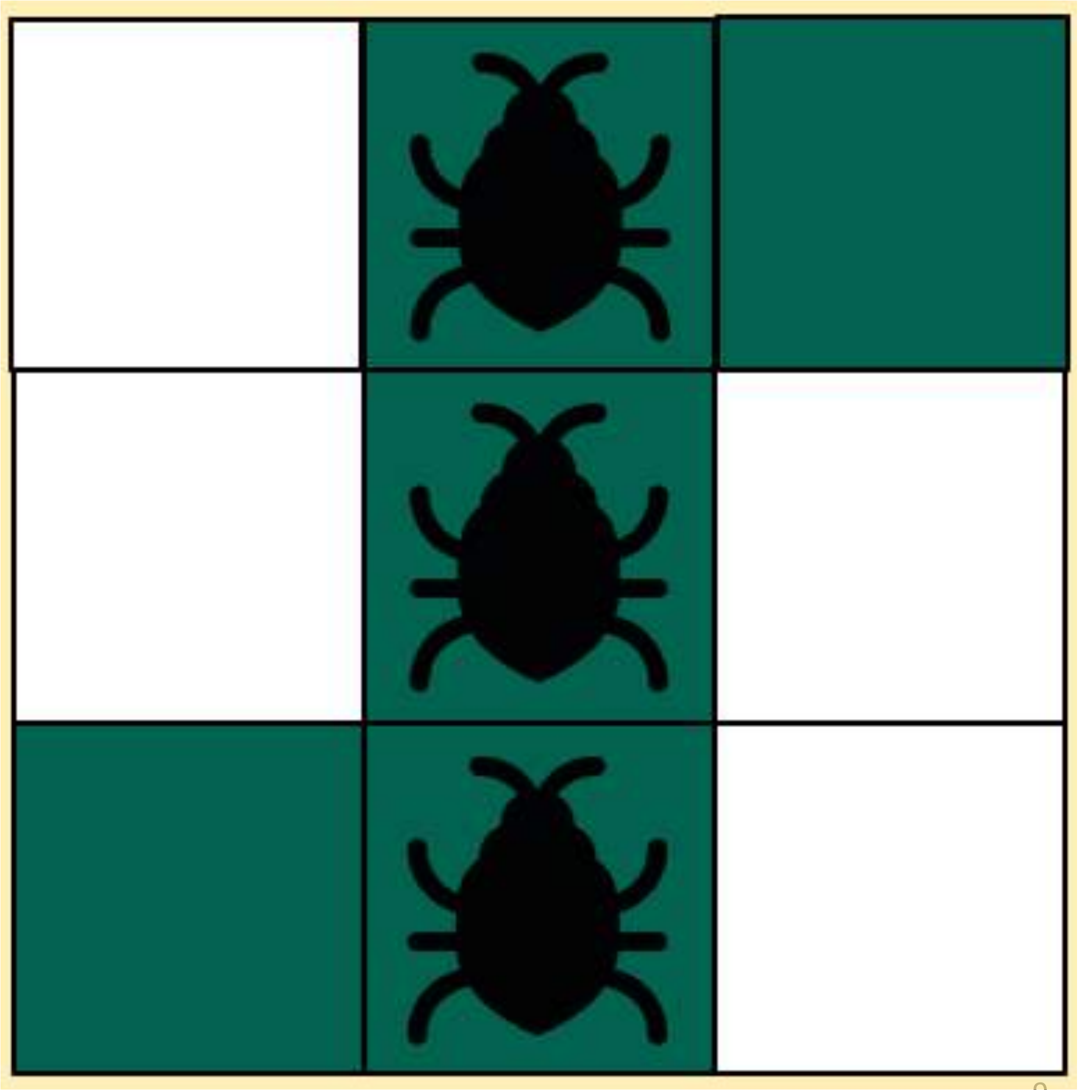
True Invasion Dynamics



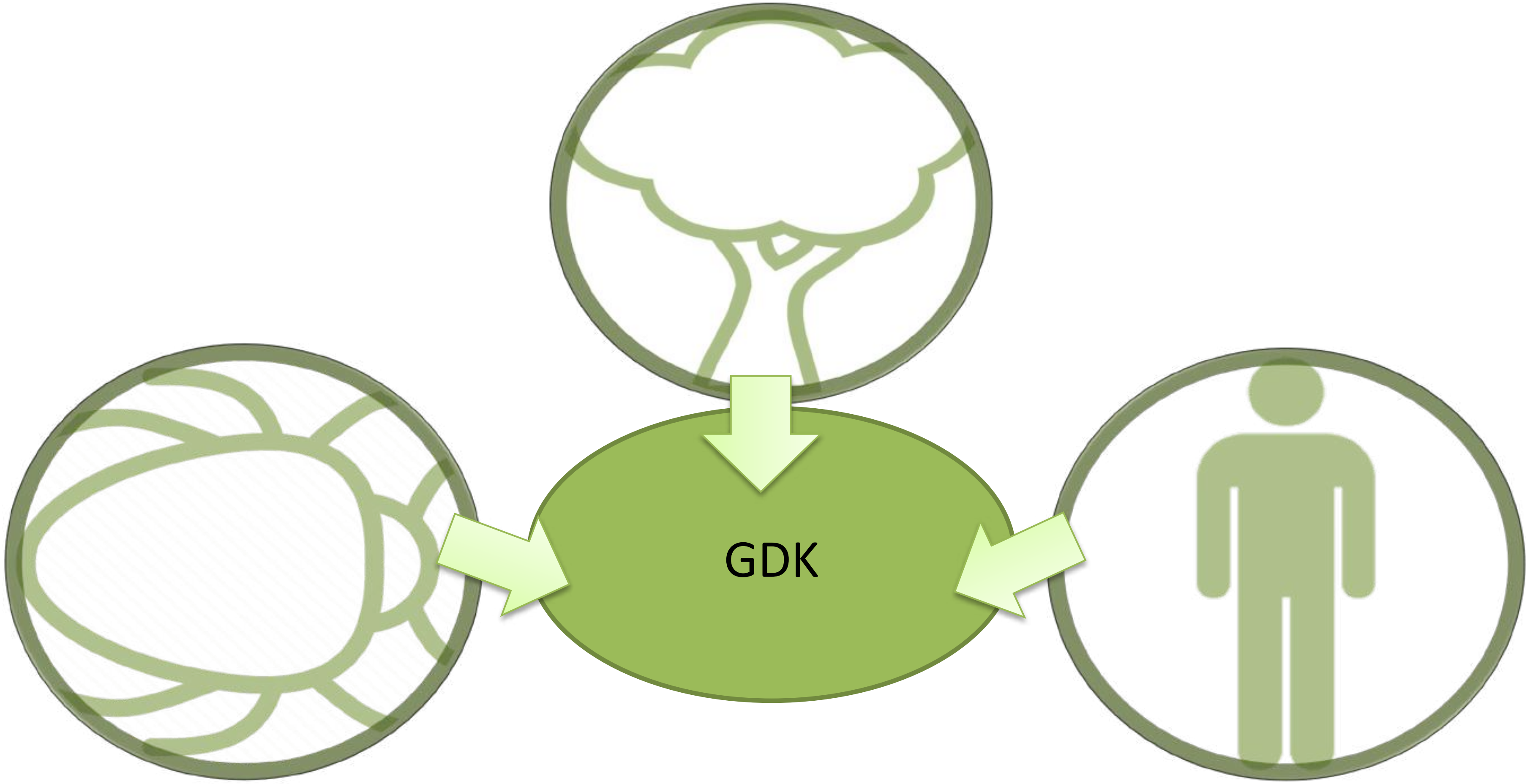
Simulated Invasion Dynamics



True Invasion Dynamics



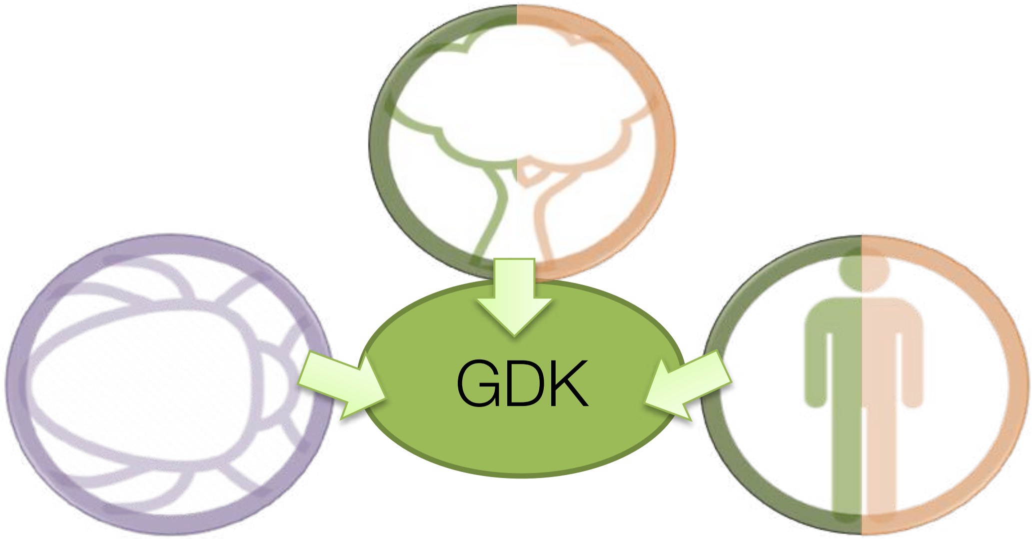
Generalized Dispersal Kernel



$$T_{\boldsymbol{i,j}} = e^{-d_{i,j}Z}$$

Hudgins et al. (2017) *Ecology Letters*

Generalized Dispersal Kernel (GDK)

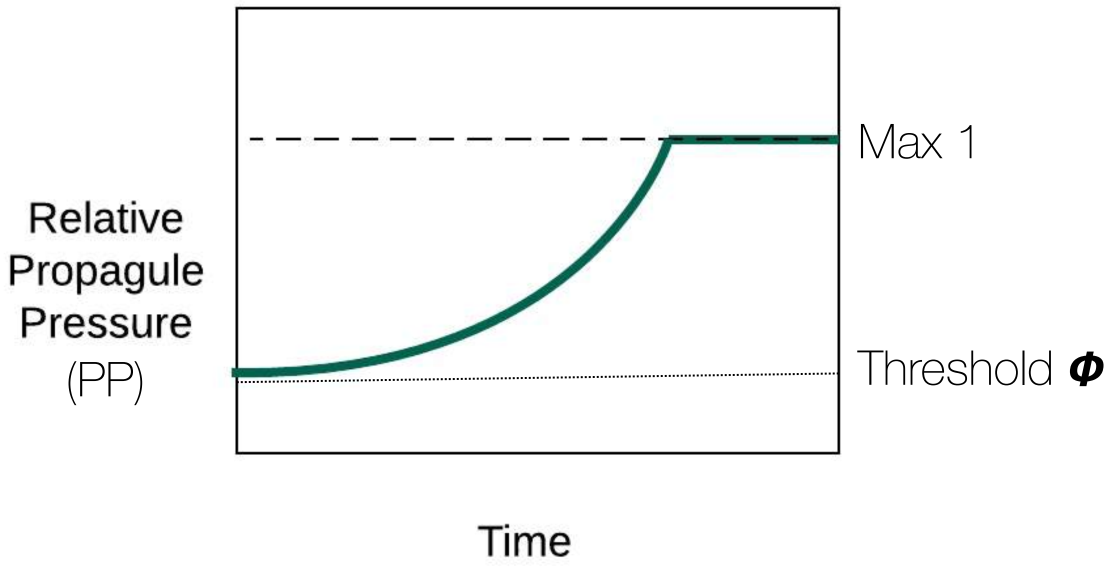


Predictors = Species + Dispersal In + Dispersal Out

$$Z = 2\alpha \frac{e^{Z_S + Z_I + Z_O}}{1 + e^{Z_S + Z_I + Z_O}}$$

$$Z_V = \sum_{p=1}^{n} \beta_p X_p$$

Temporal Changes



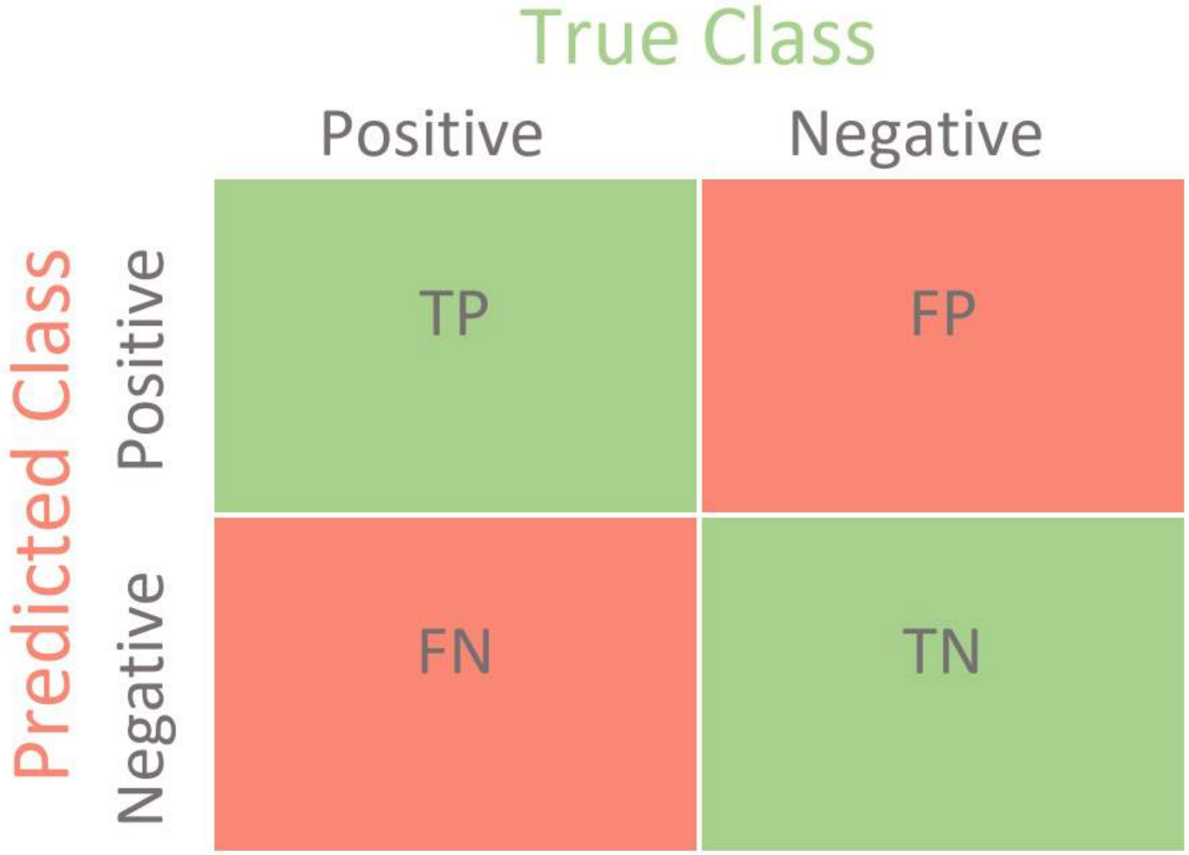
$$X_{j,t+1} = (X_{j,t} - \sum_{i} T_{i,j} X_{i,t} + \sum_{j} T_{j,i} X_{j,t})\delta$$

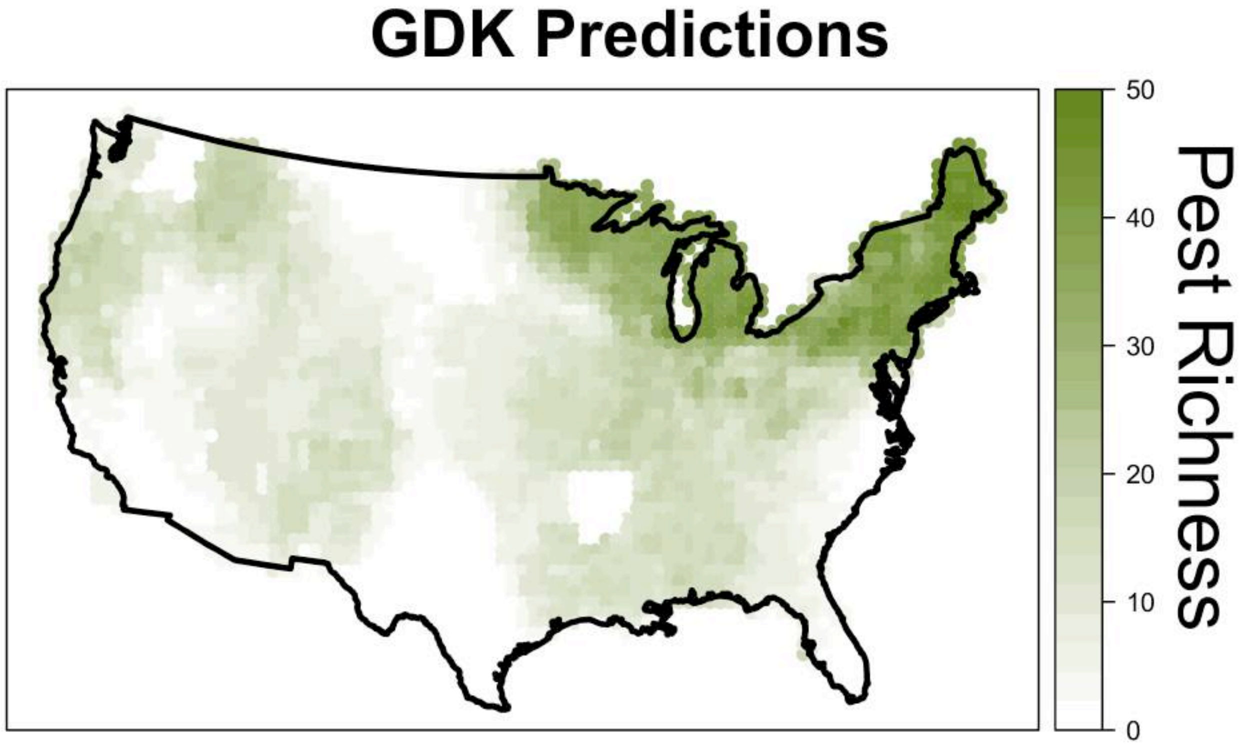
PP (t+1)= (PP(t) – Emigration + Immigration) * Growth

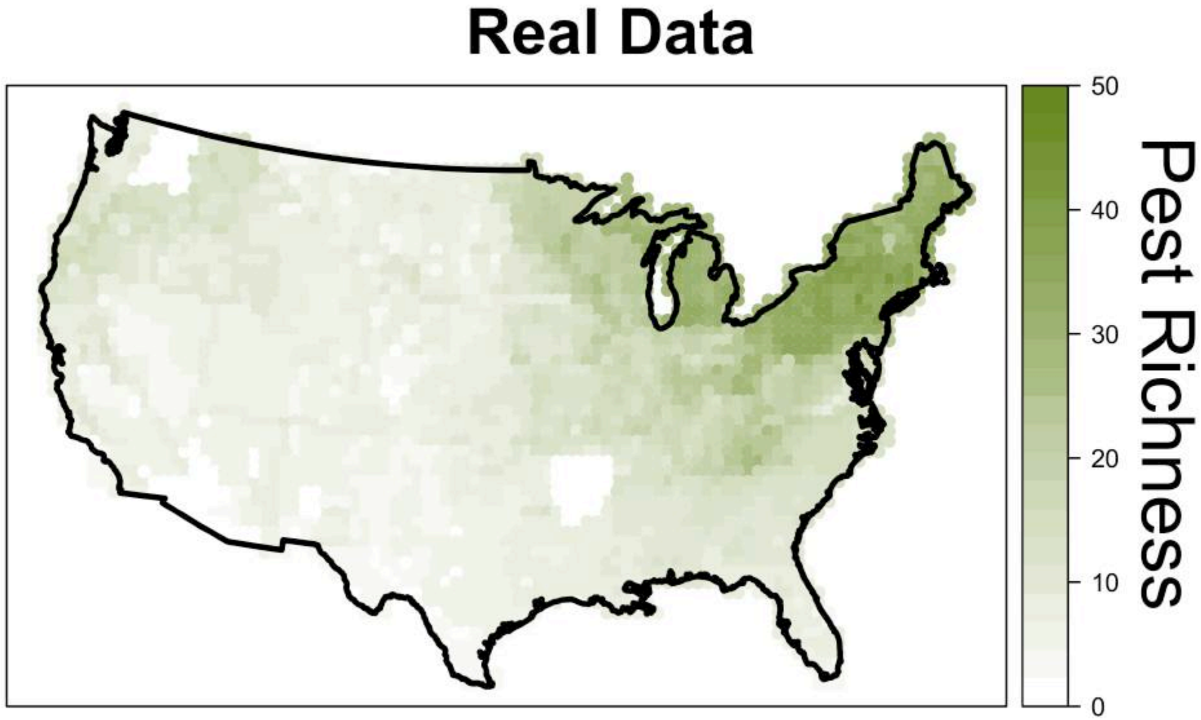
Kot et al. 1996 E*cology*

Metrics of fit

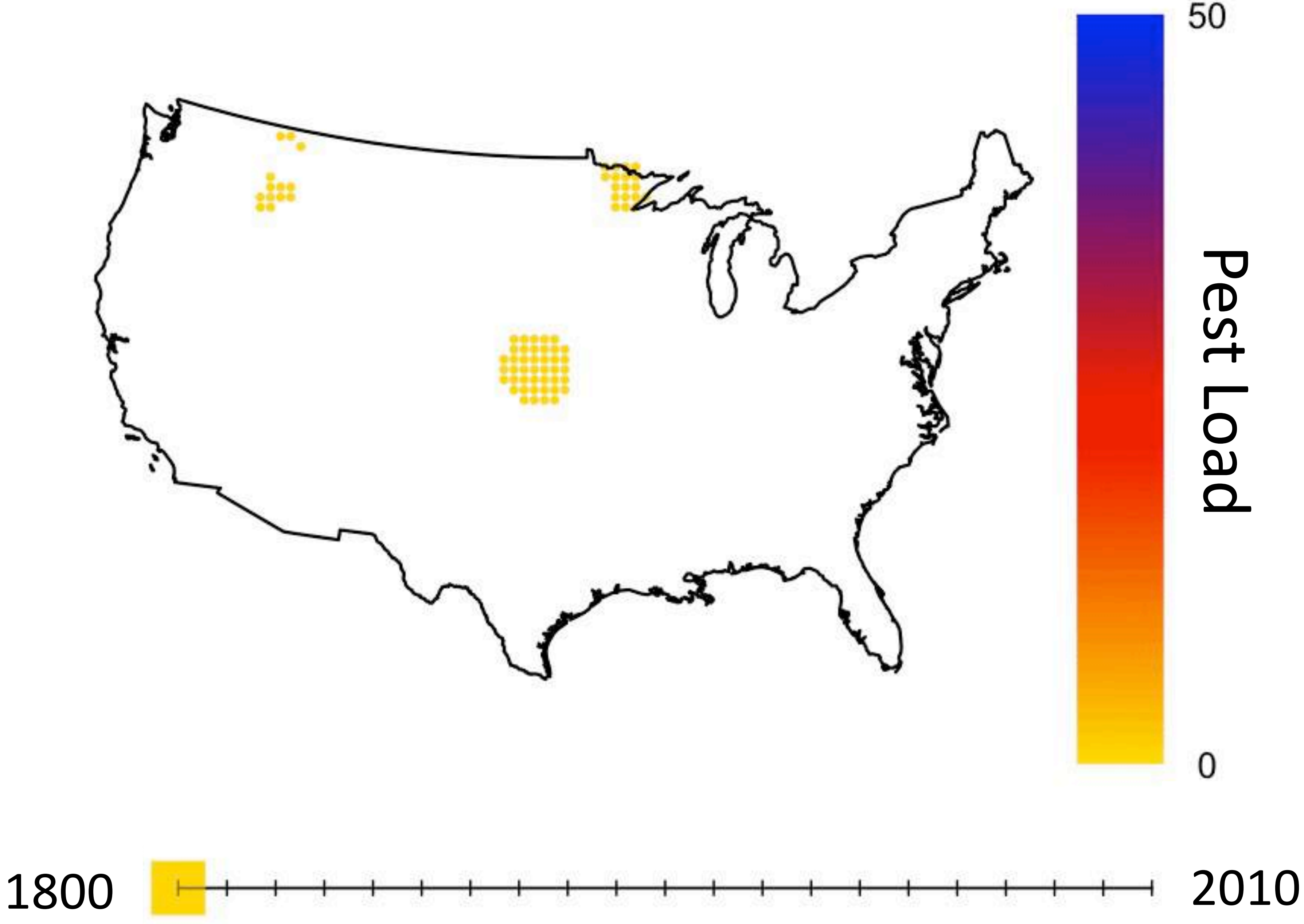
- Root mean squared error in dispersal distance
- Sensitivity TP/(TP+FN)
- Specificity TN/(TN+FP)
- Accuracy (TP+TN)/(TP+TN+FP+FN)
- Spatial Accuracy (complex functions)







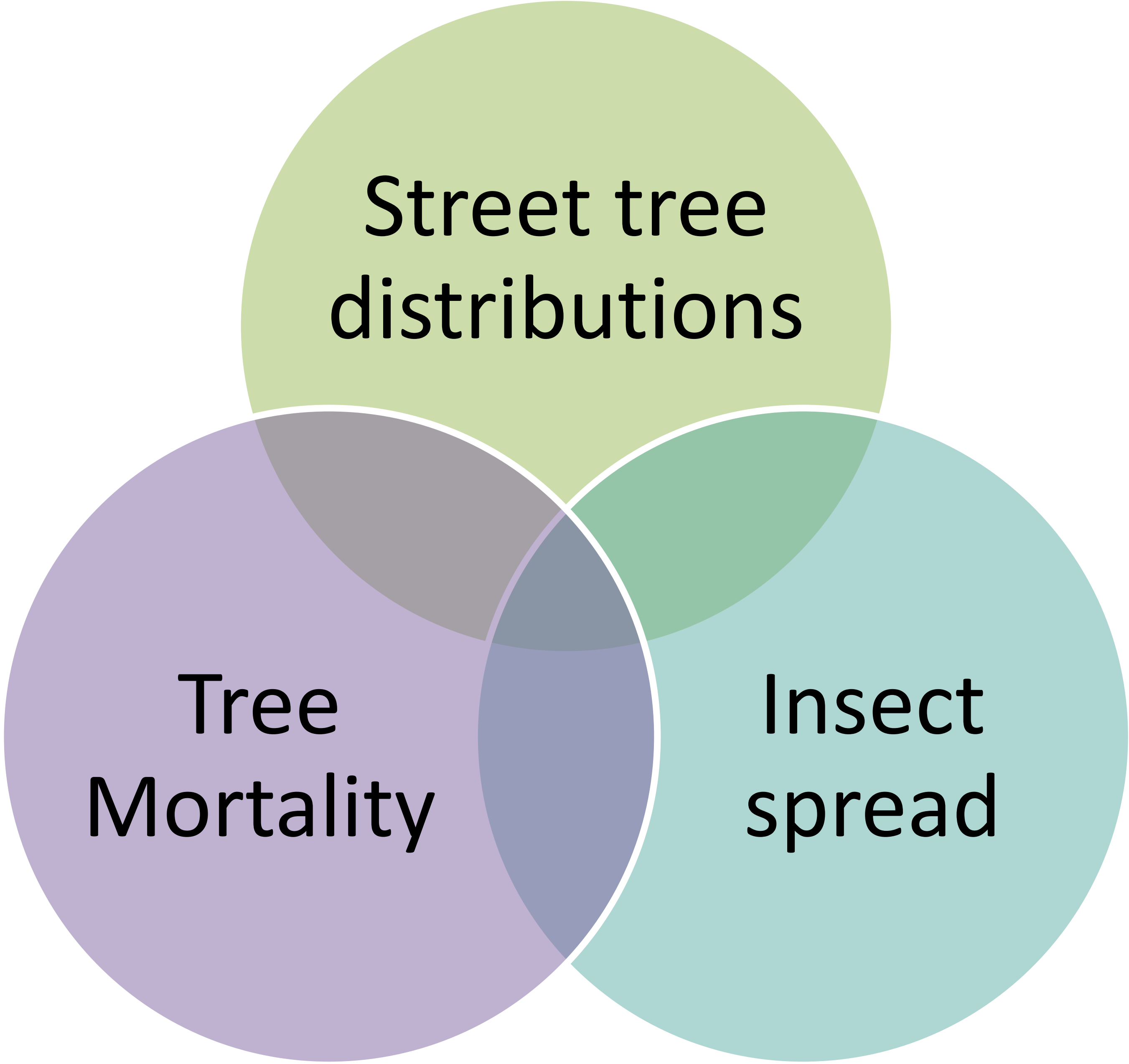
Hudgins et al. (2017) *Ecology Letters*



Hudgins et al. (2017) *Ecology Letters*

2. Economic models of impacts

Nature-based solutions under threat



Hudgins, E.J., Koch, F. H., Ambrose, M. J., & Leung, B. (2022). *Journal of Applied Ecology*

Extrapolating from 600 to ~30,000 communities

Hurdle Model:

Predicted number of trees of a given genus= Probability of tree presence * number of trees present, given presence

Binomial model * Poisson Model

Koch et al. (2018) *Forest Ecol. Manage.*

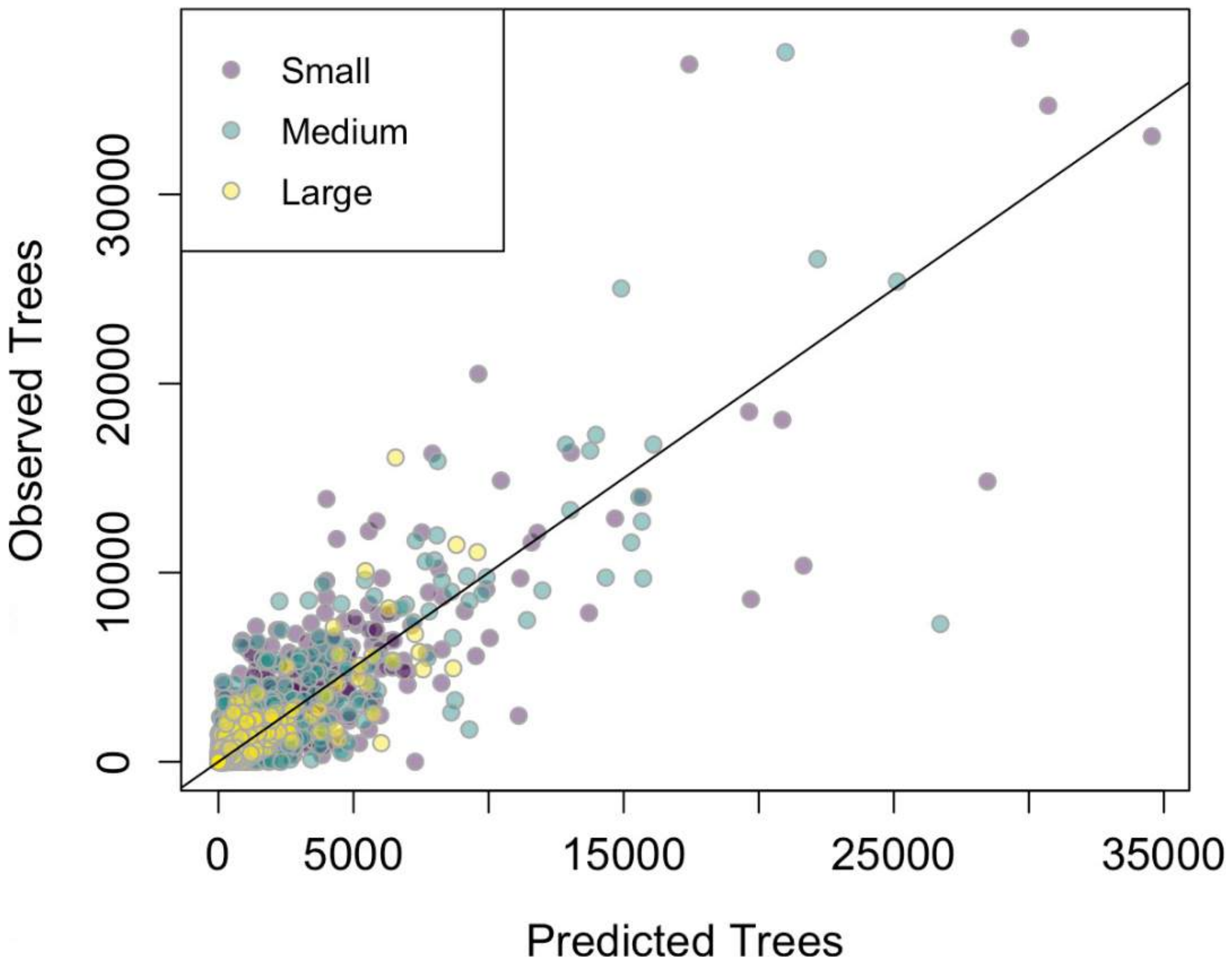
Genus-level models

Small: $R^2 = 0.78$

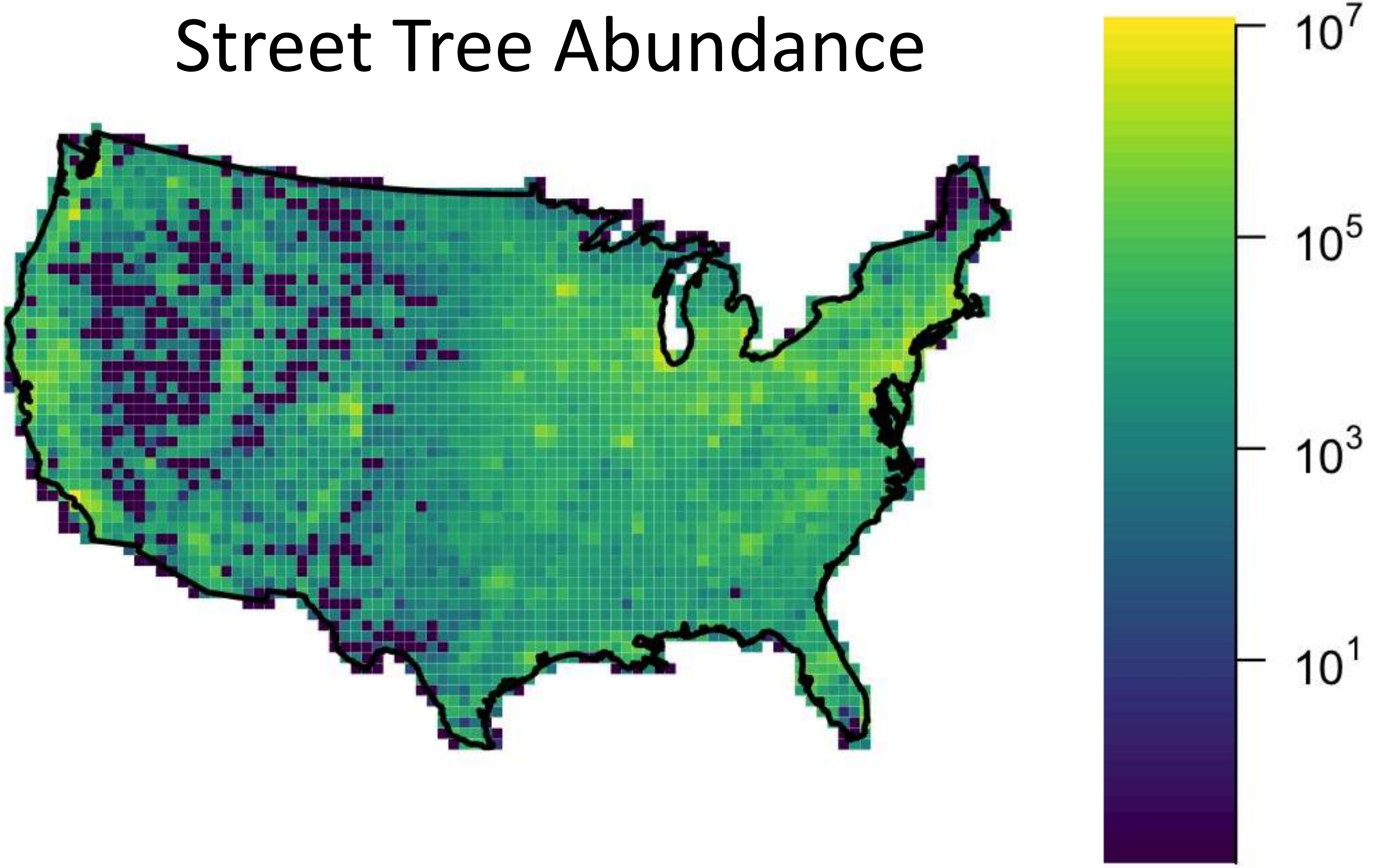
Medium: $R^2 = 0.83$

Large: $R^2 = 0.77$

Overall $R^2 = 0.80$

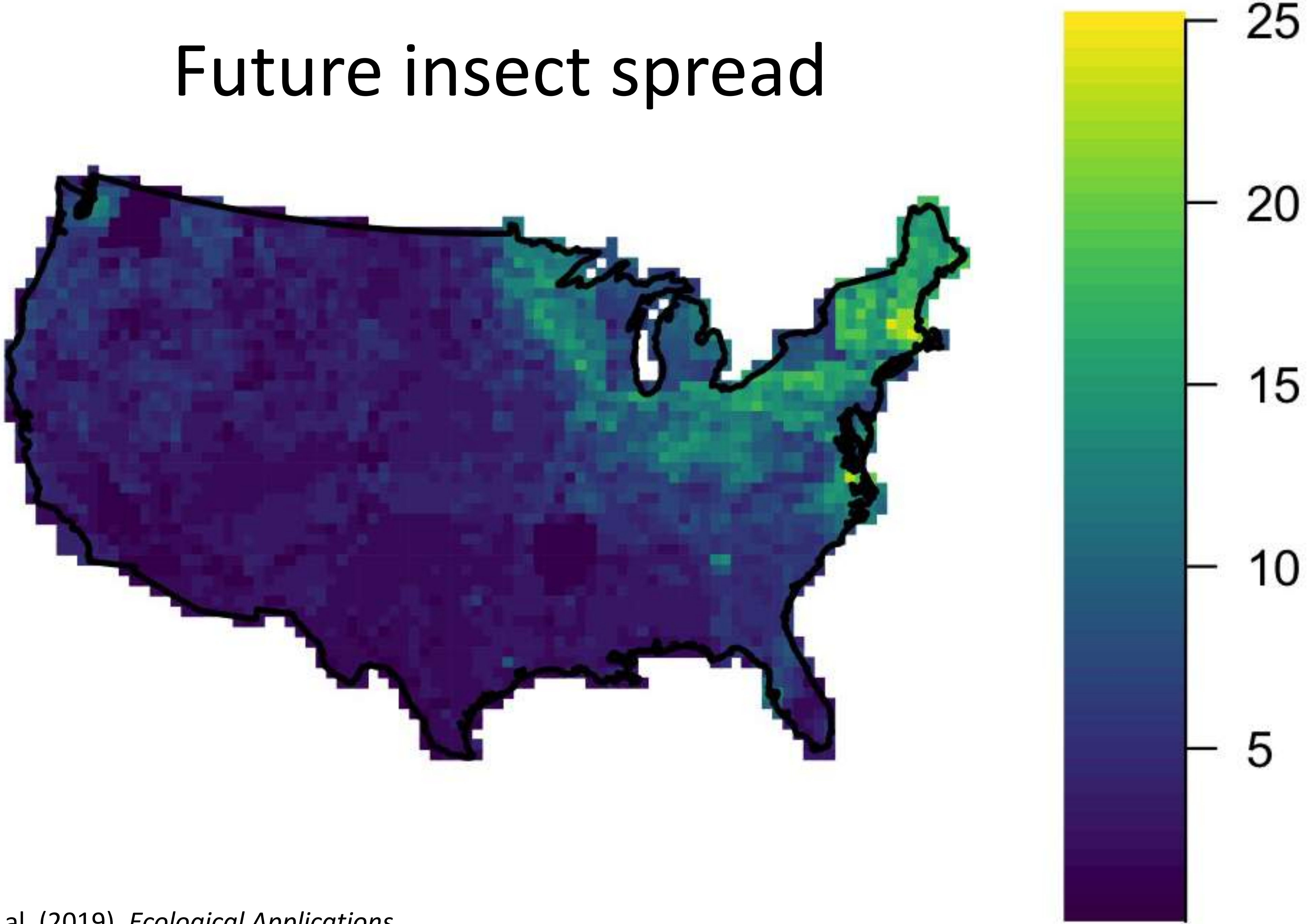


Street Tree Abundance



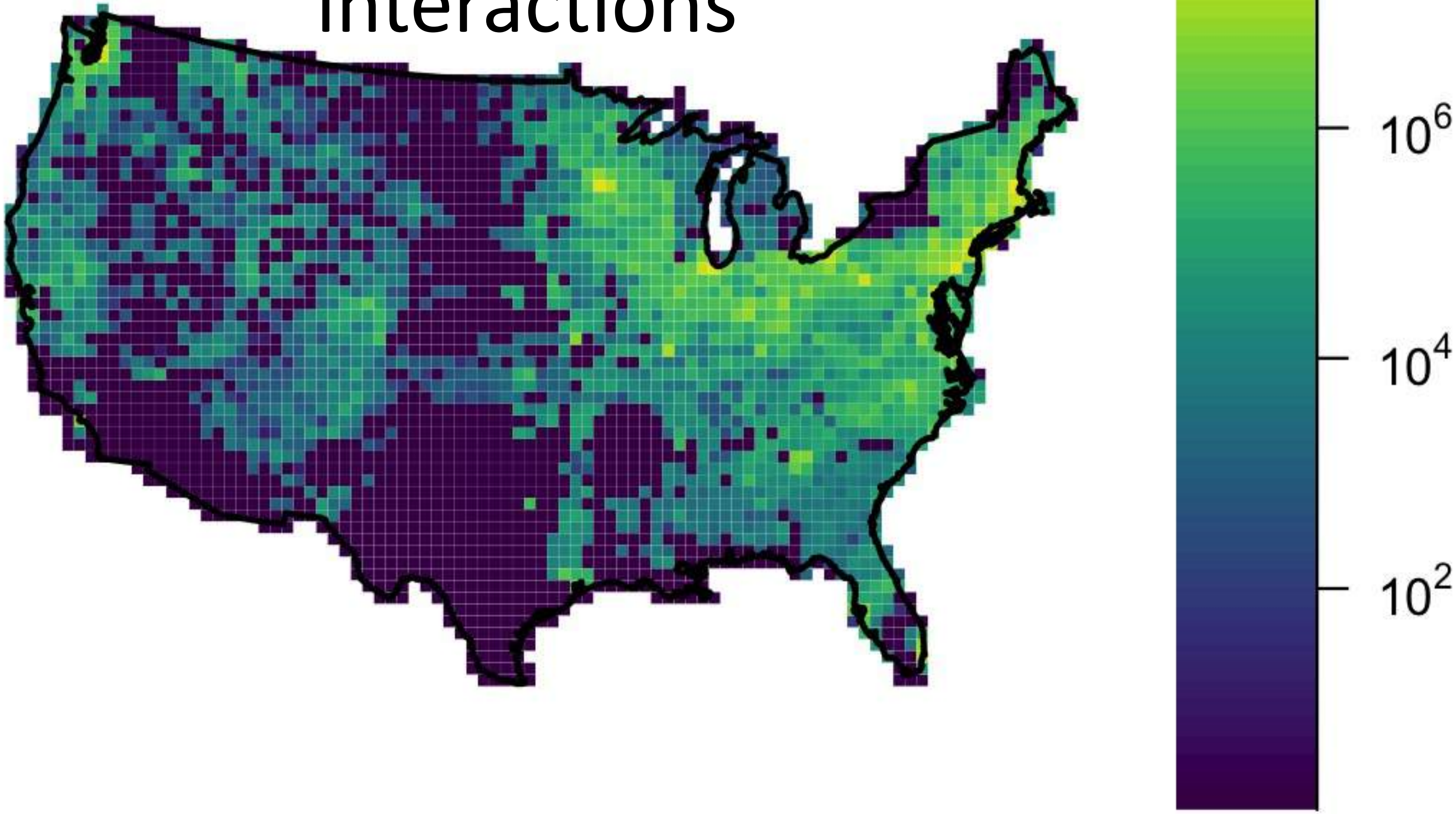
Hudgins et al. (2022). Journal of Applied Ecology

Future insect spread



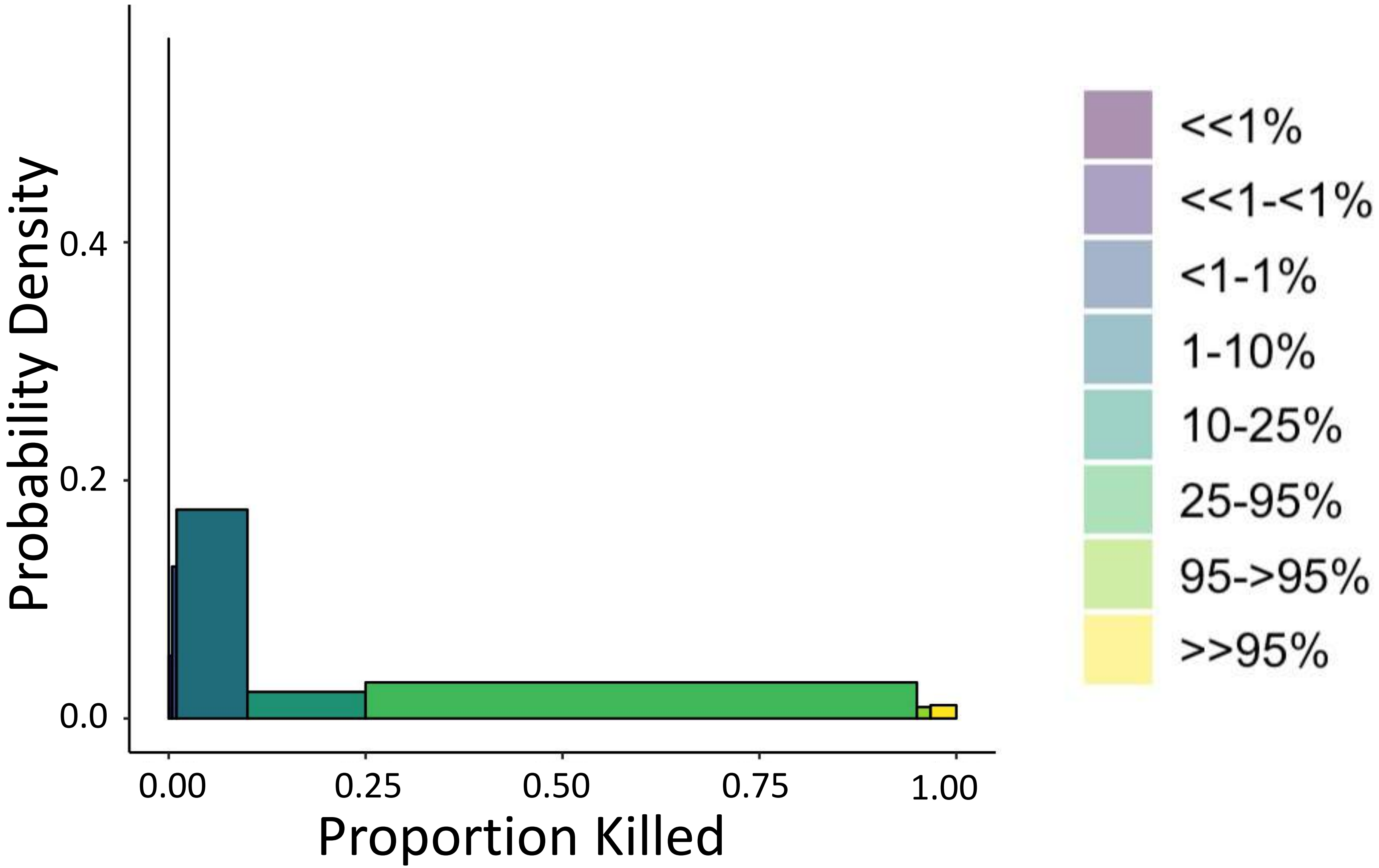
From Hudgins et al. (2019). *Ecological Applications*

Future street tree-insect interactions

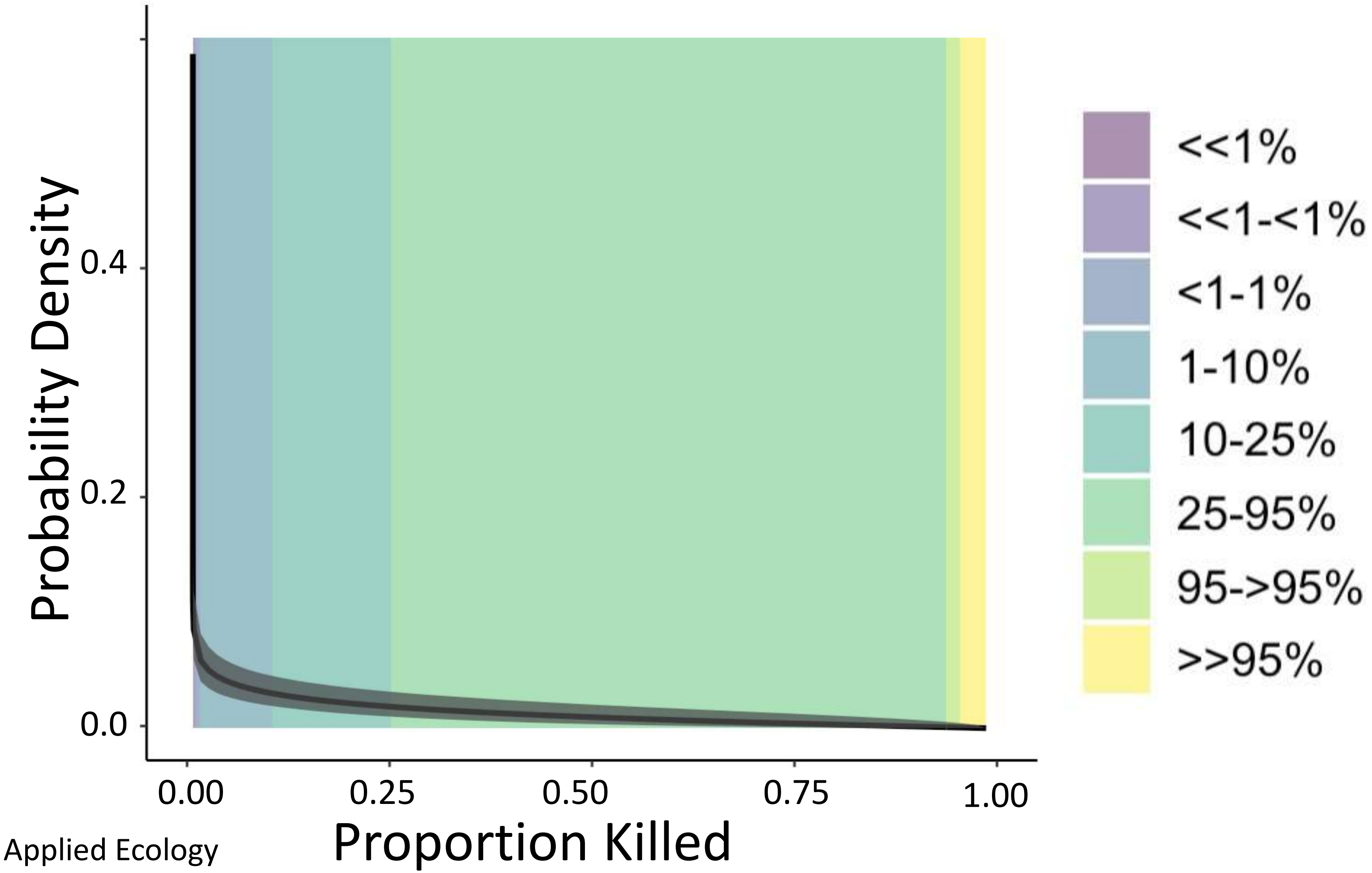


Hudgins et al. (2022) *Journal of Applied Ecology*

Street Tree Mortality



Street tree mortality



Hudgins *et al. 2022* Journal of Applied Ecology

Damage estimates to 2050

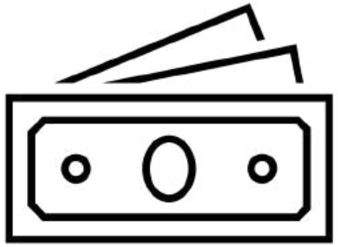
1.5M trees killed

94% in 23% of communities

$31M USD/yr, $907M total

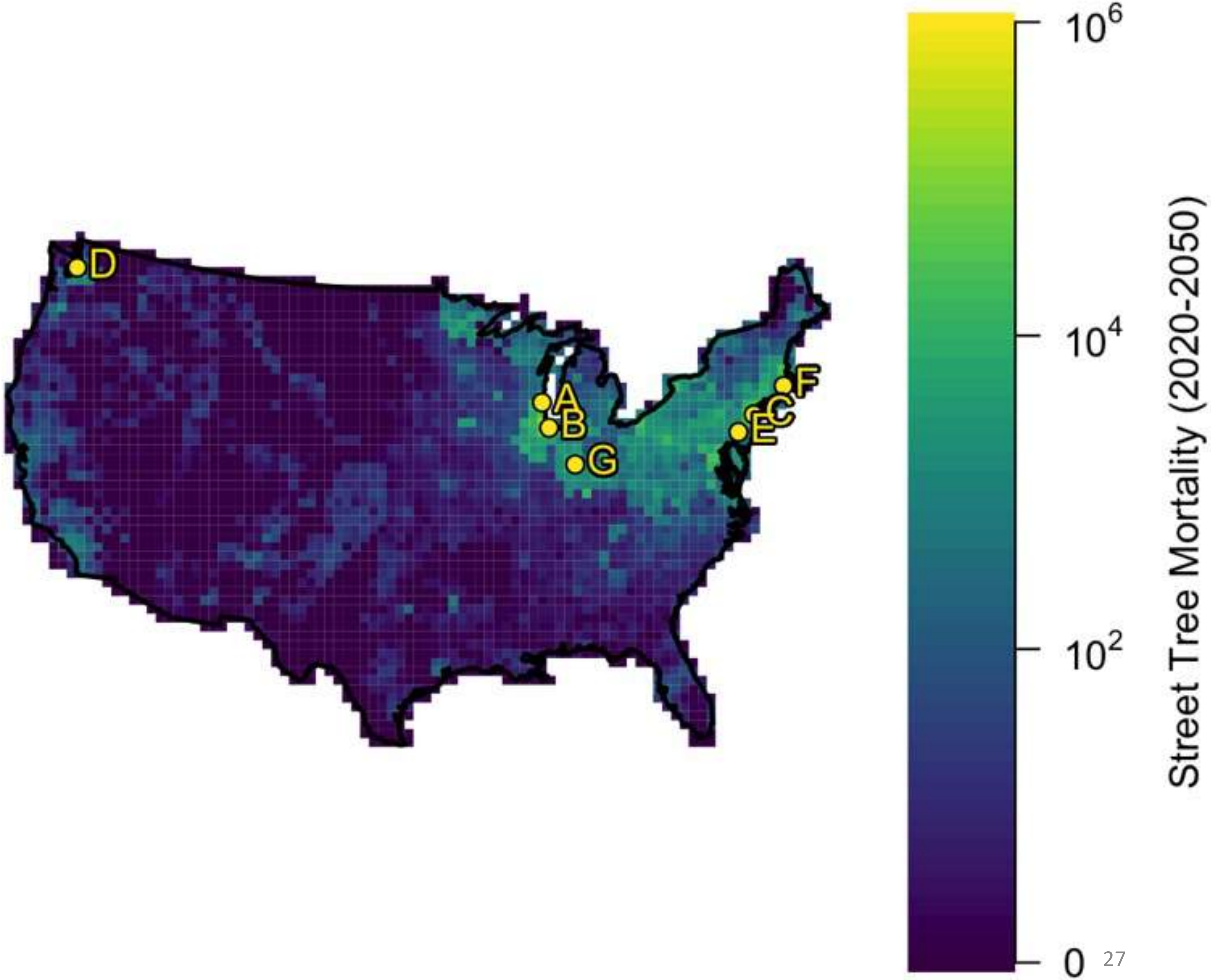
Hudgins *et al.* 2022. Journal of Applied Ecology

Triblive.com



damages up to $13M

A. Milwaukee, WI
B. Chicago Region, IL
C. New York City, NY
D. Seattle, WA
E. Philadelphia, PA
F. Warwick, RI
G. Indianapolis, IN



Hudgins *et al.* 2022. Journal of Applied Ecology

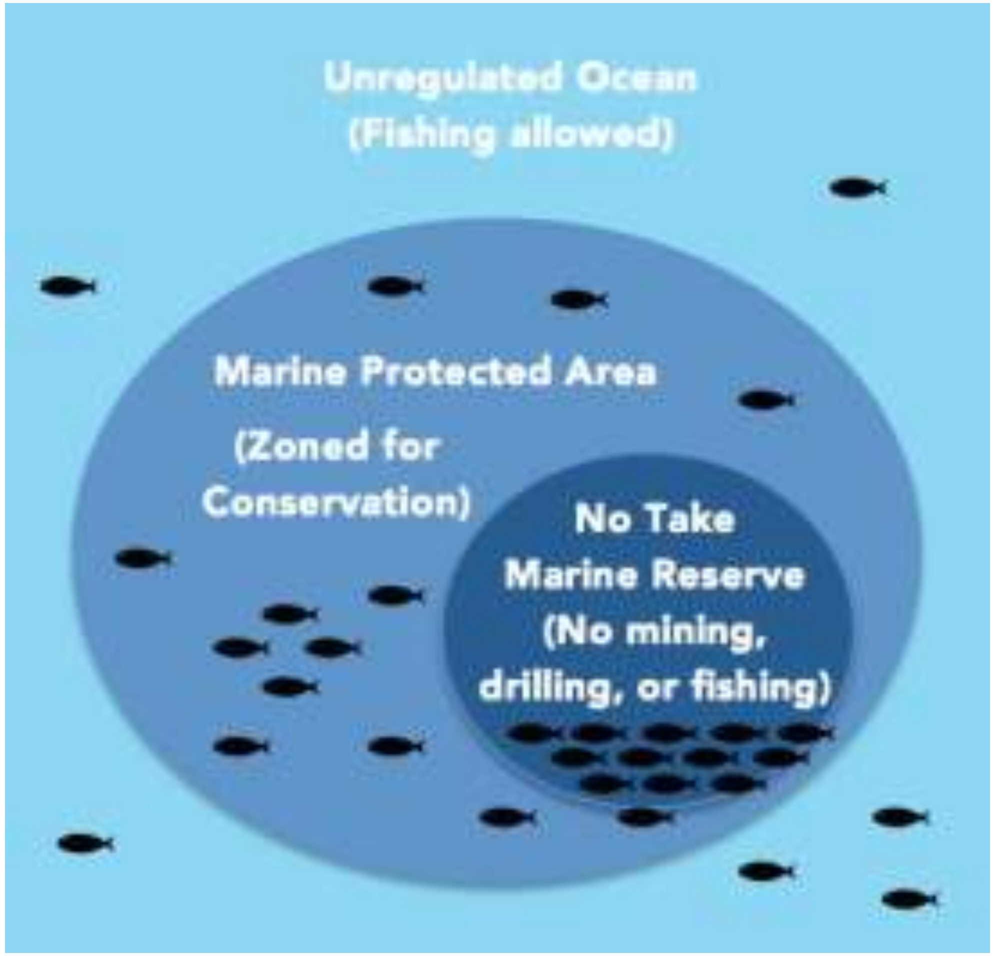
So far

- Focused on getting the best estimate of the current situation
- Descriptive rather than prescriptive
- Doesn't take into account which management options are available, budget, and interactive effect of spread

This is where Optimization and Spatial Planning come in!

Spatial Planning

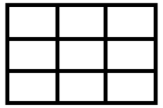
- **Structured decision problem:** selection of an option among a set of alternatives
- Alternatives are typically locations and therefore spatially explicit
- Parameters are known and the solution (decision) can be computed
- Forces transparency around management decisions
- **Transparent and more defensible decision making process**



https://mathmarecol.github.io/SpatialPlanning_Workshop2021/overview-of-the-conservation-planning-problem.html

Key Terms

- **Study Area**: all the areas relevant to the decision maker



- **Planning units**: discrete localities in the study area that can be managed independently of other areas, often created as grid cells that are sized according to the scale of the management actions

- **Cost**: This should be specified for each potential intervention, and could either be a function of pest density or constant.

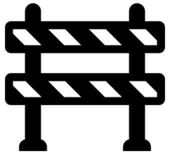
Key Terms Cont'd

- **Objectives**: the overall goal of a conservation planning problem (either a minimization or maximization)
- **Constraints**: Constraints can be used to ensure that solutions exhibit a range of different characteristics, such as total costs meeting a budget
- **Efficiency:** A common specification for the impact a decision has on the objective function (e.g. % population reduction)

Optimizations

- The *objective function* describes the quantity we are trying to minimize (e.g. exposed hosts, cost) or maximize (e.g. healthy hosts, benefit-cost ratio).

- The *decision variables* describe the entities that we can control, and indicate which areas are selected for management, which of those are not, and what type of management is applied.

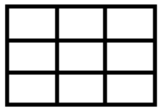


- C*onstraints* can be thought of as rules that the need decision variables need to follow. They not only include the budget, but can also formalize how management impacts the objective function (e.g. a treatment knocking down pest density)

Optimizations

Optimizations minimize (or maximize) an *objective function*

e.g. Minimize the number of trees exposed to a given pest across a study area of n planning units



$$\min \sum_{i=1}^{n} p_{i,t} h_i$$

$p_{i,t}$= pest presence/absence in site i
$h_{i,t}$= host abundance in site

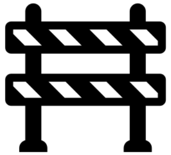
Optimizations

Optimizations minimize (or maximize) an *objective function* **that is calculated using a set of *decision variables*, subject to a series of *constraints***

$$\min \sum_{i=1}^{n} p_i h_i$$

Such that

$p_i = 1 - m_i$ Effect of management



$\sum_{i=1}^{n} m_i \leq B$ Budget constraint

$m_i \in \{0,1\}$ Binary Decision Variable

Optimizations

5	2	3
10	1	8
7	2	6

For B=3, optimal management decision is to manage the 3 sites with the greatest host volume

$$\min \sum_{i=1}^{n} p_i h_i$$

Objective value at optimal solution
= 5+2+3+0+1+0+0+2+6
= 19

Optimizations

5	2	3
10	1	8
7	2	6

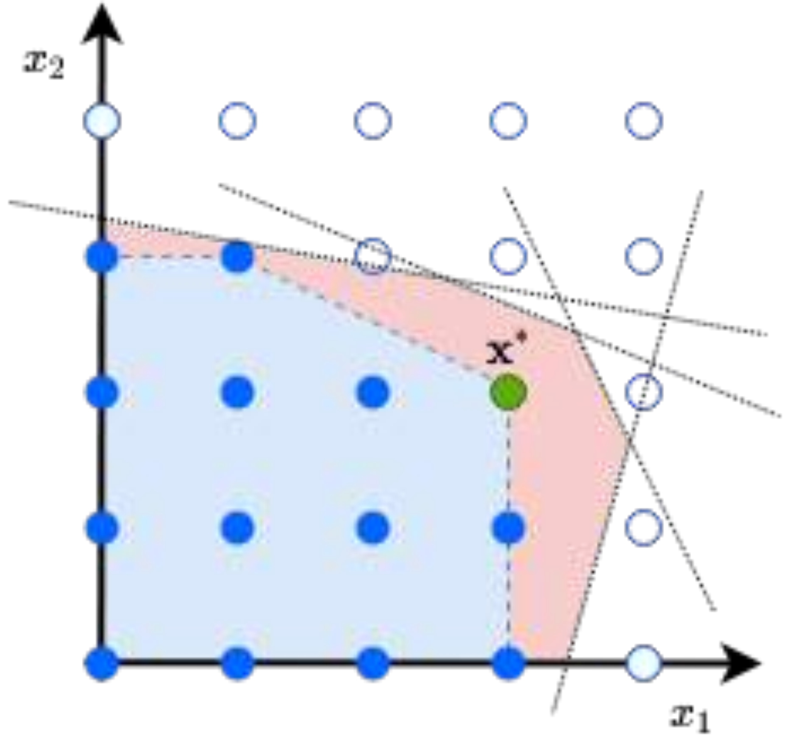
For B=3, optimal management decision is to manage the 3 sites with the greatest host volume

$$\min \sum_{i=1}^{n} p_i h_i$$

Objective value at suboptimal solution
= 0+0+0+10+1+8+7+2+6
= 34

Mixed Integer Linear Programs

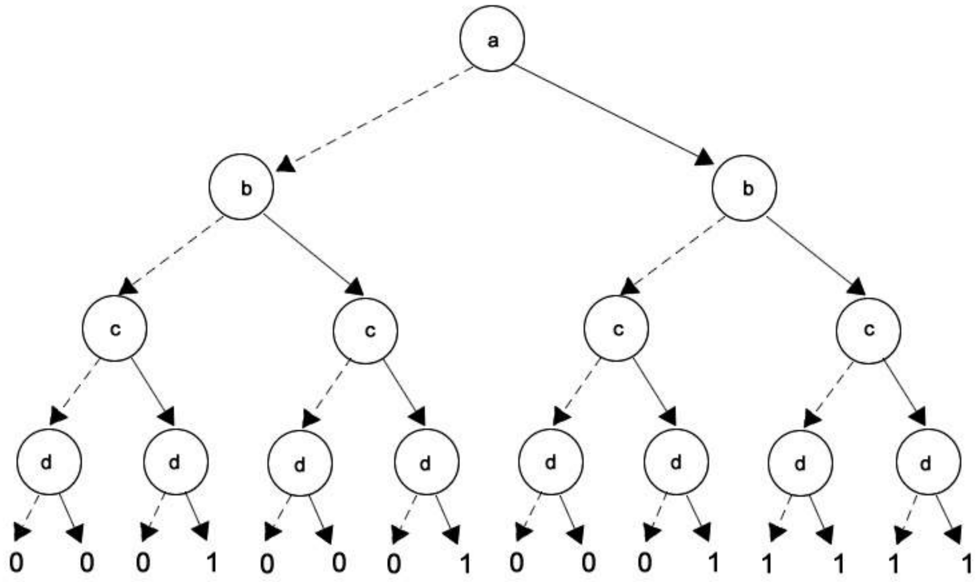
- Statistical models tend to have continuous values of variables
- Decision variables are all or nothing (usually)
- It is much harder for computers to fit integers, and continuous solutions can be wildly different than integer solutions
- The solver works on the continuous problem and then tries to work back to an integer version



Towardsdatascience.com

Large decision problems

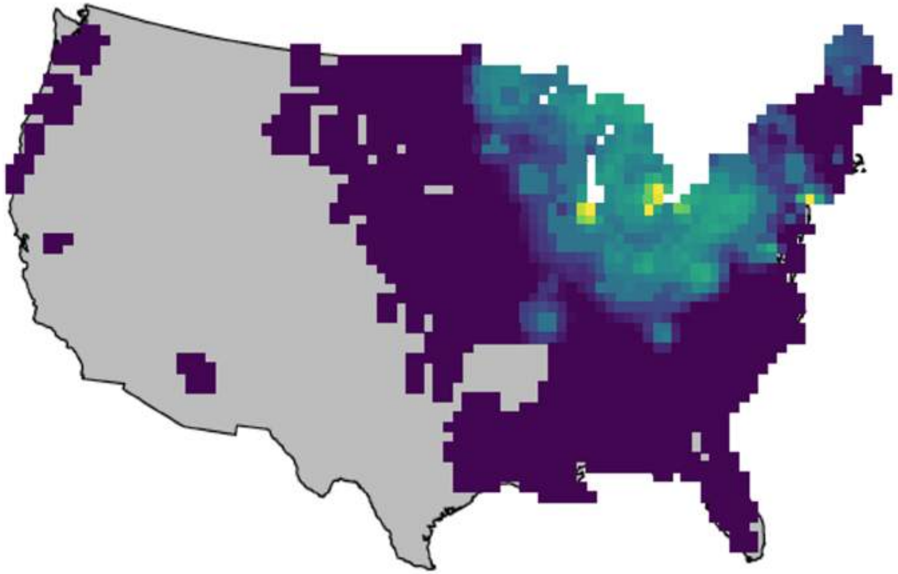
- Complexity of possible decisions scales combinatorically (for binary decisions, 2^n where n is the number of planning units)
- We need to use software to help
- This software works best when problems are specified as simple inequalities where variables do not get multiplied (these are considered nonlinear problems)



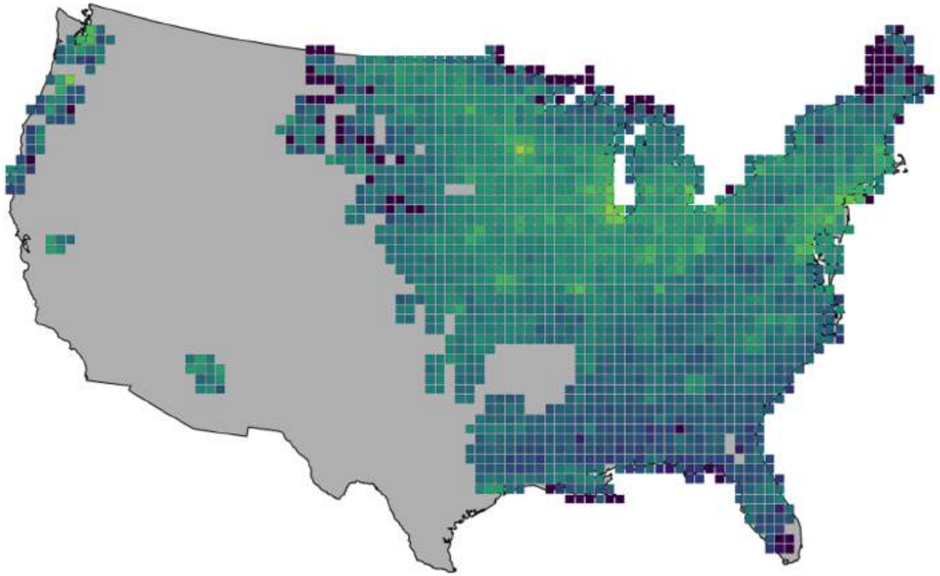
Example 1. Optimal Emerald Ash Borer management

Hudgins, E.J., Hanson, J.O., MacQuarrie, C., Yemshanov, D., McDonald-Madden, E., Holden, M., Baker, C., Bennett, J.R., *in prep*

Predicted EAB density



Predicted street ash

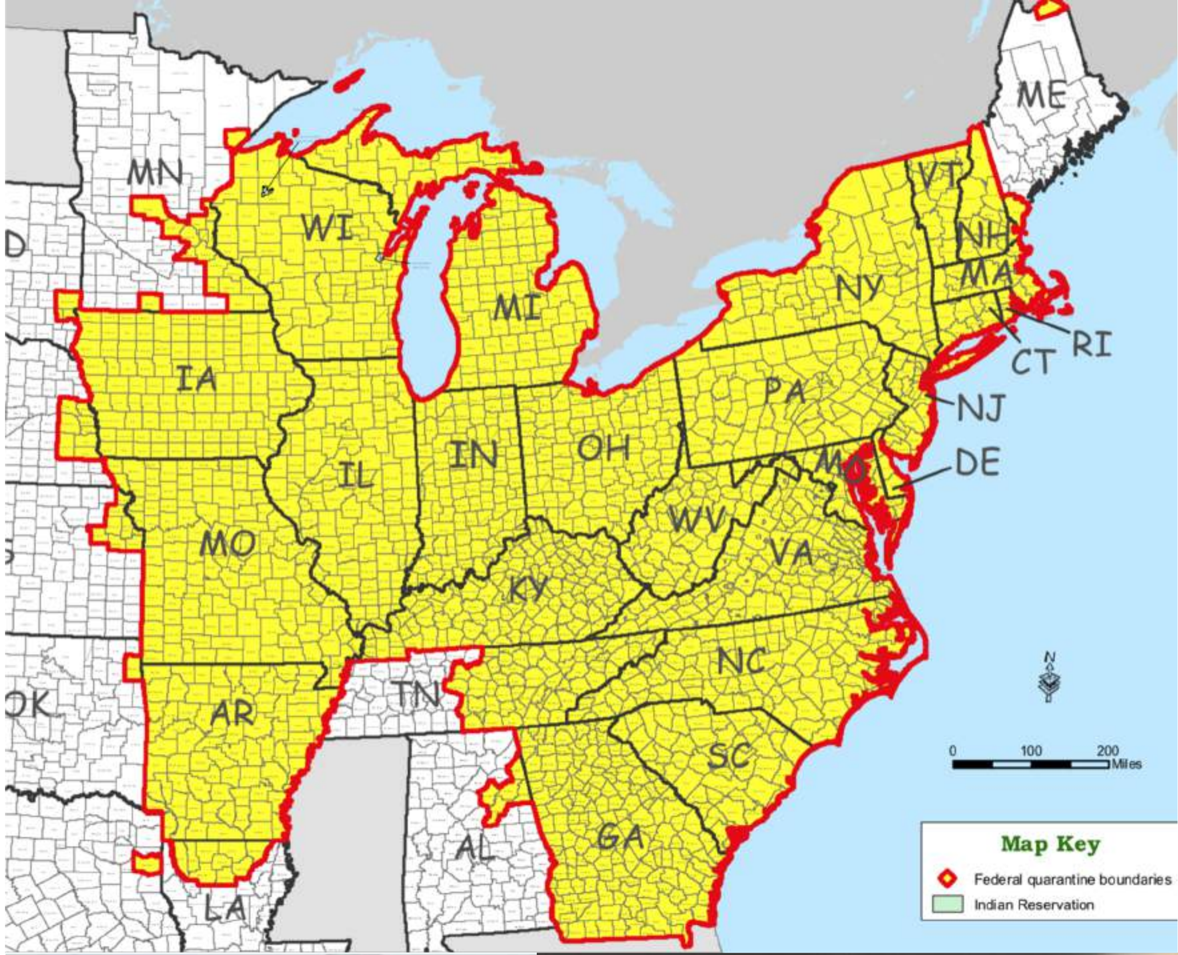


Management Actions

Immigration Quarantine $\alpha_{i,t}$

Emigration Quarantine $\beta_{i,t}$

Biological control release $\gamma_{i,t}$

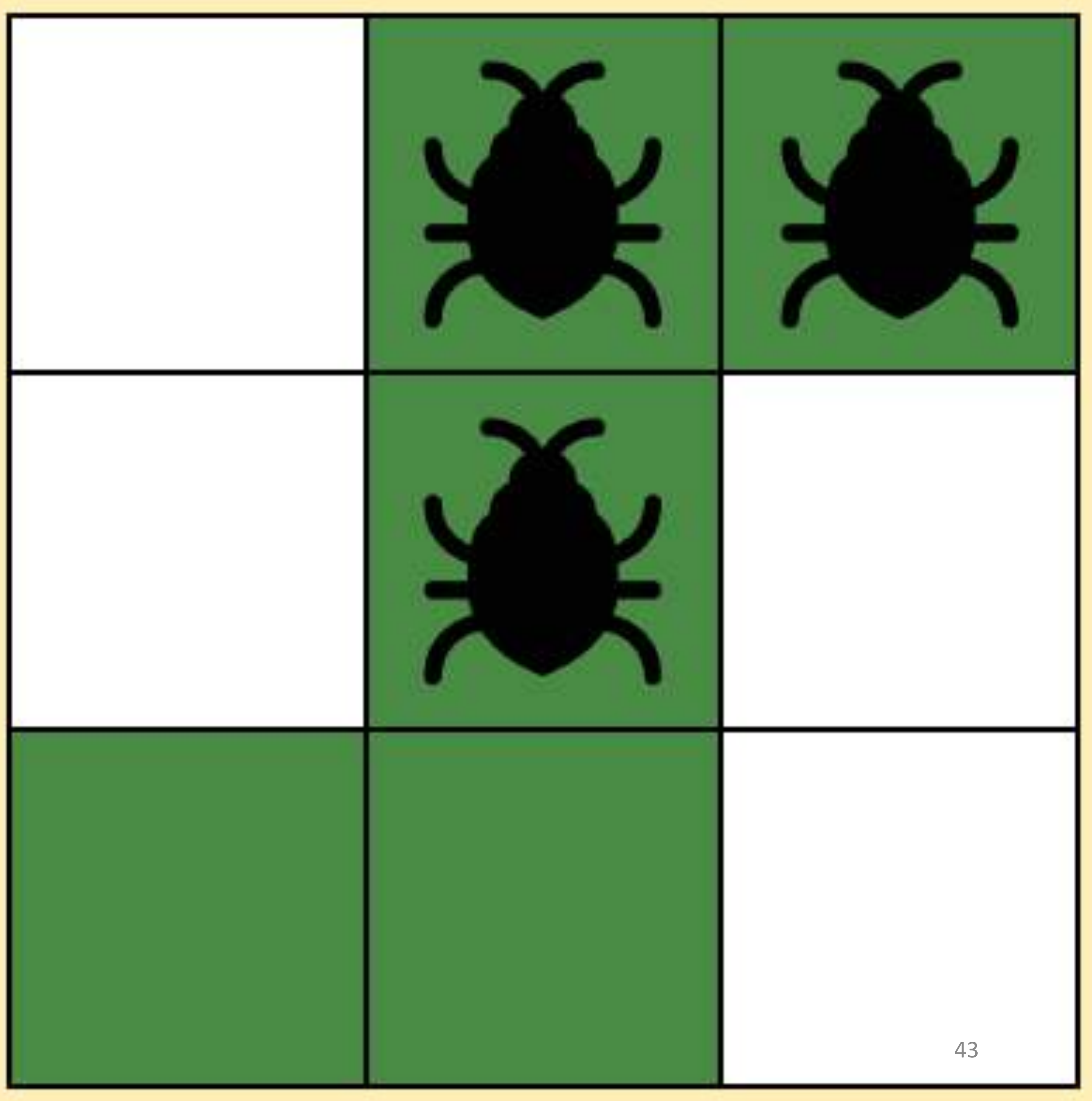


Rationale

Immigration Quarantines limit **dispersal in**

Emigration Quarantines limit **dispersal out**

Biological control reduces **focal densities**



Objective

Minimize the number of street trees exposed to EAB over time within the budget

Exposure = Ash trees in cell * EAB density in cell

$$\sum_{t} \sum_{i} P_{i,t} V_i$$

Constraints

$\alpha_{i,t}, \beta_{i,t}, \gamma_{i,t} \epsilon \{0,1\}$ Decision variables

$\alpha_{i,t} + \beta_{i,t} + \gamma_{i,t} \leq 1$ One action per cell

$\sum_i \alpha_{i,t} c_\alpha + \beta_{i,t} c_\beta + \gamma_{i,t} c_\gamma \leq B$ Management Budget with costs c

$0 \leq P_{i,t} \leq 1$ Continuous pest density (expressed as proportion of carrying capacity)

Impact of Management

$$P_{i\ ,t+1} = \left[P_{i,t} + \sum_j P_{j,t} M_{j,i,t} - \sum_j P_{i,t} M_{i,j,t}\right] \delta$$

Density at the next timestep in the absence of management =

[Current Density

+Sum(Immigrant propagules)

– Sum(Emigrant propagules)]*Growth Rate

Impact of Management

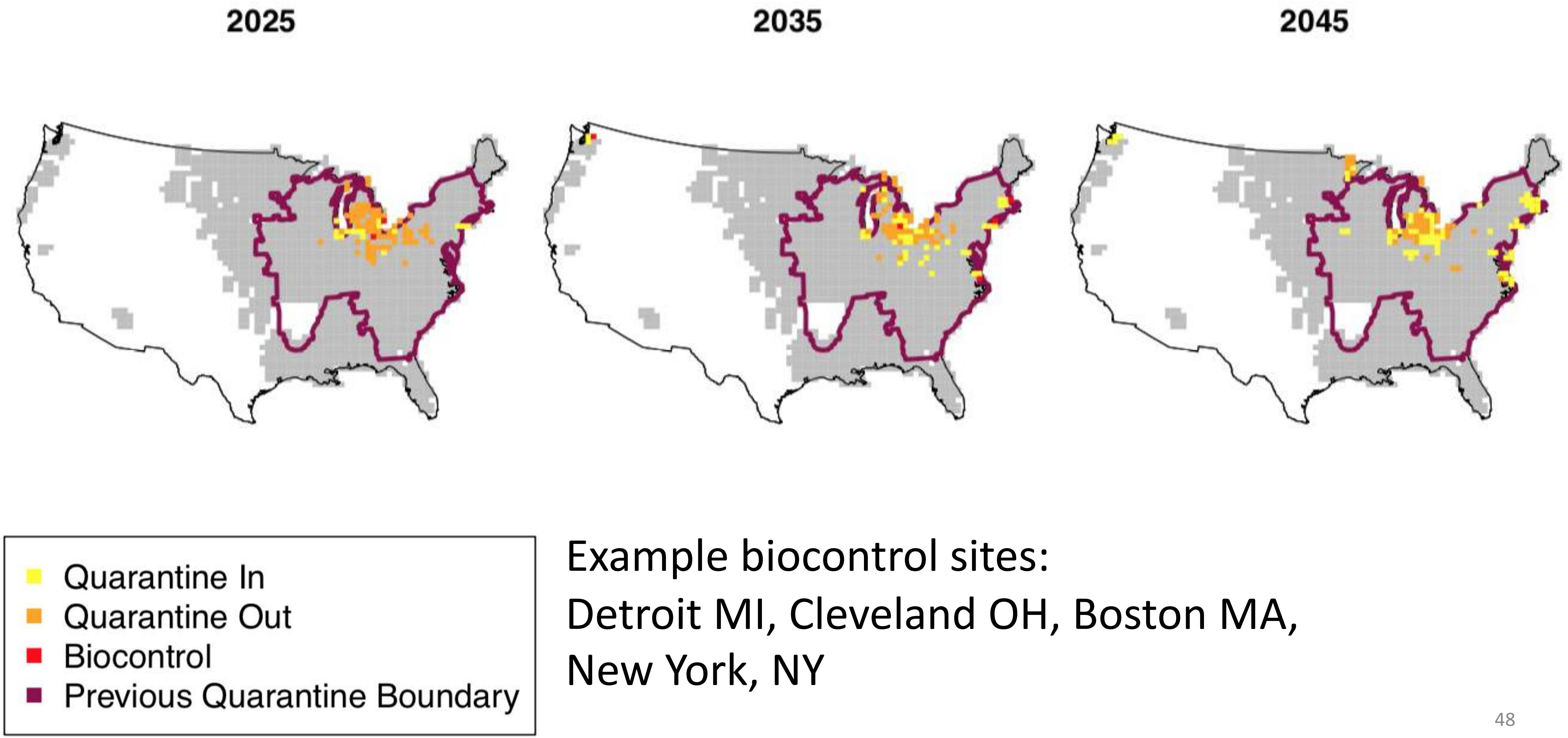
$$P_{i,t+1} = \left[P_{i,t} \left(1 - \varepsilon_\gamma \gamma_{i,t}\right) + \sum_j P_{j,t} M_{j,i,t} \left(1 - \varepsilon_\alpha \alpha_{i,t}\right) - \sum_j P_{i,t} M_{i,j,t} \left(1 - \varepsilon_\beta \beta_{i,t}\right) \right] \delta$$

Density at the next timestep with management =

[Current Density*(1-Biocontrol Decision*Biocontrol efficiency)

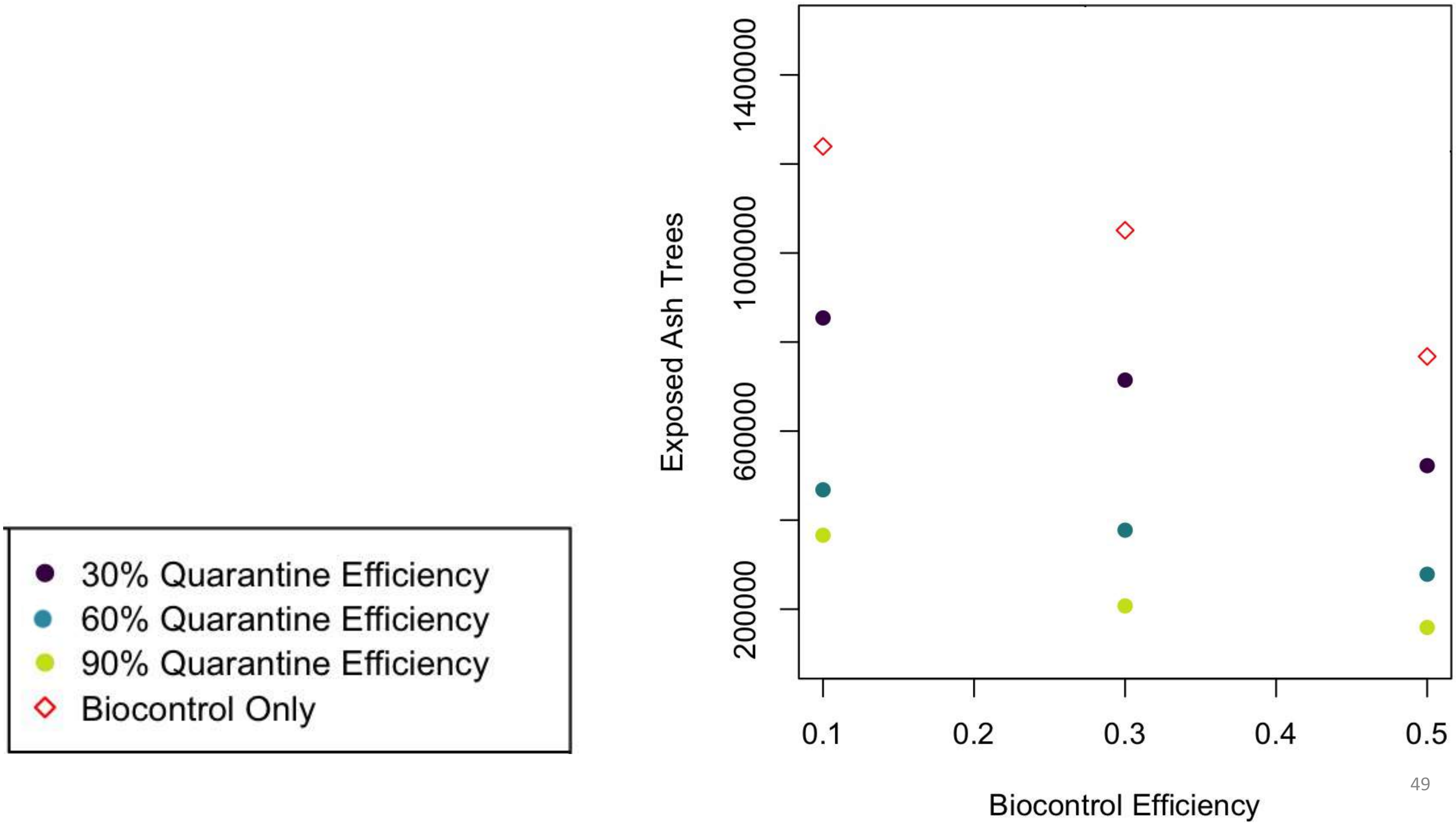
+Sum (Immigrant propagules*(1-Immigration Quarantine Decision*Immigration Quarantine efficiency)

– Sum(Emigrant Propagules*(1-Emigration Quarantine Decision*Emigration Quarantine Efficiency))]*Growth Rate



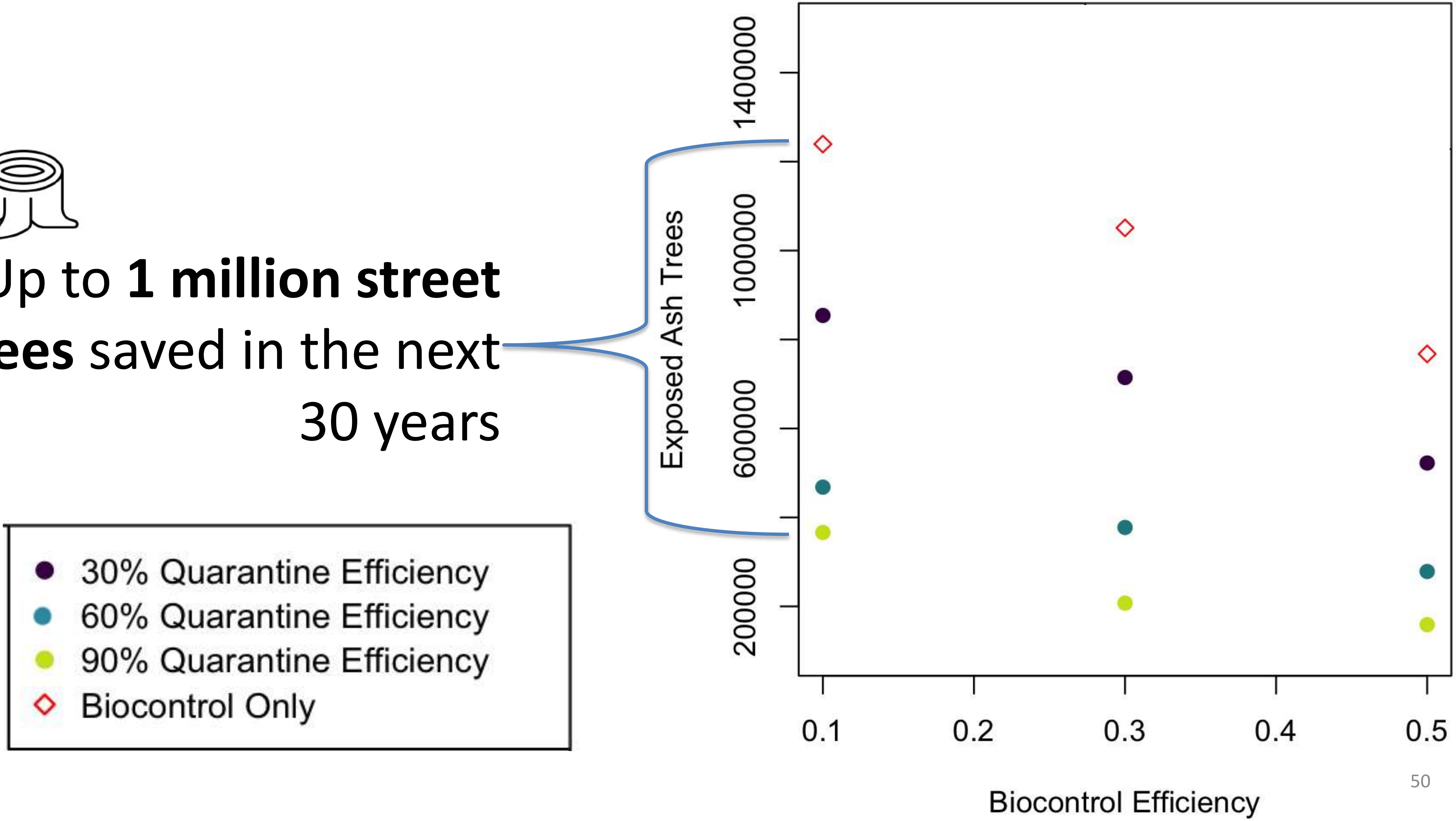
Example biocontrol sites:

Detroit MI, Cleveland OH, Boston MA, New York, NY



Exposed Ash Trees
1400000
1000000
600000
200000
0.1
0.2
0.3
0.4
0.5
Biocontrol Efficiency
30% Quarantine Efficiency
60% Quarantine Efficiency
90% Quarantine Efficiency
Biocontrol Only

Up to **1 million street trees** saved in the next 30 years

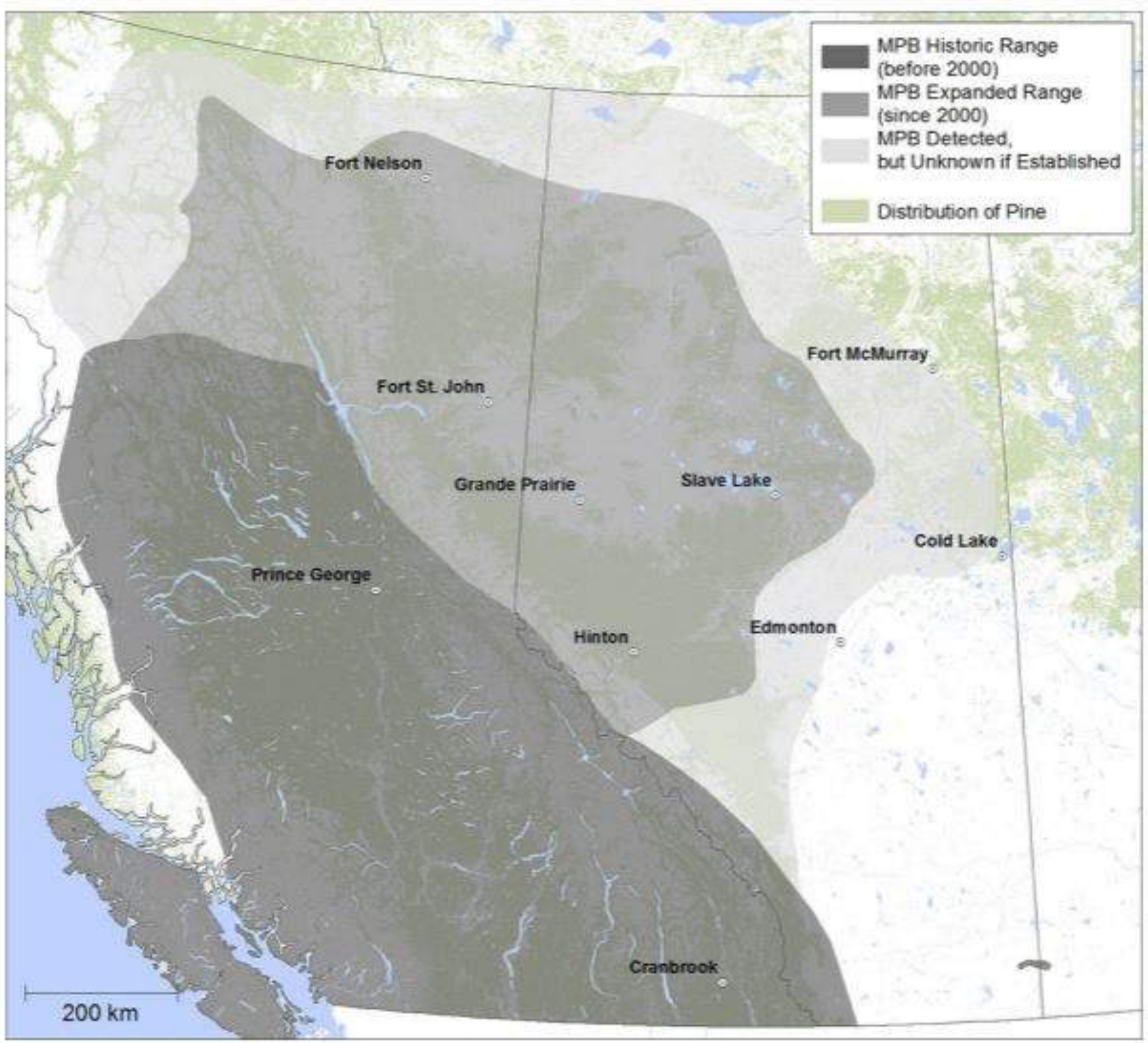


Take Home Messages

- Statistical models work to describe and predict a system, but are not sufficient to decide what **should** be done to change dynamics
- Spatial planning requires tools designed for binary decision variables, and involves setting an objective subject to constraints
- Optimizations can lead to huge cost and conservation benefits compared to conventional wisdom

Example 2. MPB Cooperation

Saskatchewan currently pays Alberta to manage Mountain Pine Beetle and limit its eastward spread



Up to $1M approved by Saskatchewan government to battle mountain pine beetle threat

By Moises Canales-Lavigne • Global News
Posted December 6, 2021 11:24 am

How much, if any, money should Saskatchewan transfer to Alberta in order to control the spread of mountain pine beetle?

Optimization + Game Theory can help!

Two-Way Nash Game

		friend 1	
		work	sleep
friend 2	work	-2,-2	(3,-4)
	sleep	(-4,3)	(3,3)

The Prisoner's Dilemma

The prisoner's dilemma

Prisoner A \ Prisoner B	Confess	Keep quiet
Confess	Both go to jail for ten years	Prisoner B gets life imprisonment, A goes free
Keep quiet	Prisoner A gets life imprisonment, B goes free	Both go to jail for one year

Economist.com

PRISONER 2

PRISONER 1	Confess	Lie
Confess	-8 , -8	0 , -10
Lie	-10 , 0	-1 , -1

Extended for Mountain Pine Beetle

Saskatchewan

Alberta	Spend 200	Spend 400	Spend 500
Spend 500	X	X	100, 20
Spend 600	X	50, 15	X
Spend 800	40, 10	X	X

Assume both provinces have a budget of 500, and Saskatchewan can transfer funds to Alberta

The matrix shows infested area in each province as a result of the strategy

The payoff is highest for both parties when Saskatchewan transfers 300 to Alberta to give it a budget of 800.

Extended for Mountain Pine Beetle

Saskatchewan (columns) / **Alberta** (rows)

	Spend 200	Spend 400	Spend 500
Spend 500	X	X	100, 18
Spend 600	X	50, 19	X
Spend 800	40, 20	X	X

In contrast, there is no mutually beneficial strategy here

BUT the transfer of funds reduces the total area of the infestation

Increase federal funding for Alberta?

This problem is linear

$$\min \sum_{i=1}^{n} p_i h_i$$

Such that

$\boldsymbol{p_i = 1 - m_i}$	**Effect of management**
$\sum_{i=1}^{n} m_i \leq B$	Budget constraint
$m_i \in \{0,1\}$	Binary Decision Variable

This one isn't – intertemporal constraint

$$\min \sum_{t=1}^{5} \sum_{i=1}^{n} p_{it} h_i$$

Such that

$$\boldsymbol{p_{it+1} = (1 - m_{it}) p_{it}}$$ **Effect of management**

$$\sum_{i=1}^{n} m_{it} \leq B$$ Budget constraint

$$m_i \in [0,1]$$ Binary Decision Variable

This one isn't – intertemporal constraint

$$\min \sum_{t=1}^{5} \sum_{i=1}^{n} p_{it} h_i$$

Such that

$$p_{it+1} = p_{it} - m_{it}\, p_{it}$$ Effect of management

This one isn't – intertemporal constraint

$$\min \sum_{t=1}^{5} \sum_{i=1}^{n} p_{it} h_i$$

Such that

$$p_{it+1} = p_{it} - m_{it}\, p_{it}$$

Effect of management

$$p_{it+1} = p_{it} - v_{it}$$

Where $v_{it} = m_{it} p_{it}$

Minimizing host exposure over time depends on previous pest exposure, and management has a lasting effect over time

Linearization

$$v_{it} = m_{it} p_{it}$$

$$v_{it} \in [0,1]$$

We want it to equal 0 when either *m_{it} or p_{it} is equal to 0*

We want it equal to 1 when both are equal to 1

Linearization

$$v_{it} = m_{it} p_{it}$$
$$v_{it} \in \{0,1\}$$

$$v_{it} \geq m_{it} + p_{it} - 1$$
$$v_{it} \leq m_{it}$$
$$v_{it} \leq p_{it}$$

Think through the different scenarios of values of *m* and *p* to convince yourself that this is equivalent to multiplying the two binary variables