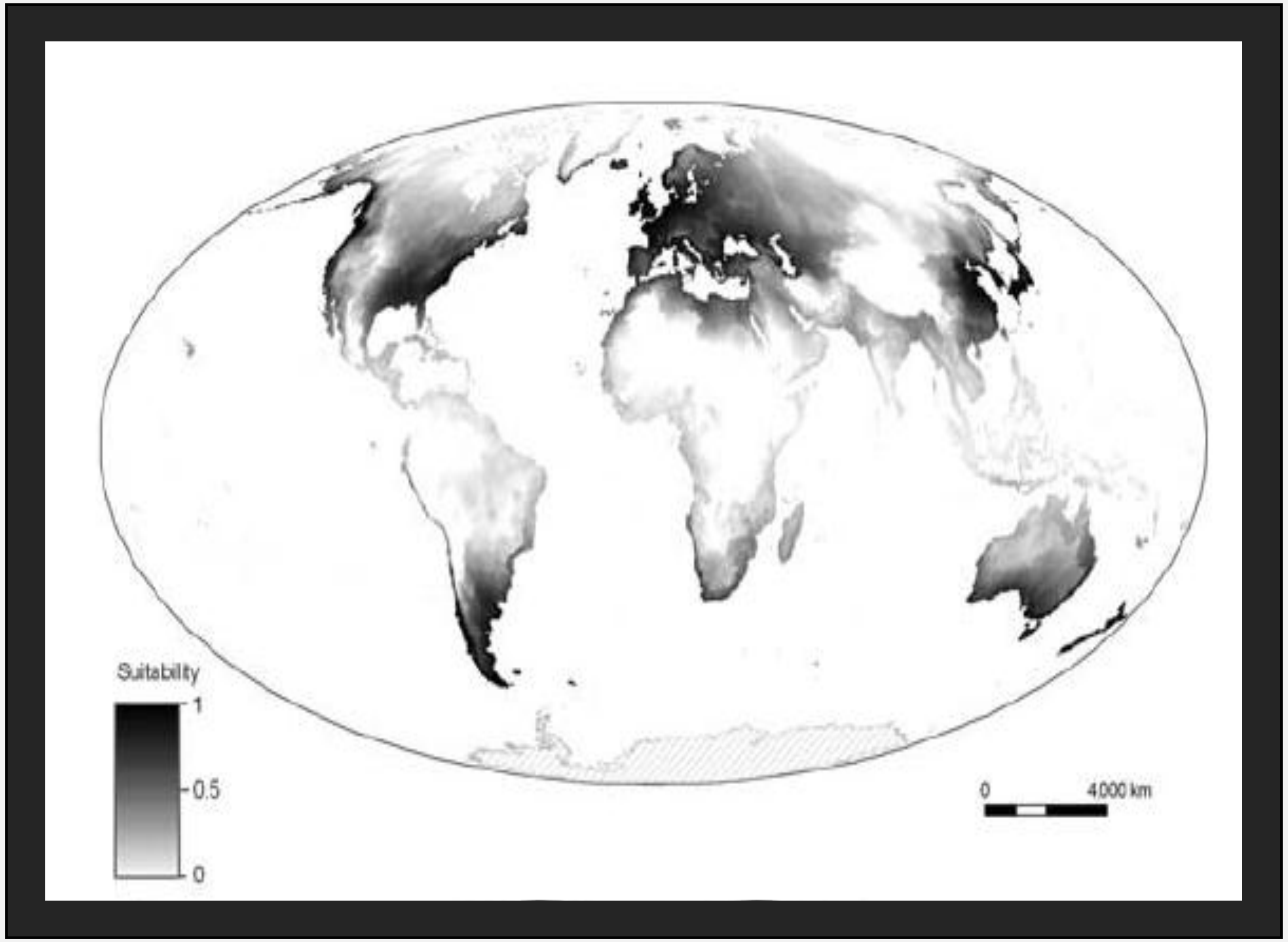
# Predictive ecology:
## Modeling the risk of pest invasions

Brian Leung
McGill University



# Predictive ecology:
## Modeling the risk of pest invasions

Overview

Options

Examples

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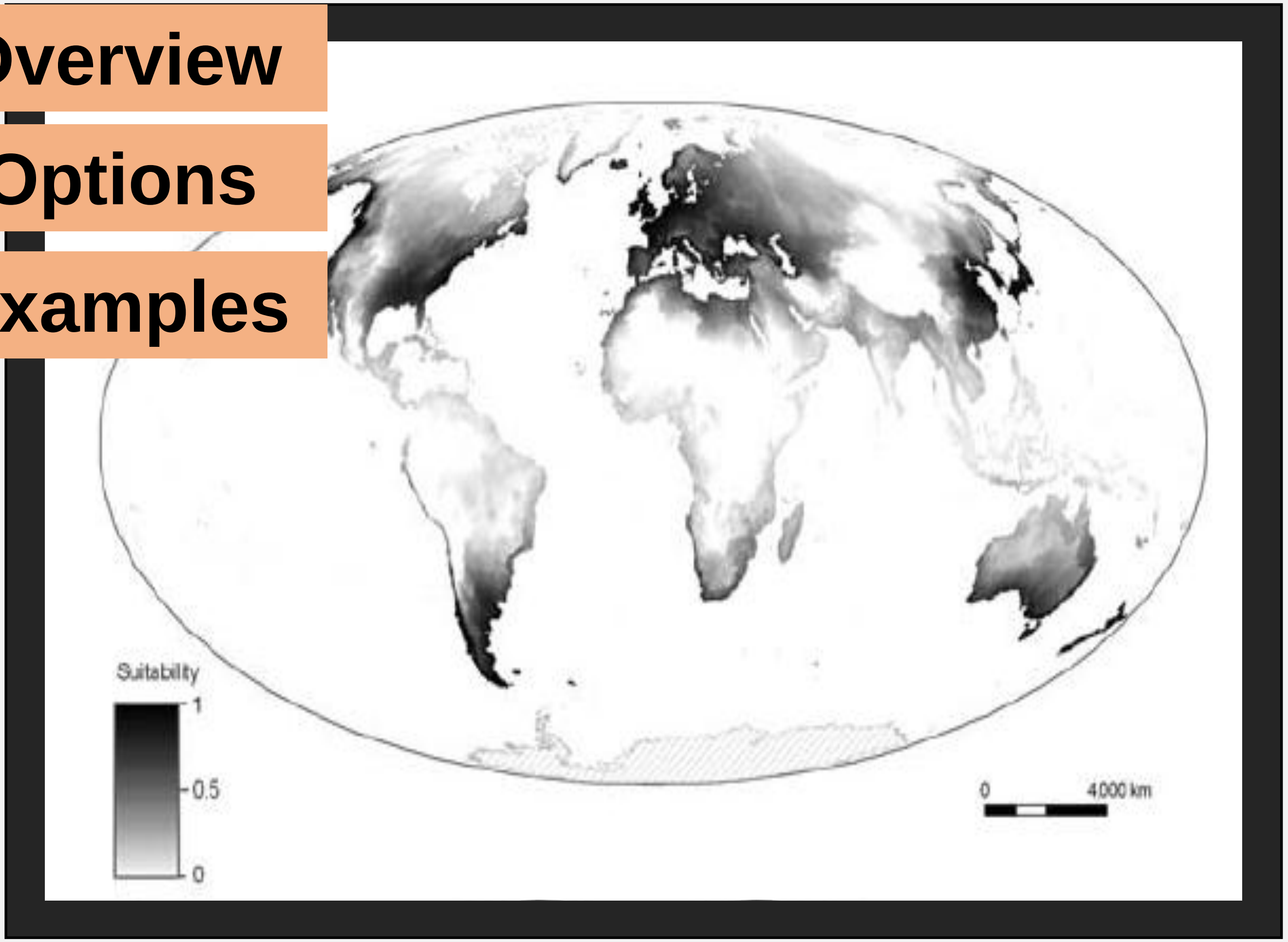
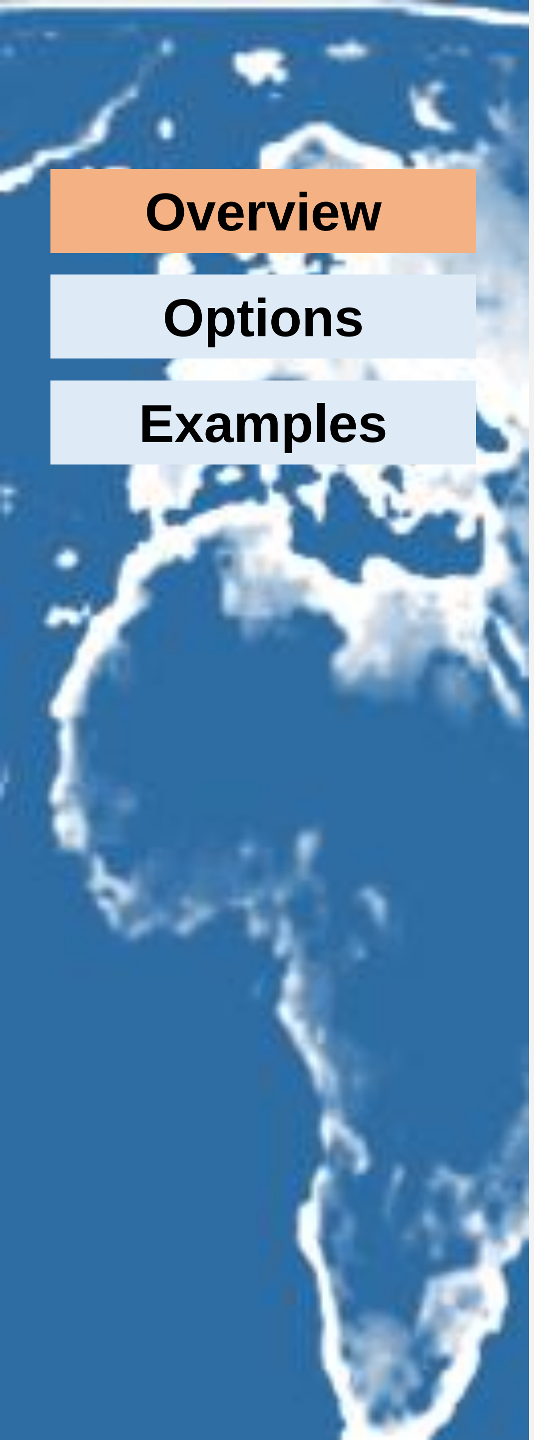



McGill



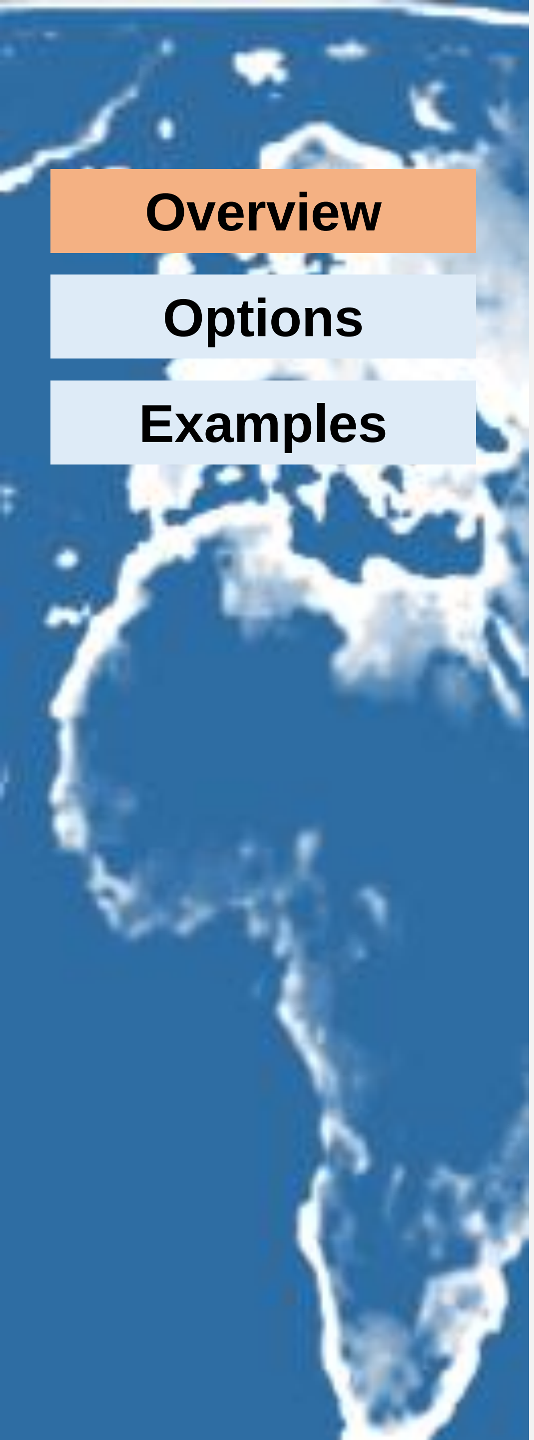


# General challenges

Limited time

Limited information

Limited resources



**Overview**

**Options**

**Examples**

## The EPPO prioritization process for invasive alien plants

S. Brunel[1], E. Branquart[2], G. Fried[3], J. van Valkenburg[4], G. Brundu[5], U. Starfinger[6], S. Buholzer[7], A. Uludag[8], M. Joseffson[9] and R. Baker[10]

[1]OEPP/EPPO, 21 Bld Richard Lenoir, 75011 Paris, France; e-ma
[2]Belgian Biodiversity Platform, Centre de recherche de la Nature, Belgium
[3]LNPV, Station de Montpellier, Campus International de Baillargu
[4]Plant Protection Service, Geertjesweg 15, P.O. Box 9102, 6700 H
[5]Regione Autonoma della Sardegna, Assessorato della Difesa dell' Generale, Via Biasi n. 7, 09131 Cagliari, Italy
[6]Julius Kühn Institut (JKI), Federal Research Centre for Cultivate 11/12, 38104 Braunschweig, Germany
[7]Agroscope Reckenholz- Tänikon Research Station ART, Reckenho
[8]EEA, Kongens Nytorv 6, 1050 Copenhagen, Denmark
[9]Swedish Environmental Protection Agency, S-106 48 Stockholm, S
[10]Food and Environment Research Agency, Sand Hutton, YO41 1L

## RISK

ASSESSMENT FOR THE IMPORT AND KEEPING OF EXOTIC VERTEBRATES IN AUSTRALIA

Mary Bomford

Bureau of Rural Sciences

*Journal of Applied Ecology* 2005 **42**, 1020–1030

## Slowing down a pine invasion despite uncertainty in demography and dispersal

YVONNE M. BUCKLEY,*† ECKEHARD BROCKERHOFF,‡ LISA LANGER,‡ NICHOLAS LEDGARD,‡ HEATHER NORTH§ and MARK REES¶

*The Ecology Centre, University of Queensland, School of Integrative Biology, St Lucia, QLD 4072, Australia; †CSIRO Sustainable Ecosystems, Queensland Bioscience Precinct, 306 Carmody Road, St Lucia, QLD 4067, Australia; ‡Ensis (a joint venture between CSIRO and New Zealand Forest Research, Institute Ltd), Forestry Road, University of Canterbury, PO Box 29237, Christchurch, New Zealand; §Landcare Research, PO Box 69, Lincoln 8152, New Zealand; and ¶Department of Animal and Plant Sciences, University of Sheffield, Sheffield S10 2TN, UK

OPEN ACCESS Freely available online PLoS one

## Predicting Invasive Fungal Pathogens Using Invasive Pest Assemblages: Testing Model Predictions in a Virtual World

Dean R. Paini[1,2]*, Felix J. J. A. Bianchi[3¤a], Tobin D. Northfield[4¤b], Paul J. De Barro[2,3]

*Journal of Environmental Management* (1999) **57**, 239–251
Article No. jema.1999.0297, available online at http://www.idealibrary.com on IDEAL®

## A weed risk assessment model for use as a biosecurity tool evaluating plant introductions

P. C. Pheloung†‡, P. A. Williams§*, S. R. Halloy¶

*Journal of Applied Ecology* 2009, **46**, 787–795 doi: 10.1111/j.1365-2664.2009.01674.x

## A global risk assessment for the success of bird introductions

Miquel Vall-llosera[1,*] and Daniel Sol[1,2]

Biological Invasions (2006) 8: 241–254 © Springer 2006
DOI 10.1007/s10530-004-5573-8

## Boats, pathways, and aquatic biological invasions: estimating dispersal potential with gravity models

Brian Leung[1,2,*], Jonathan M. Bossenbroek[1] & David M. Lodge[1]

Received 23 Marc

Vol. 20(2011): 15–28.

## A review of risk prioritisation schemes of pathogens, pests and weeds: principles and practices

Contents lists available at ScienceDirect

Journal for Nature Conservation

journal homepage: www.elsevier.de/jnc

## Review of risk assessment systems of IAS in Europe and introducing the German–Austrian Black List Information System (GABLIS)

Franz Essl[a,*], Stefan Nehring[b], Frank Klingenstein[b,c], Norbert Milasowszky[d], Christelle Nowack[b], Wolfgang Rabitsch[a]

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

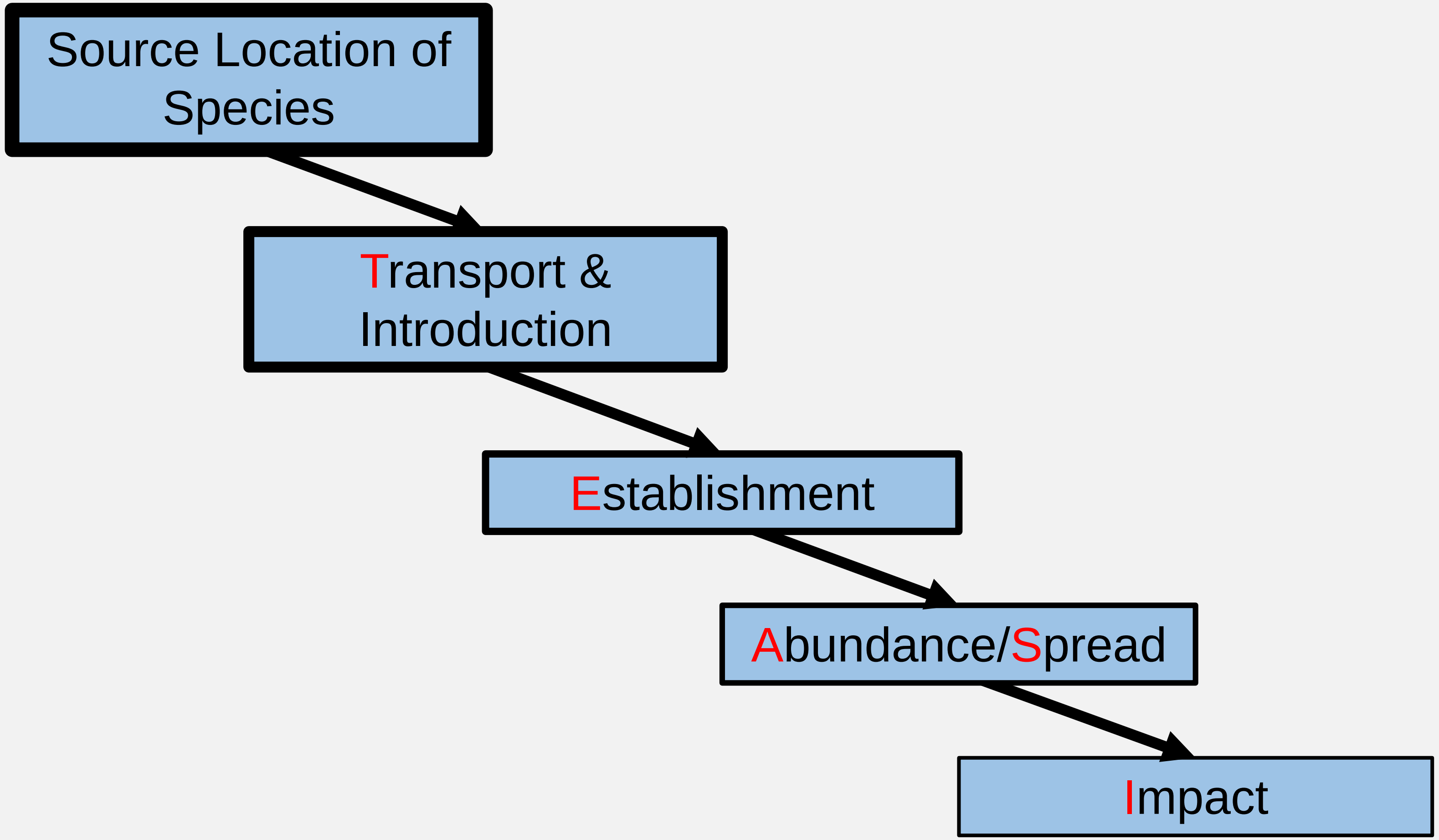
## Unveiling human-assisted dispersal mechanisms in invasive alien insects: Integration of spatial stochastic simulation and phenology models

L.R. Carrasco[a,b,*], J.D. Mumford[a], A. MacLeod[b], T. Harwood[c], G. Grabenweger[d], A.W. Leach[a], J.D. Knight[a], R.H.A. Baker[b]

[a] Centre for Environmental Policy, Imperial College London, Exhibition Road, London SW7 2AZ, UK
[b] The Food and Environment Research Agency, Sand Hutton, York YO41 1LZ, UK
[c] CSIRO Entomology, Clunies Ross St., Black Mountain, Canberra, ACT 2601, Australia
[d] Institute for Plant Health, Austrian Agency for Health and Food Safety, Spargelfeldstraße 191, A-1220, Vienna, Austria

**RISK = Probability of event * Severity of event**

# Predicting invasion risk



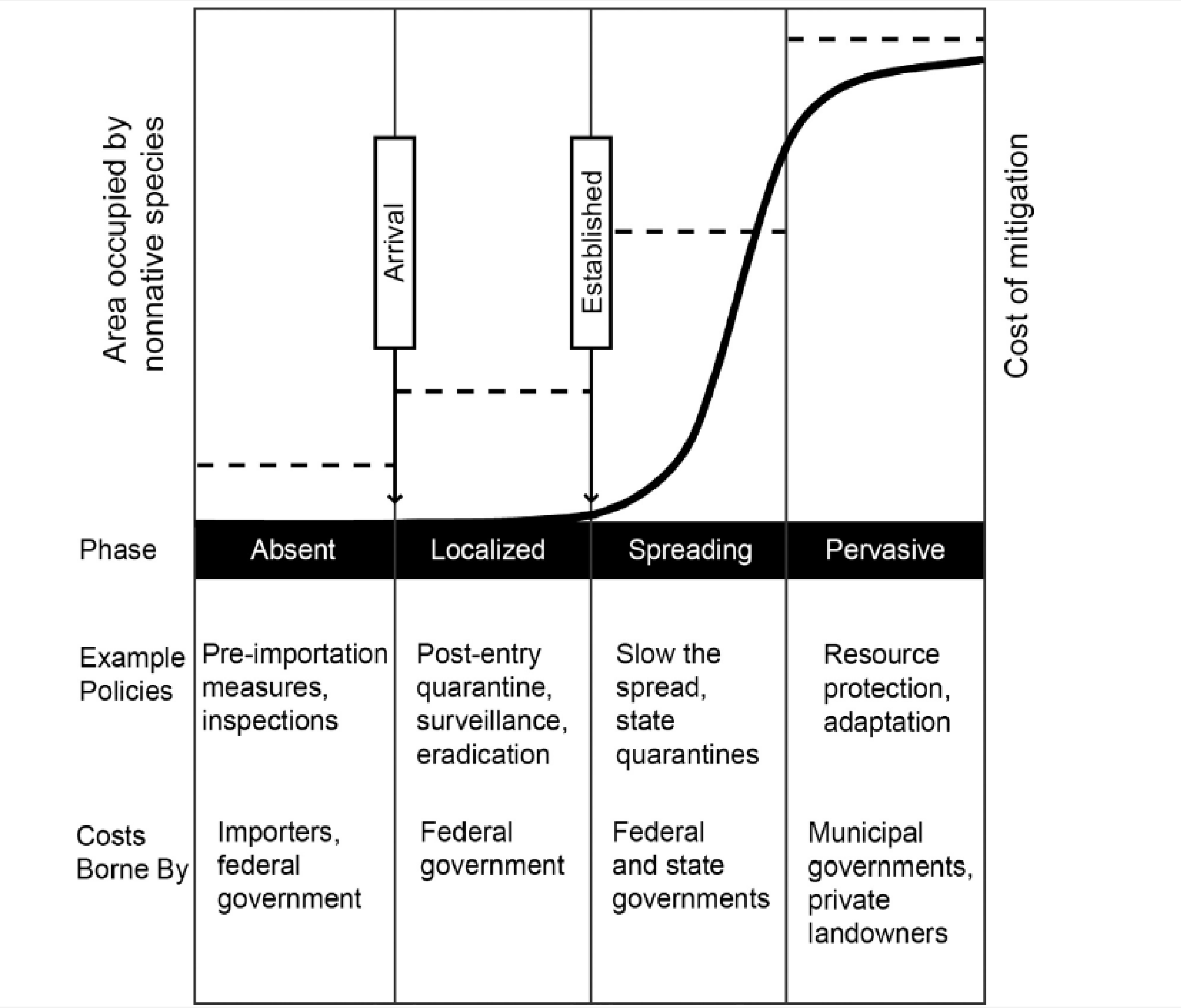

RISK = Probability of invasion * Severity of impact

Overview

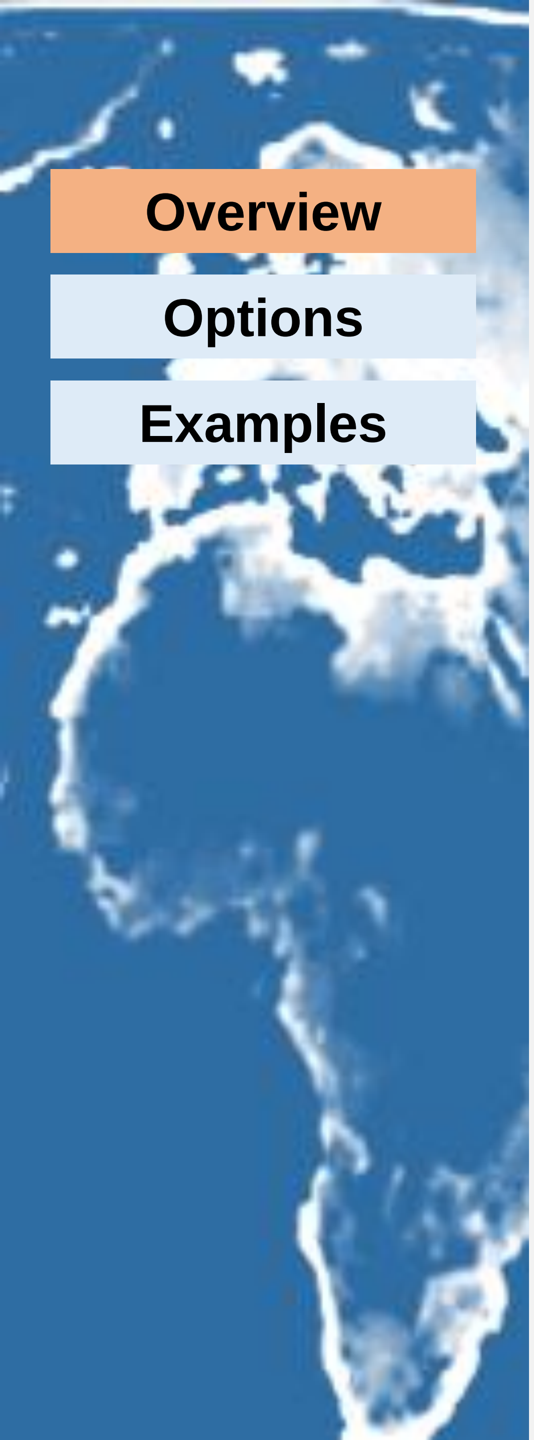
Options

Examples

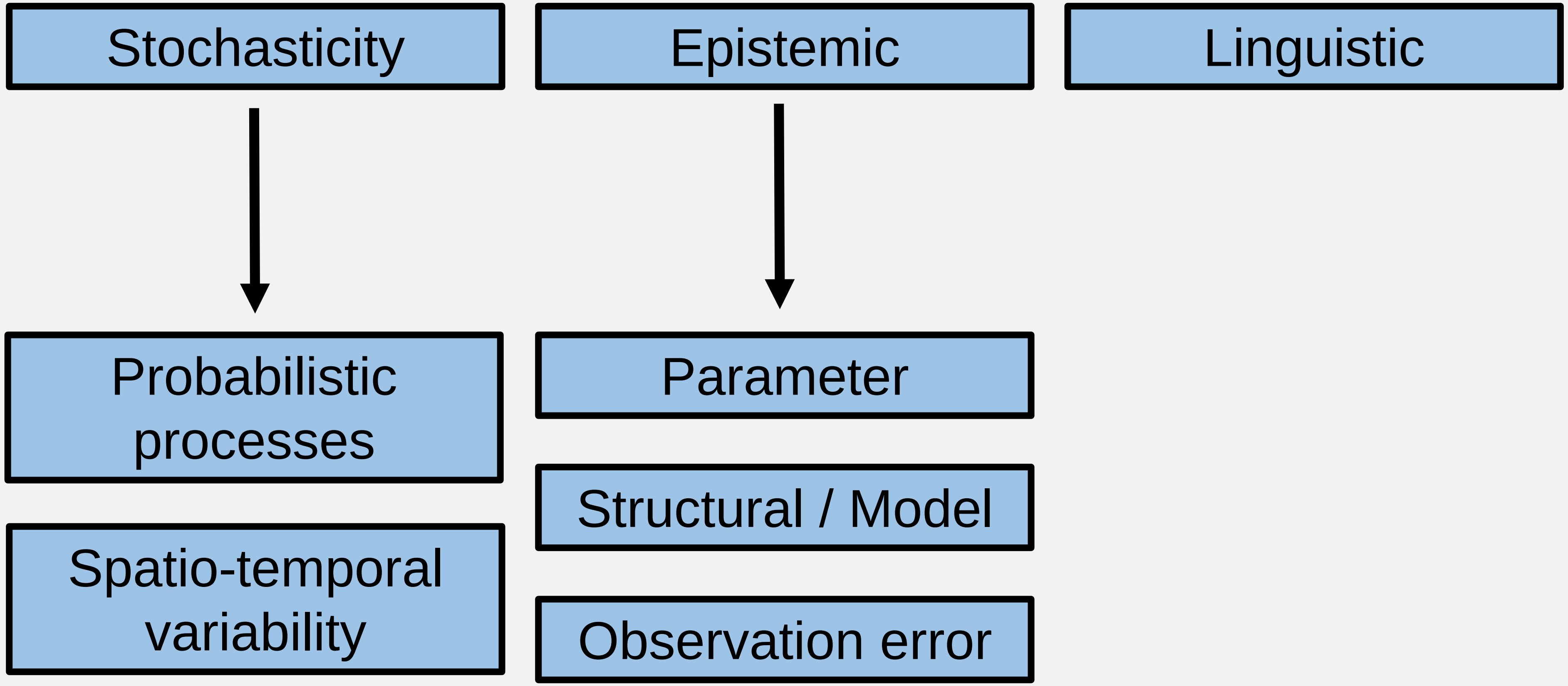
# Related topics
## Management

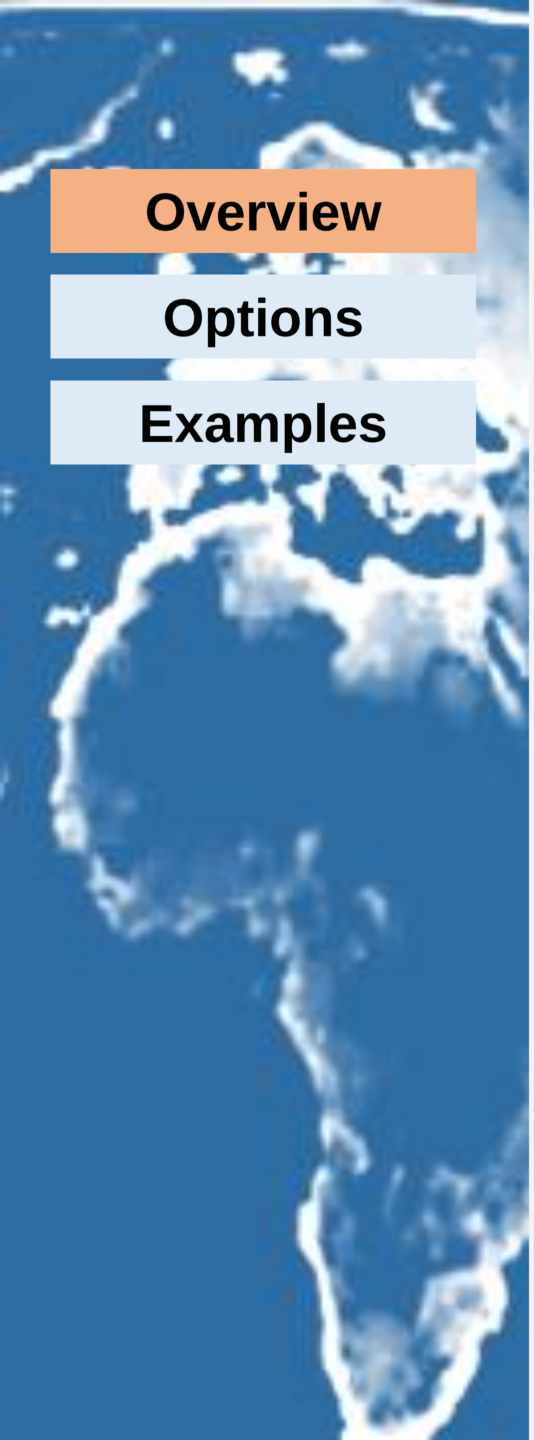



Lovett et al. 2016. Ecological Applications




# Related topics
## Uncertainty





Overview
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# Related topics
## Risk analysis: choice of tools

### Invasion risk & management

**Data Available**
Probability models
Likelihoods

**Severe Uncertainty**
(fewer assumptions, but many still exist!)
Expert opinion
Scenario analysis

### Decision theory

**Optimality**
(e.g., cost-benefit cost-effectiveness)

**Bounds/thresholds**
(e.g., info-gap, minimax)

Polasky et al. 2011. TREE

cf. Hayes et al. 2013. MEE.

Overview

Options

Examples

# Related topics
## Risk analysis: choice of tools

| Invasion risk & management | Decision theory |
|---|---|
| **Data Available**<br>Probability models<br>Likelihoods | **Optimality**<br>(e.g., cost-benefit cost-effectiveness) |
| **Severe Uncertainty**<br>(fewer assumptions, but many still exist!)<br>Expert opinion<br>Scenario analysis | **Bounds/thresholds**<br>(e.g., info-gap, minimax) |

Polasky et al. 2011. TREE

cf. Hayes et al. 2013. MEE.

# Options
## Predicting Invasion Risk

**RISK ASSESSMENTS**

**96% SINGLE SPECIES**

- Evaluate purposeful introduction
- Prioritize effort after establishment

**4% MULTISPECIES OR PATHWAY**

- Multiple, often unmeasured, species
- Accidental introductions
- Trade policy

Leung et al. 2012. Ecology Letters

# Options
## Predicting Invasion Risk

SEMI-QUALITATIVE SCORING APPROACHES

QUANTITATIVE APPROACHES

RISK ASSESSMENTS

96% SINGLE SPECIES

4% MULTISPECIES OR PATHWAY

Leung et al. 2012. Ecology Letters

Overview

Options

Semi-Qualitative

Quantitative

Examples

# Scoring Risk Assessment
## > 70 RA tools developed

e.g., screening tool for Freshwater Invertebrates (FI-ISK)

| Number | Question | Guidance |
|---|---|---|
| 1 | Is the species adapted for aquacultural or ornamental purposes? | The taxon must have been grown deliberately and subjected to substantial human selection for at least 20 generations, or is known to be easily reared in captivity (e.g. aquaculture or aquaria). |
| 2 | Has the species become naturalised where introduced? | The taxon must be known to have successfully established self-sustaining populations in at least one habitat other than its usual habitat (e.g. lotic vs. lentic) and persisted for at least 50 years (response modifies the effect of Q1). |
| 3 | Does the species have invasive races/varieties/sub-species? | This question emphasizes the invasiveness of domesticated, in particular ornamental, species (modifies the effect of Q1). |
| 4 | Is species reproductive tolerance suited to climates in the risk assessment area (0-low, 1-intermed, 2-high)? | Climate matching is based on an approved system such as Climex, GARP or Climatch. If not available, then assign the maximum score (2). |
| 5 | What is the quality of the climate match data (0-low; 1-intermediate; 2-high)? | The quality is an estimate of how complete the data used to generate the climate analysis is. If not available, then the minimum score (0) should be assigned. |

Tricarico et al. 2010. Risk Analysis

Overview

**Options**

**Semi-Qualitative**

Quantitative

Examples

# Scoring Risk Assessment
## Uncertainty

- Often unmeasured
- Meaning questionable

  (e.g., number unanswered questions)
- Linguistic uncertainty problematic

# Quantitative Risk Assessments

Mapping risk literature onto 15 **TEASI** equations

**T**ransport
**E**stablishment
**A**bundance
**S**pread
**I**mpact

$$N_{i,t} = \sum_{j=1}^{J} \sum_{k=1}^{V_{i,j,t}} O(E_{j,t'}, v_{i,j,k,t}, S, X_{j,t'}, \sigma_O) * f_g(t - t', D_{ij}, \vec{E}, v_{i,j,k,t}, S, \sigma_g) * pr(R \mid E_{i,t}, v_{i,j,k,t}, S)$$

Leung et al. 2012. Ecology Letters

Overview

Options

Semi-Qualitative

Quantitative

Examples

# Quantitative Risk Assessments

At each stage of the invasion process and impact, we differentiated four main aspects:

TRANSPORT

$$N_{i,t} = \sum_{j=1}^{J} \sum_{k=1}^{V_{i,j,t}} O(E_{j,t'}, v_{i,j,k,t}, S, X_{j,t'}, \sigma_O) * f_g(t - t', D_{ij}, \vec{E}, v_{i,j,k,t}, S, \sigma_g) * pr(R \mid E_{i,t}, v_{i,j,k,t}, S)$$

Leung et al. 2012. Ecology Letters

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Quantitative

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# Quantitative Risk Assessments

At each stage of the invasion process and impact, we differentiated four main aspects:

| COMPONENT | SUBCOMPONENT | | |
|---|---|---|---|
| TRANSPORT | uptake before transit (*O*) | net growth during transit ($f_g$) | release after transit (*pr(R)*) |

$$N_{i,t} = \sum_{j=1}^{J} \sum_{k=1}^{V_{i,j,t}} O(E_{j,t'}, v_{i,j,k,t}, S, X_{j,t'}, \sigma_O) * f_g(t - t', D_{ij}, \vec{E}, v_{i,j,k,t}, S, \sigma_g) * pr(R \mid E_{i,t}, v_{i,j,k,t}, S)$$

Leung et al. 2012. Ecology Letters

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**Options**

Semi-Qualitative

**Quantitative**

Examples

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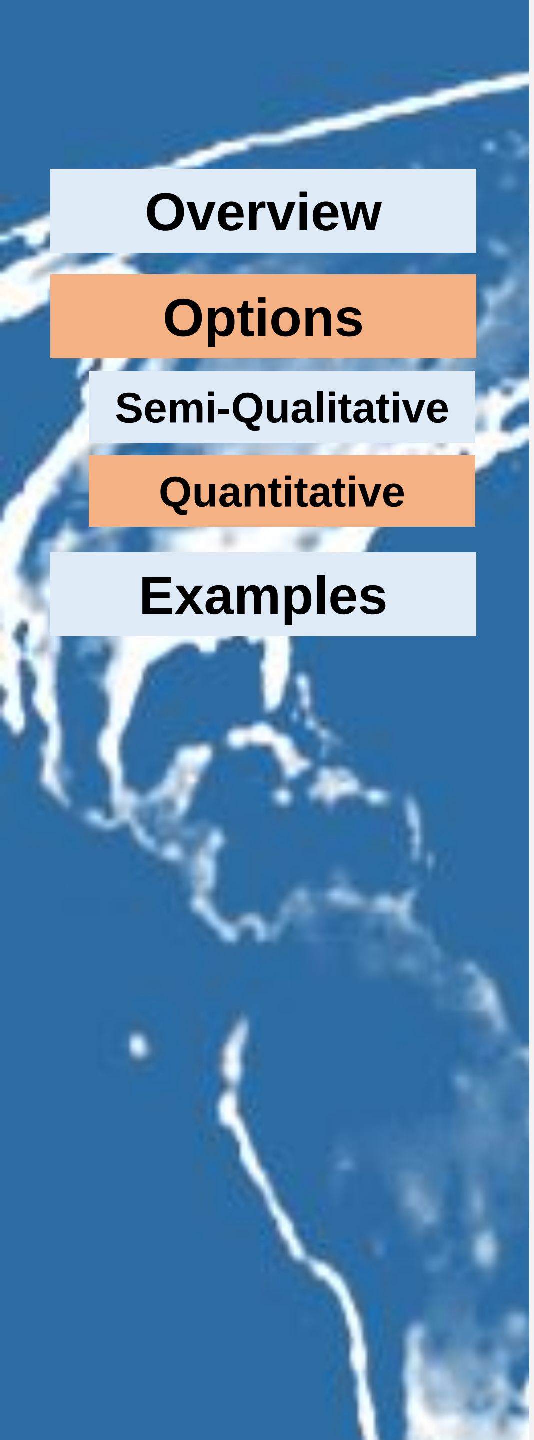
environment (E) | vector type (v) | species traits (S)

**DEPENDENCIES**

Leung et al. 2012. Ecology Letters

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vector type (v)

species traits (S)

**DEPENDENCIES**

**STRUCTURE**

Leung et al. 2012. Ecology Letters

Overview

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Semi-Qualitative

Quantitative

Examples

# Useful Predictors

## Propagule pressure, environment, species traits

**COMPONENT** | **SUBCOMPONENT**

TRANSPORT

uptake before transit (*O*)

net growth during transit ($f_g$)

release after transit (*pr(R)*)

$$N_{i,t} = \sum_{j=1}^{J} \sum_{k=1}^{V_{i,j,t}} O(E_{j,t'}, v_{i,j,k,t}, S, X_{j,t'}, \sigma_O) * f_g(t - t', D_{ij}, \vec{E}, v_{i,j,k,t}, S, \sigma_g) * pr(R \mid E_{i,t}, v_{i,j,k,t}, S)$$

environment (E)

vector type (v)

species traits (S)

**DEPENDENCIES**

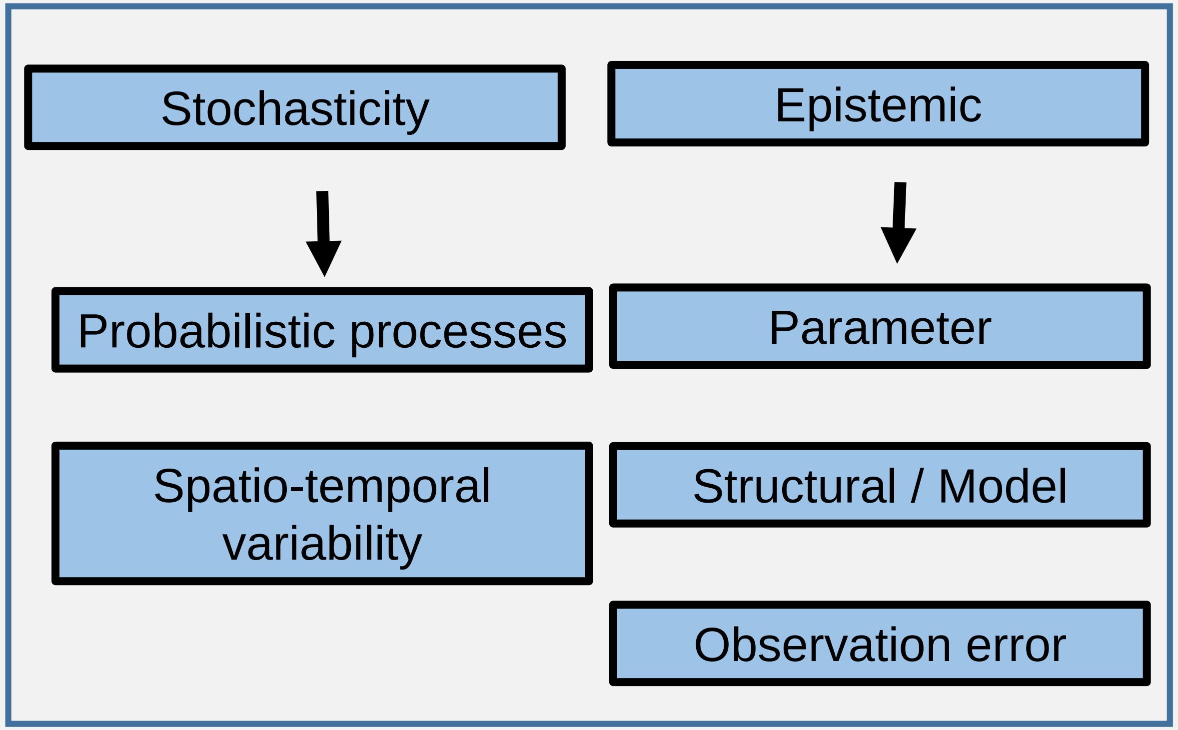
**STRUCTURE**

Leung et al. 2012. Ecology Letters

# Quantitative Risk Assessments
## Uncertainty

### Options

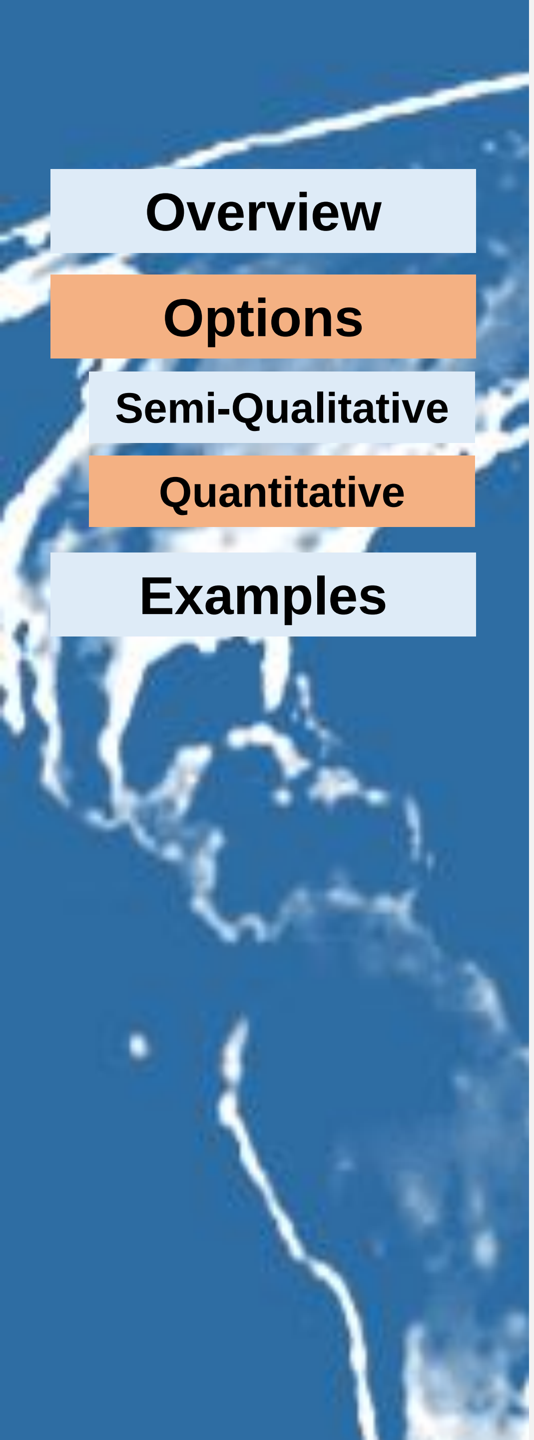
- Standard error, unexplained variation
- Misspecification rates (e.g., AUC)
- Bayesian
- Stochastic models
- Sensitivity analysis
- Ensemble models




Leung et al. 2012. Ecology Letters

# Principles for balancing complexity

- Uncertainty exists, but decisions must be made
- The world is complex, but the endpoints of interest are few
- All models are wrong, but some are better than others

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# Additional thoughts

- How can we estimate it?
- Is it useful and/or predictive?
- What factors are we missing (implicit assumptions)?

Overview

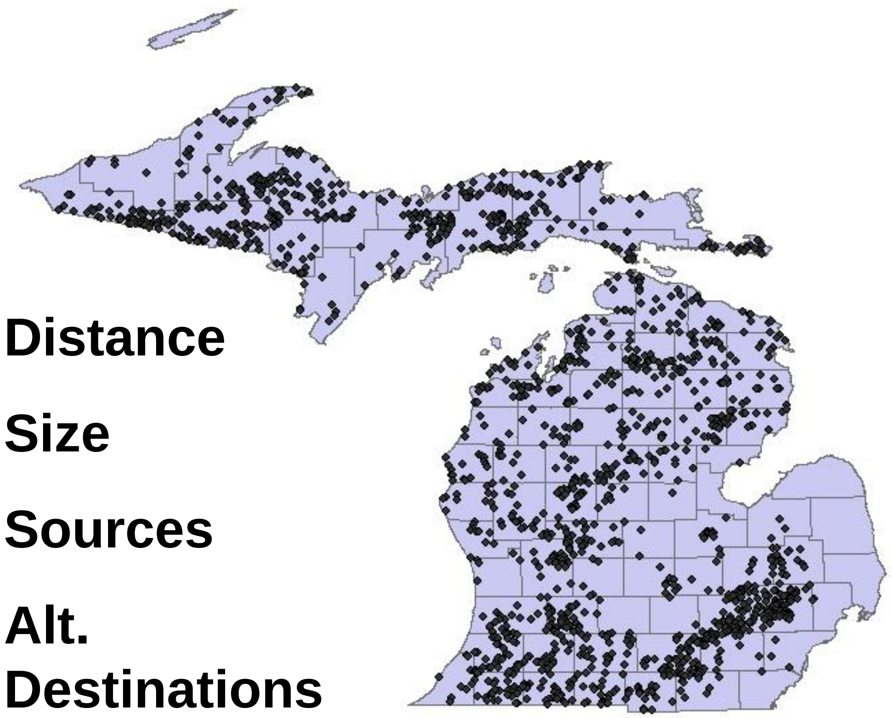
Options

Semi-Qualitative

Quantitative

Examples

# Illustrative example
## Gravity Models



↓ **Distance**

↑ **Size**

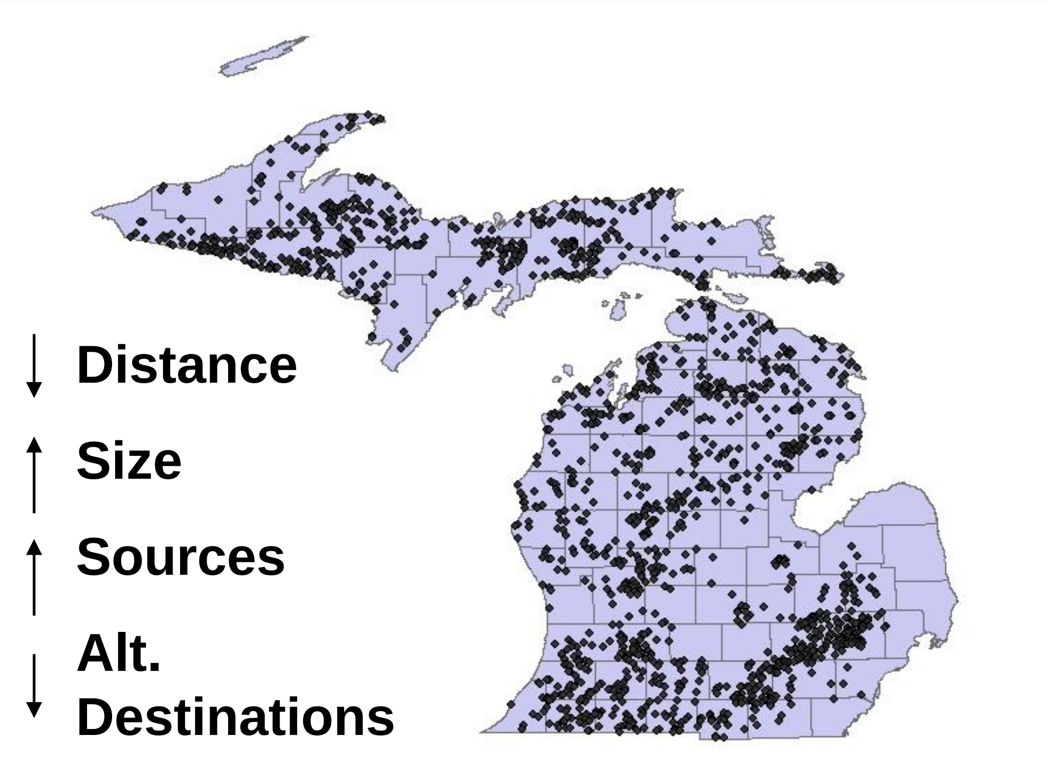
↑ **Sources**

↓ **Alt. Destinations**

$$N_{i,t} = \sum_{j=1}^{J} \sum_{k=1}^{V_{i,j,t}} O(E_{j,t'}, v_{i,j,k,t}, S, X_{j,t'}, \sigma_O) * f_g(t - t', D_{ij}, \vec{E}, v_{i,j,k,t}, S, \sigma_g) * pr(R \mid E_{i,t}, v_{i,j,k,t}, S)$$

Leung et al. 2004. Ecology

# Illustrative example
## Gravity Models

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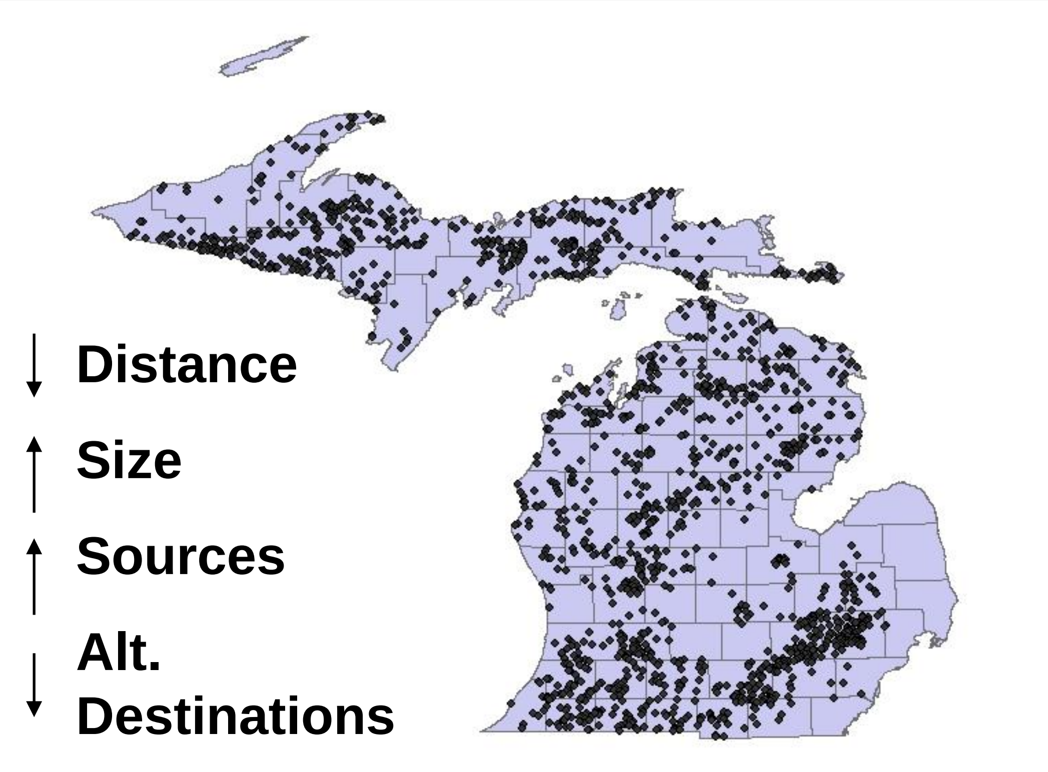
Leung et al. 2004. Ecology

# Illustrative example

## Gravity Models

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=1

Leung et al. 2004. Ecology

Overview

Options

Semi-Qualitative

Quantitative

Examples

# Summary Comparisons

## Semi-qualitative approaches

- Broader TEASI coverage
- Expert opinion
- Model structure unclear
- Uncertainty ad-hoc

## Quantitative models

- Less TEASI coverage
- Even simple models are worthwhile
- Proxy variables & predictors are useful
- Uncertainty analyzed but heterogeneous

**Few explicit comparisons between methods

# Principles for balancing complexity

- Uncertainty exists, but decisions must be made
- The world is complex, but the endpoints of interest are few
- All models are wrong, but some are better than others

# Additional thoughts

- How can we estimate it?
- Is it useful and/or predictive?
- What factors are we missing (implicit assumptions)?

Overview

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Examples

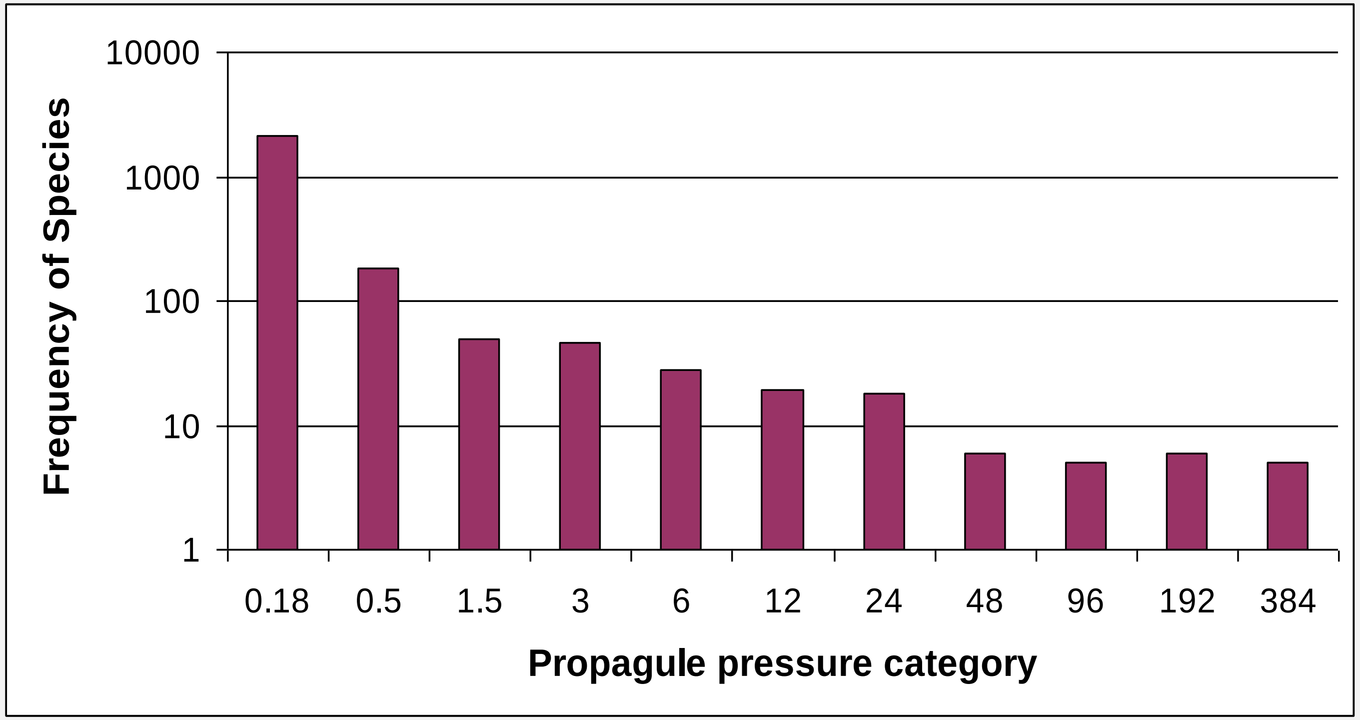
Transport

Establishment

Spread

Impact

# Transport
## Wood Borer Pest Interceptions



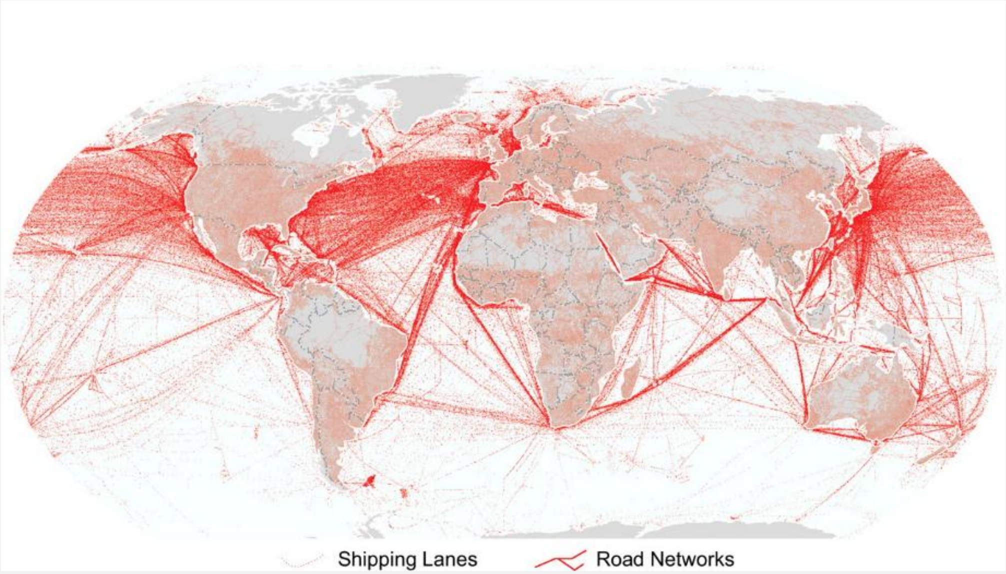

Brockerhoff et al. 2014. Ecology

# Forecasting transport
## Going global

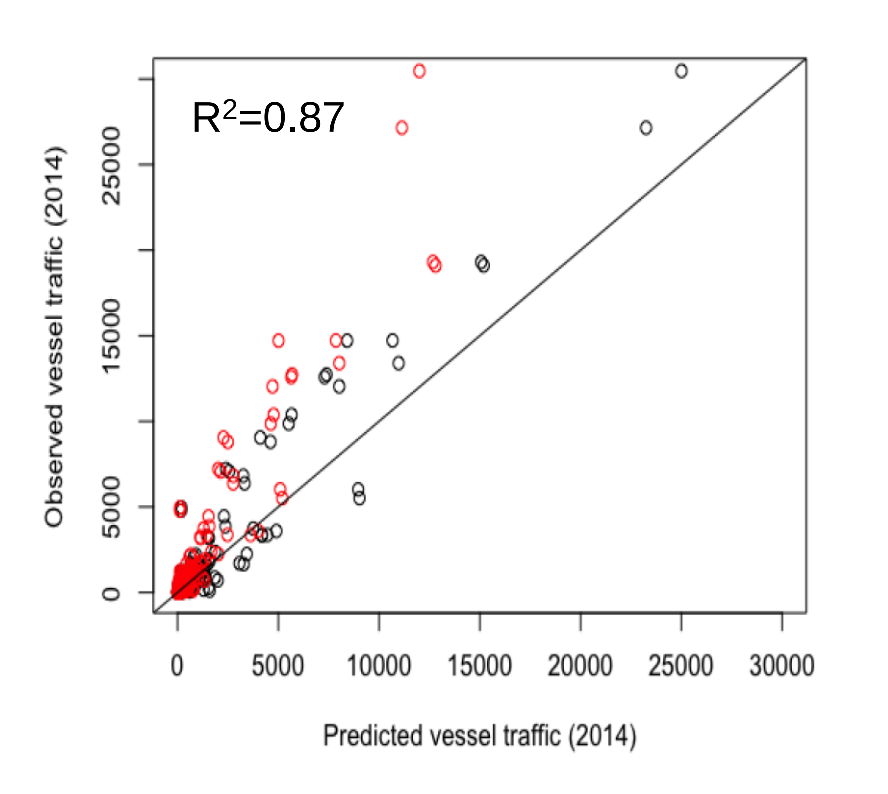
Macroeconomics

Trade Commodities

Shipping



# Forecasting transport
## Going global

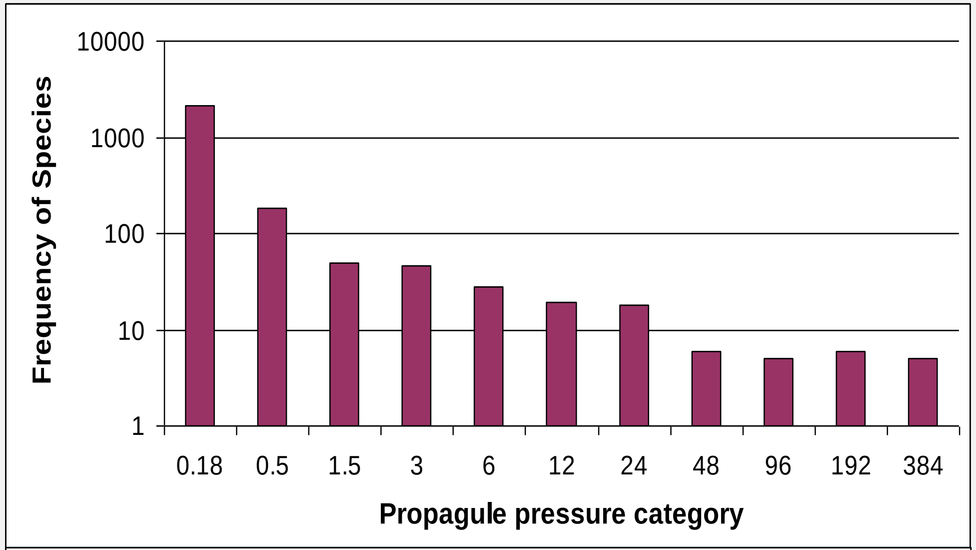


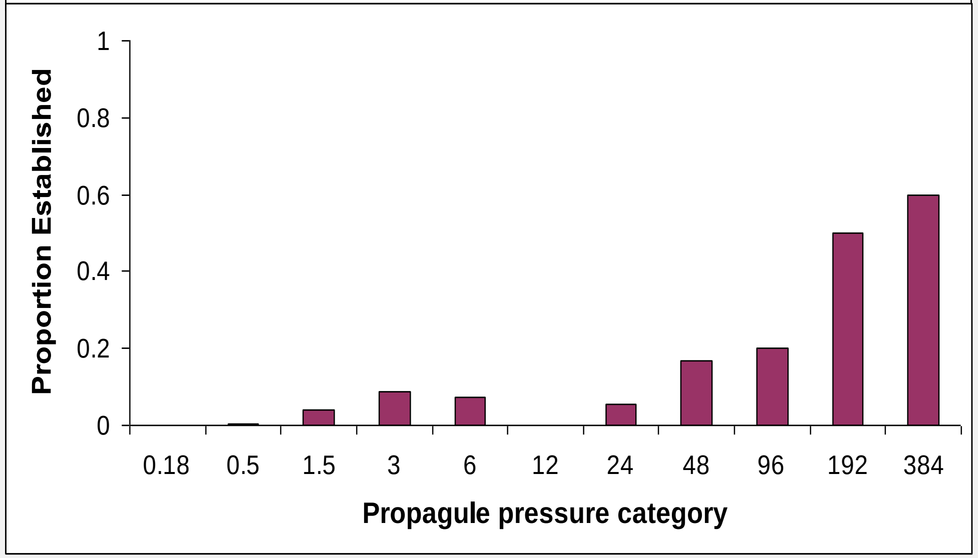

+ Shared Socioeconomic Pathways scenarios (SSPs)

Sardain, 2017. MSc

# Transport/Establishment
## Wood Borer Pest Interceptions

$$P_{i,j} = 1 - q^{N_{i,j}^{c}}$$



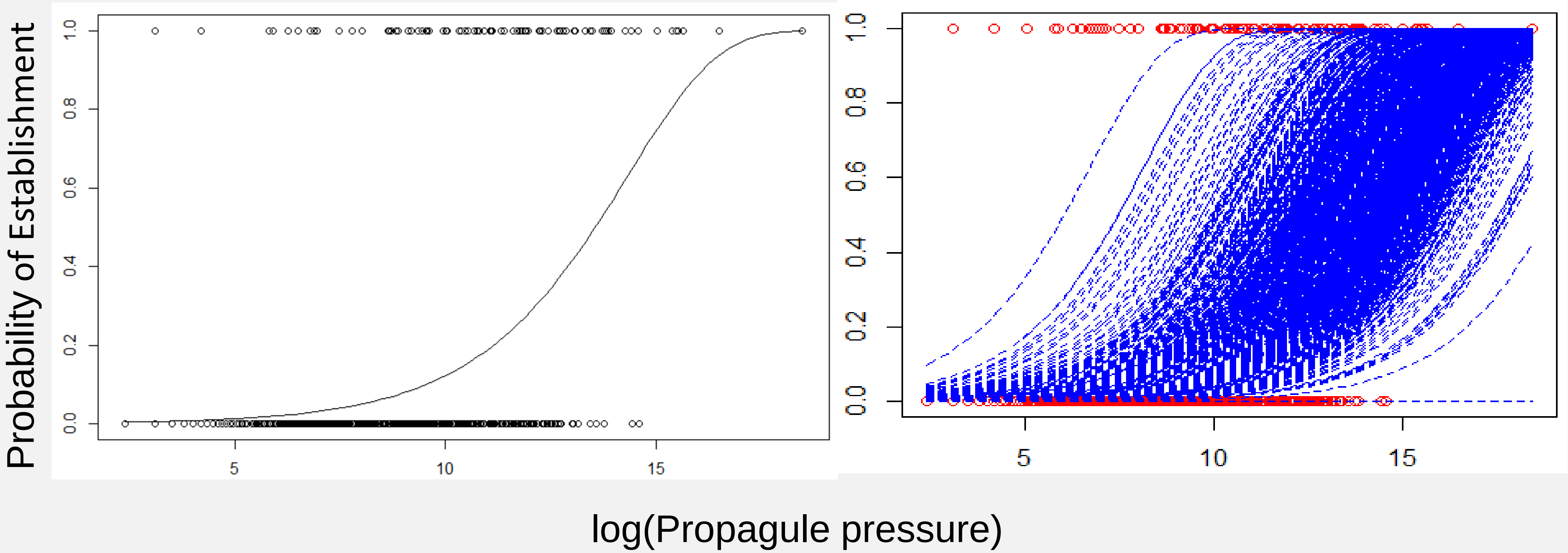




Brockerhoff et al. 2014. Ecology

# Pathway Level Joint Models

Propagule pressure & Environment & Traits ⟶ **Establishment**

$$P_{i,j} = 1 - q(E_i, S_j)^{N_{i,j}^{\,c}}$$




Bradie & Leung, 2015. J. Appl Ecol., Della Venezia & Leung. In prep.

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Establishment
Spread
Impact
Management

# Pathway Level Joint Models: Spread

Propagule pressure & Environment & Traits ⟶ **Spread**

- 64 forest pest species
- Current distribution
- Date of first discovery

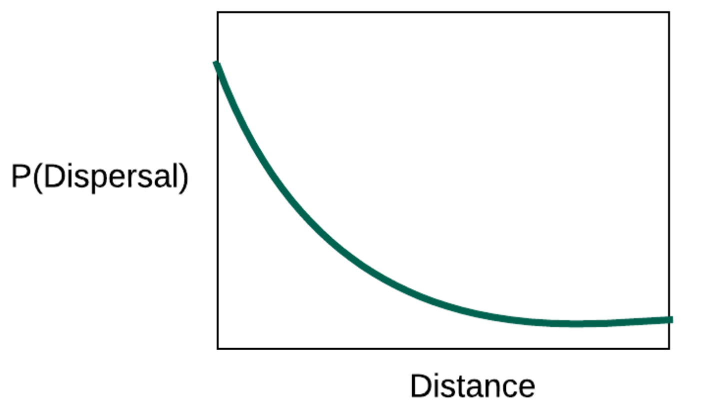
Hudgins, Liebhold & Leung. 2017. Ecology Letters

- Overview
- Options
- Examples
  - Transport
  - Establishment
  - Spread
  - Impact
  - Management

# Pathway Level Joint Models

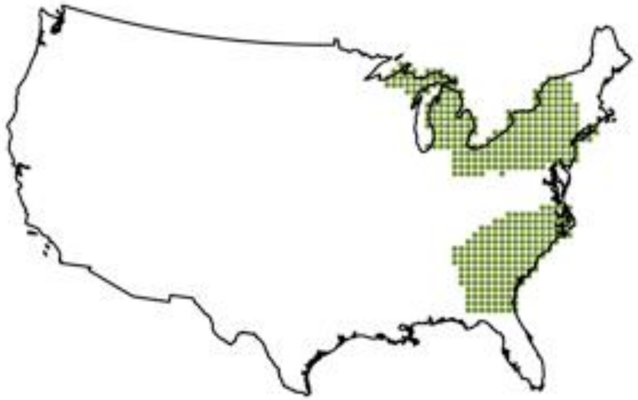
$$T_{ij} = e^{-\alpha(S,E,N)d_{i,j}}$$

**Dispersal Kernel Model**




***Ecosystem: Forests***

- 64 forest pest species
- Current distribution
- Date of first discovery

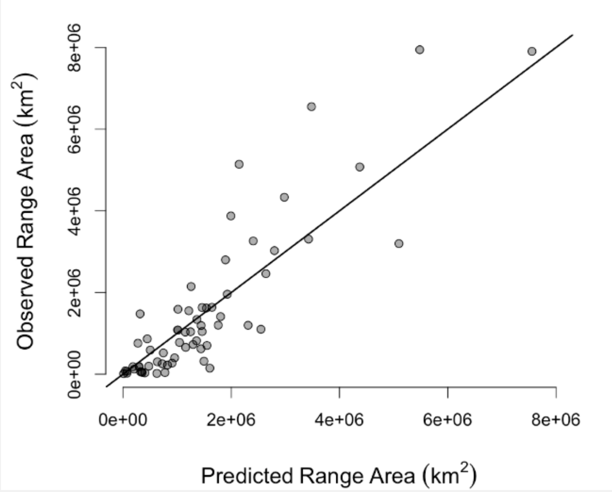


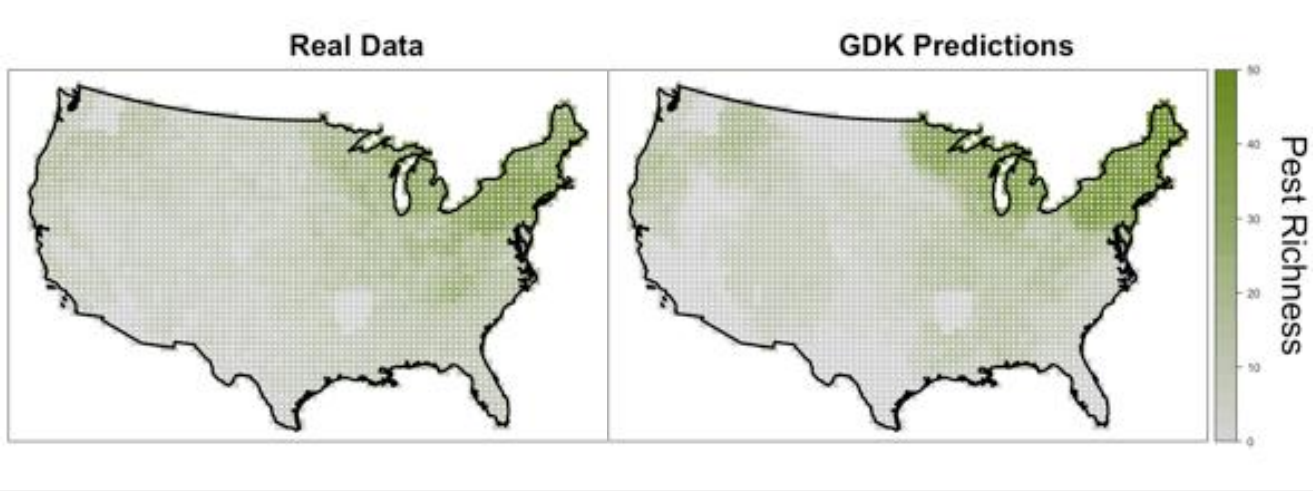
Hudgins, Liebhold & Leung. 2017. Ecology Letters

# Pathway Level Joint Models

$$T_{ij} = e^{-\alpha(S,E,N)d_{i,j}}$$

**Dispersal Kernel Model**




$R_{MSE}^2 = 0.76$

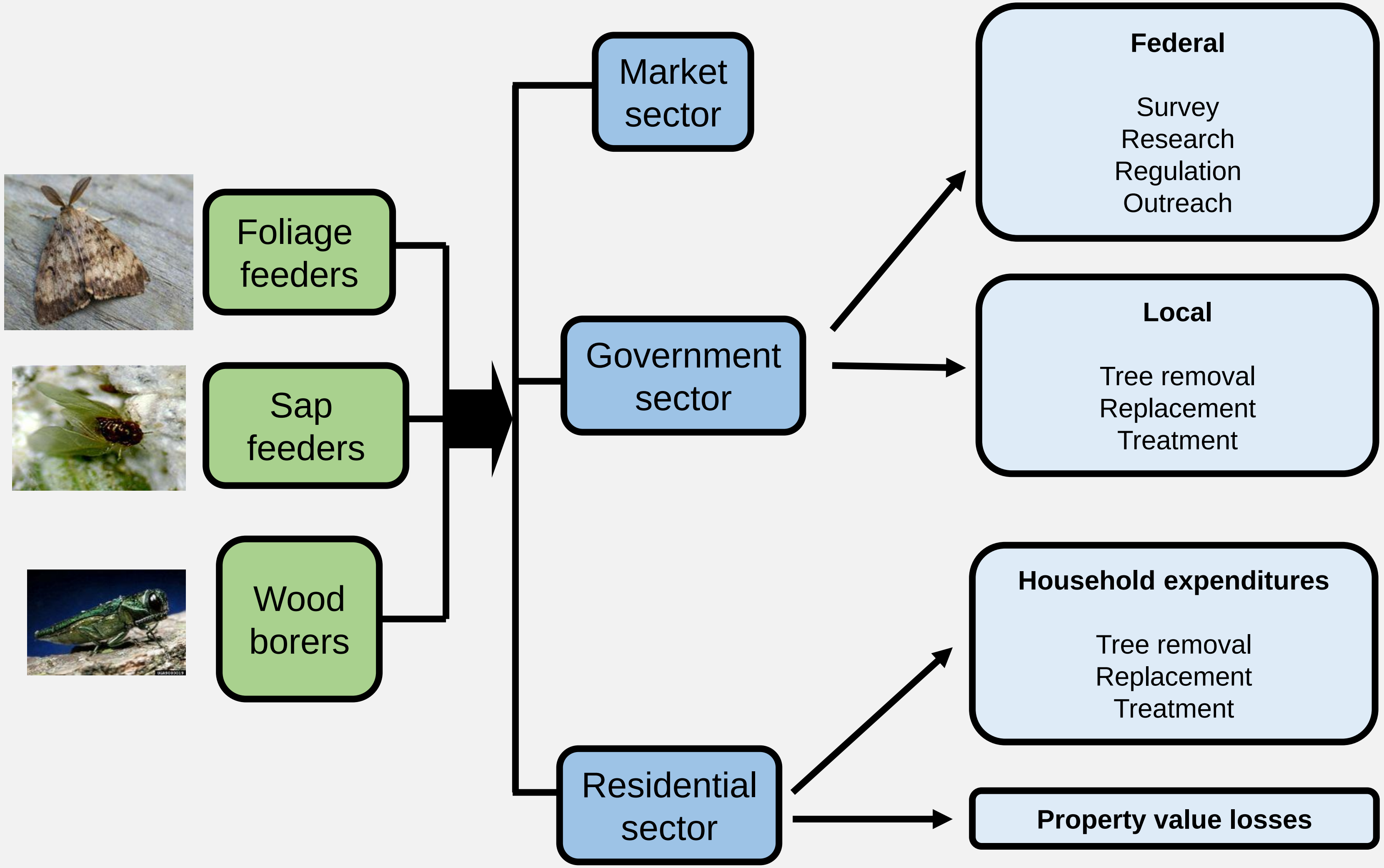
Average Locational Accuracy = 74%

** forested area

** human population density

Hudgins, Liebhold & Leung. 2017. Ecology Letters

# Pathway Level: Economic Impacts
## Species & Stakeholders Unequal




Aukema et al. 2011. PLoS One.

# Pathway Level Impact Model

## Data
1. List of all pests
2. List of damaging pests
3. Full economic estimates – poster pests

↓

## Integrative model
1. Logic
2. Fitting data

↓

## Objectives
Estimate expected impact

Aukema et al. 2011. PLoS One.

# Pathway Level Impact Model

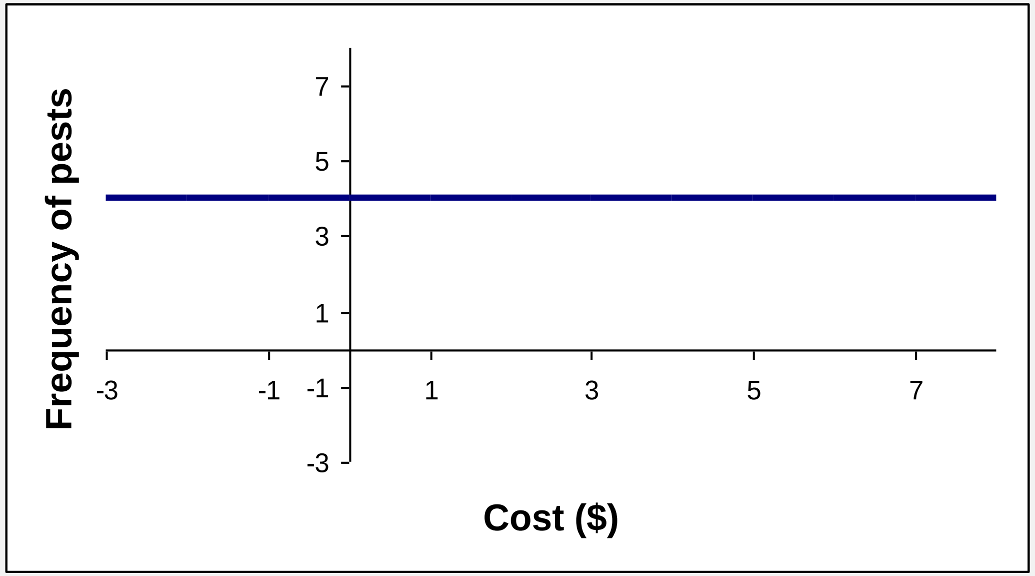
## Data
1. List of all pests
2. List of damaging pests
3. Full economic estimates – poster pests

↓

## Integrative model
1. Logic
2. Fitting data

↓

## Objectives
Estimate expected impact




## Logic

- There is a frequency distribution of costs

Aukema et al. 2011. PLoS One.

Overview

Options

**Examples**

Transport

Establishment

Spread

**Impact**

Management

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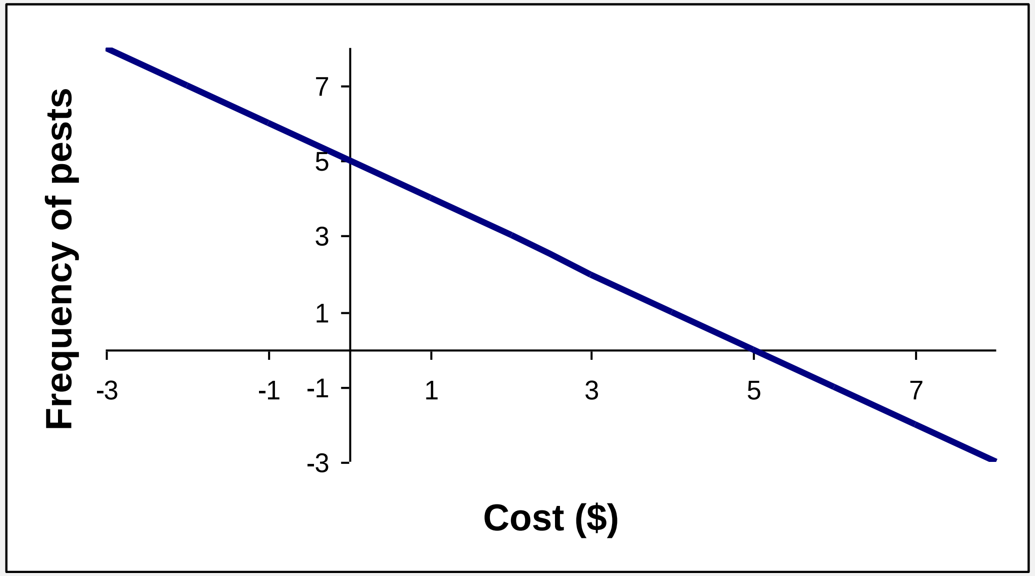


## Logic

- There is a frequency distribution of costs
- Low impact is more frequent than high

Aukema et al. 2011. PLoS One.

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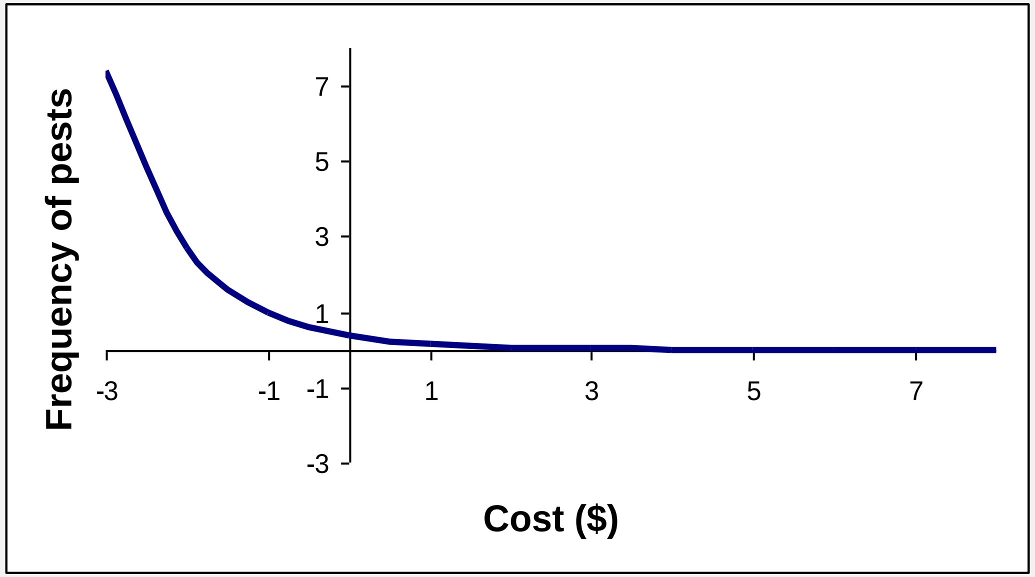


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- There is a frequency distribution of costs
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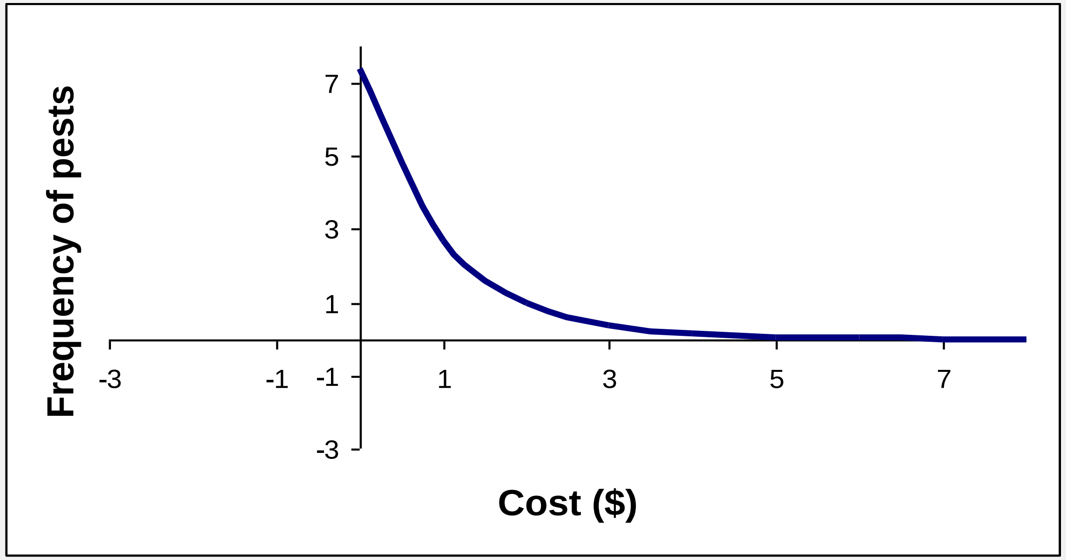
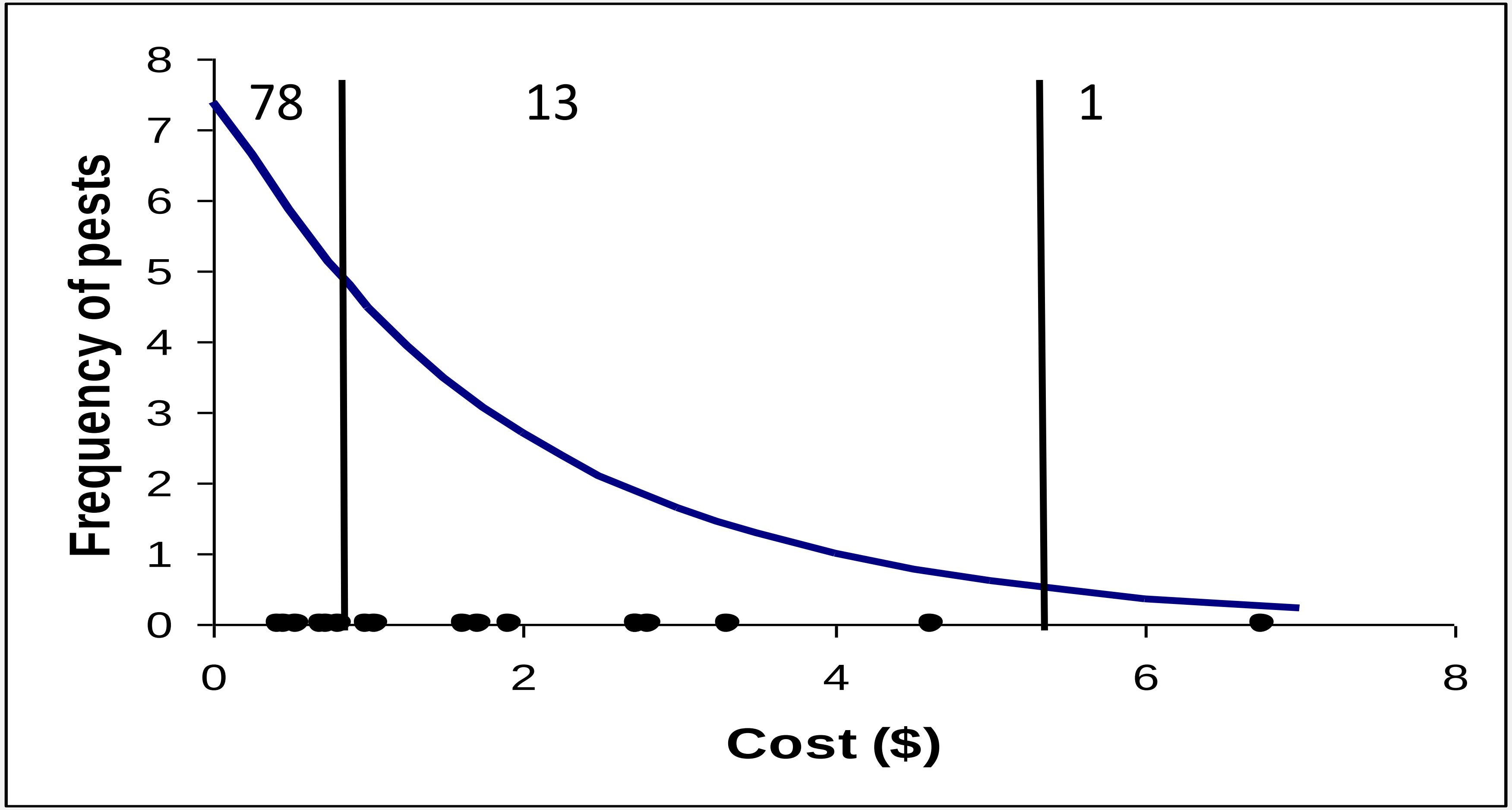



## Logic

- There is a frequency distribution of costs
- Low impact is more frequent than high
- Negative frequencies not possible
- Phytophagous insects on balance are not beneficial

Aukema et al. 2011. PLoS One.

# Fitting Data



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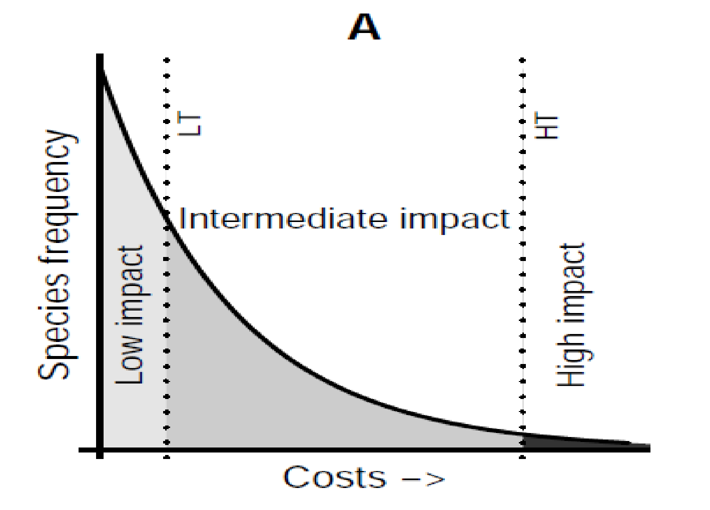

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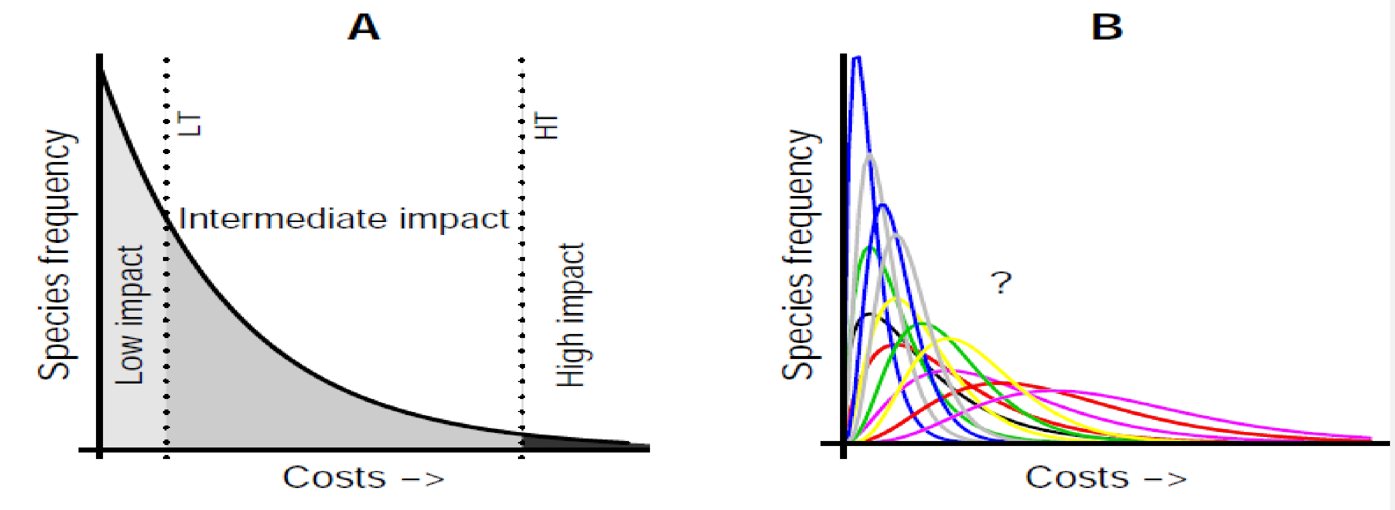

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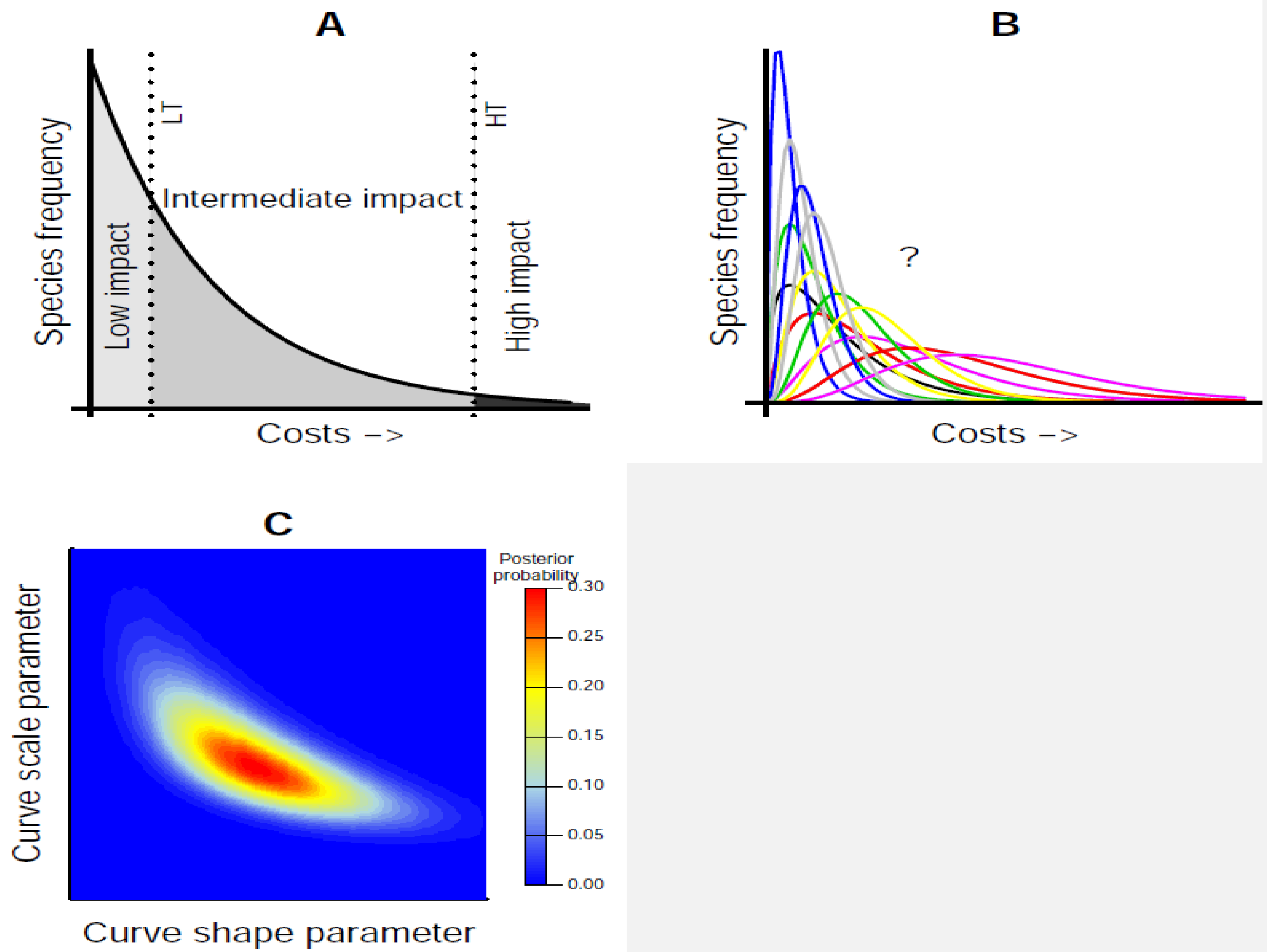

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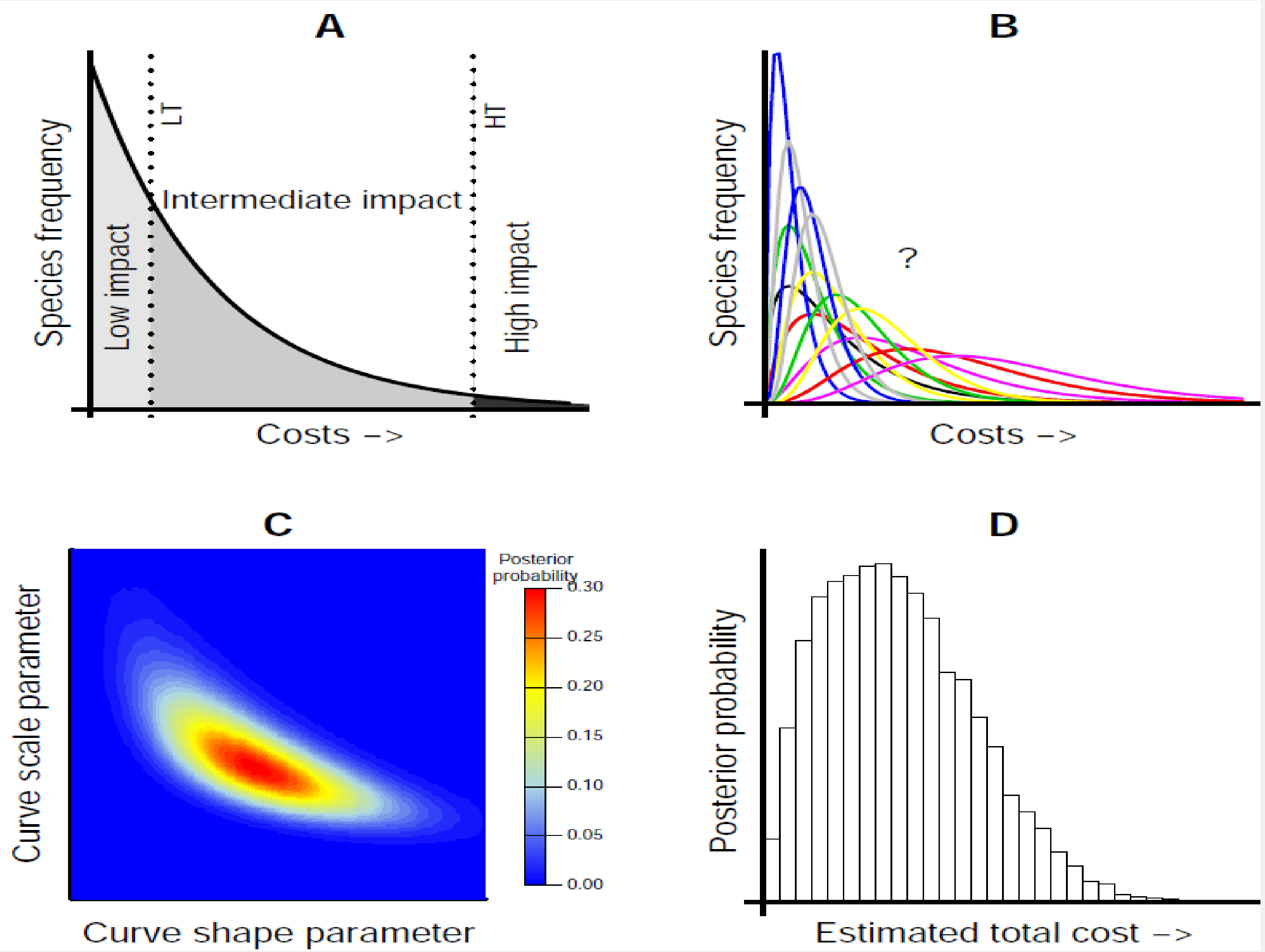

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# Economic Impacts
## Species & Stakeholders Unequal

- Local Government/Residential pays most
- Poster pest account for 25-50%
- Wood borers worse (1.7 Billion)
- 32% chance of another borer poster pest in 10 yrs

Aukema et al. 2011. PLoS One.

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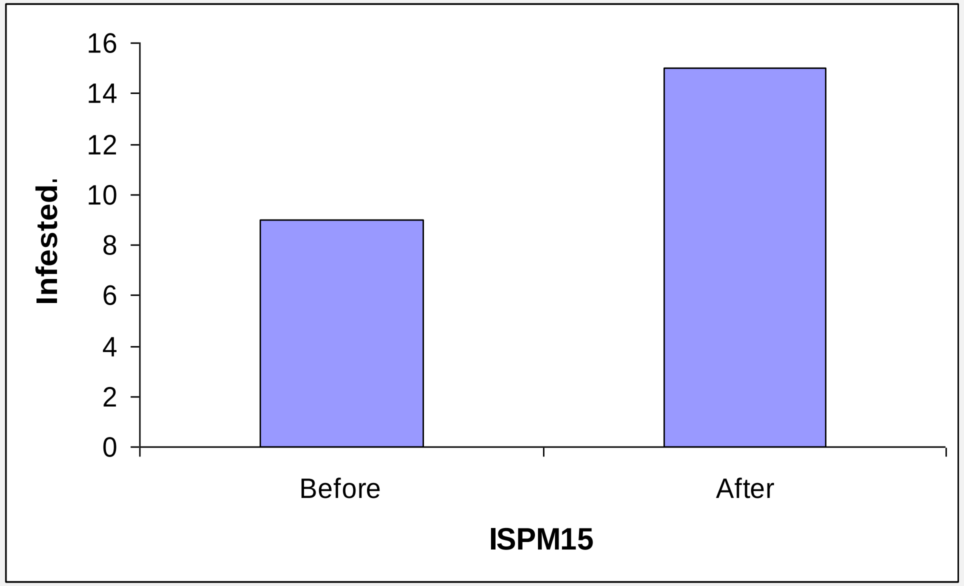
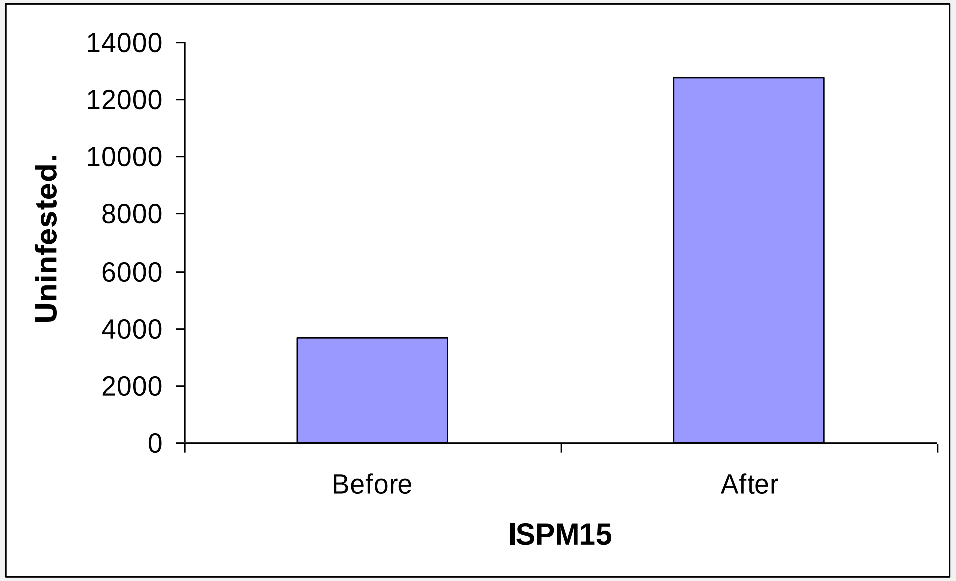
# Management & Policy (ISPM15)

## Effectiveness of ISPM15




Haack et al. 2014. PLoS One.

# Management & Policy (ISPM15)

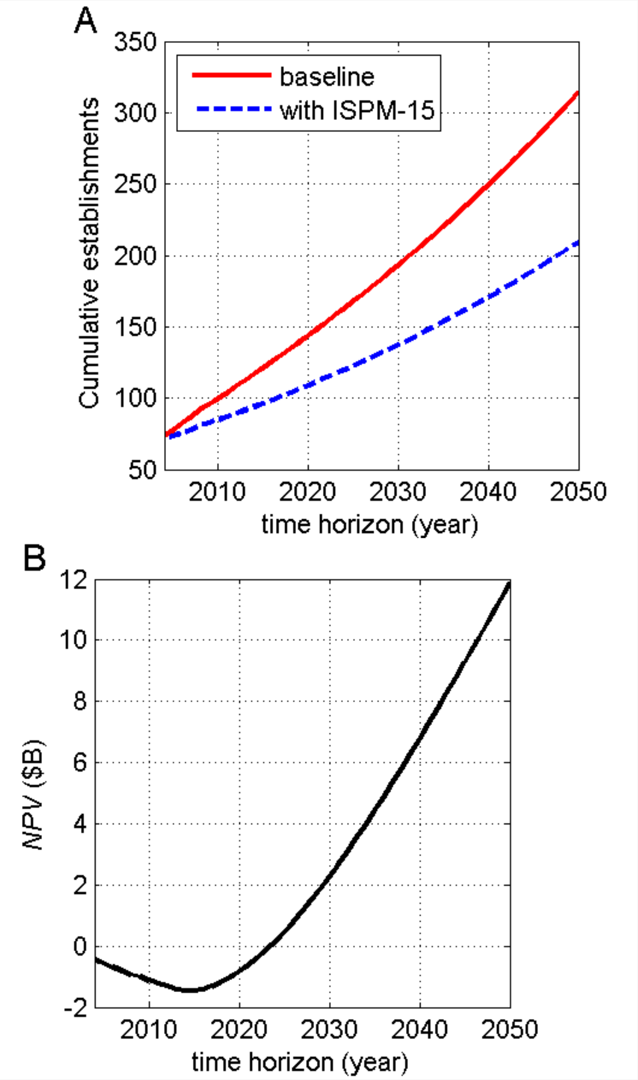
## Cost of ISPM15

- GTAP-M economic model
- Incorporates feedbacks in economic flows
- 437M initial cost of ISPM15

Strutt et al. 2013. Forest Policy Economics

# Pathway Level Economic Risk Analysis
## Wood packing material and borers (ISPM15)

- 34 Million avg pest cost (most innocuous) (Aukema, Leung, et al. 2011)
- 437 Million treatment cost (Strutt et al. 2013)
- 52% efficacy of treatment (Haack et al. 2014)




Leung et al. 2014. Frontiers in Ecology and the Environment

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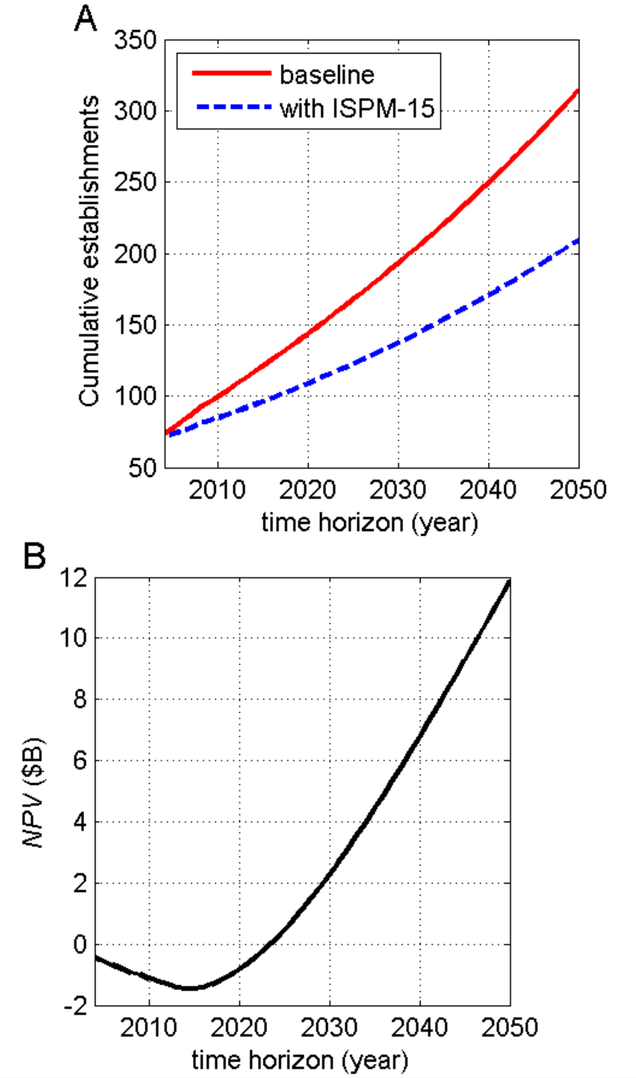


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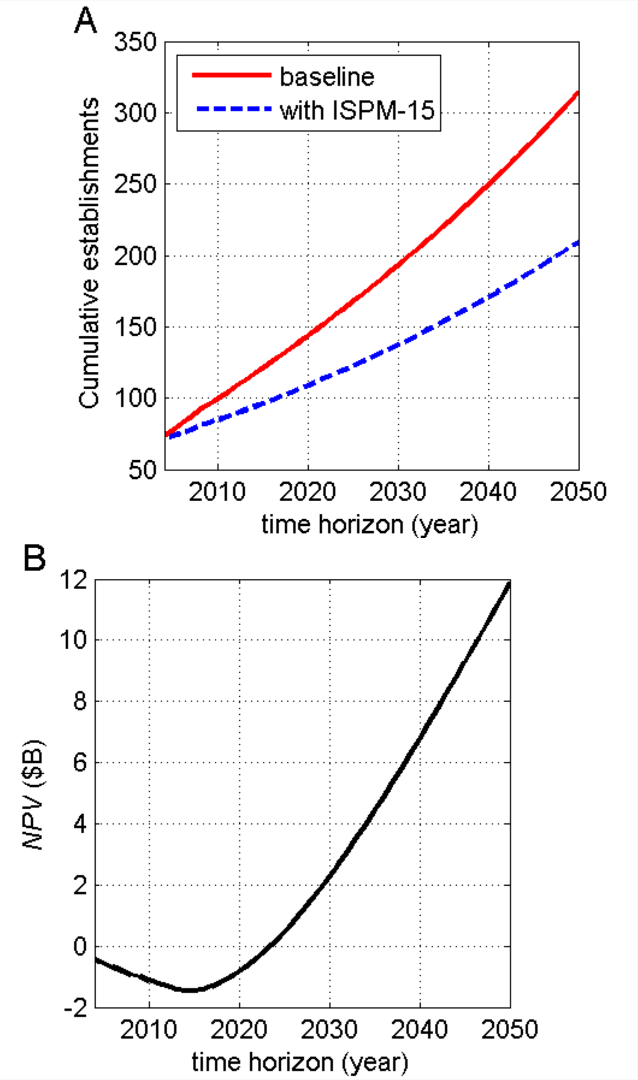


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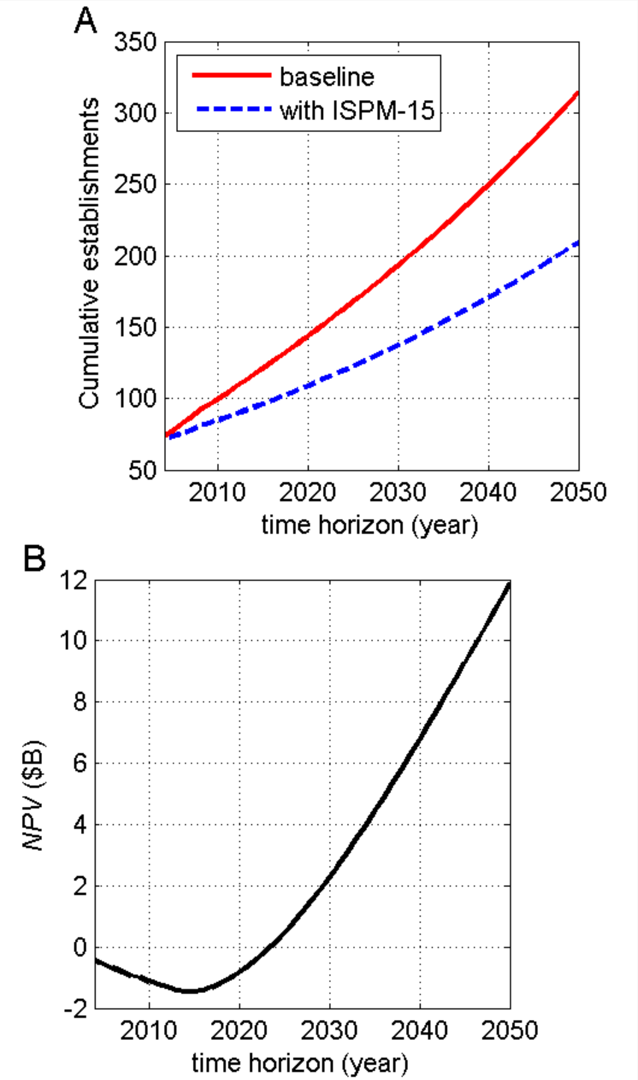


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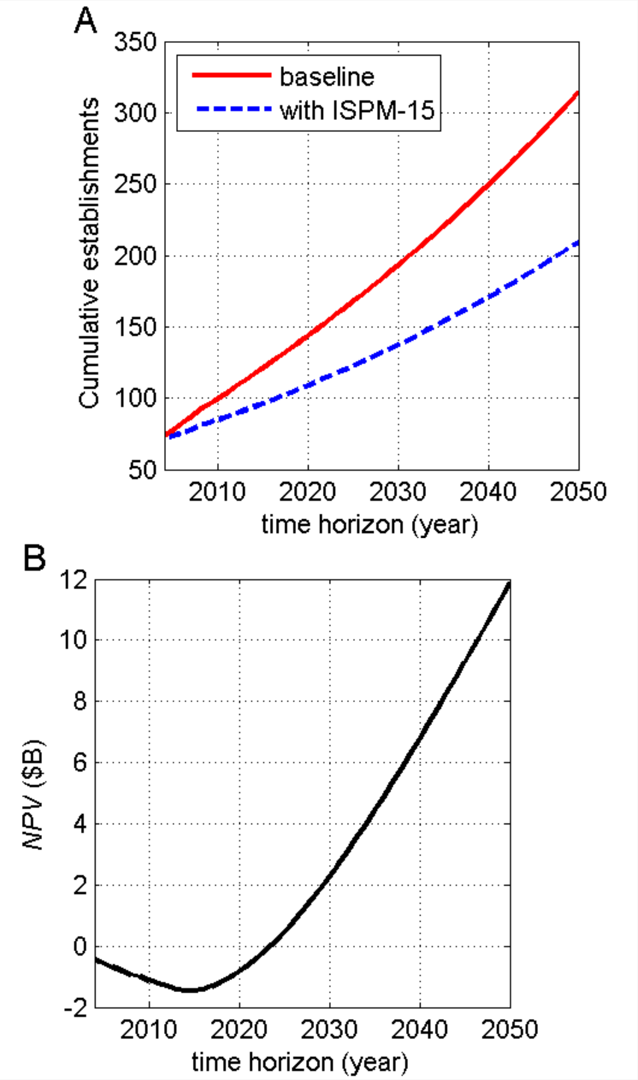


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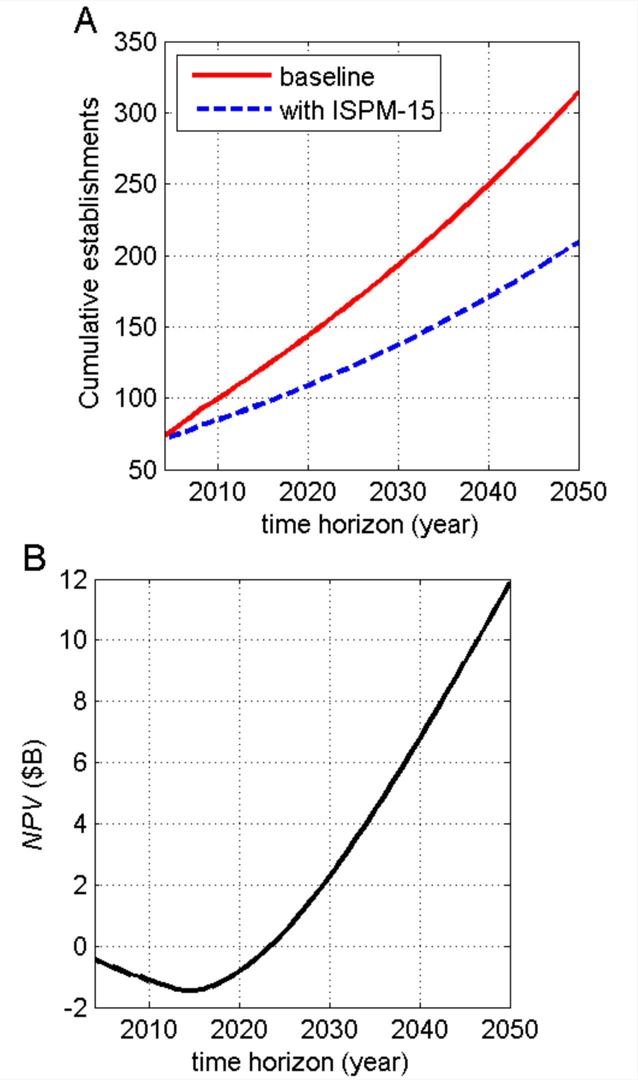
- Establishments projected to triple

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# Thanks!





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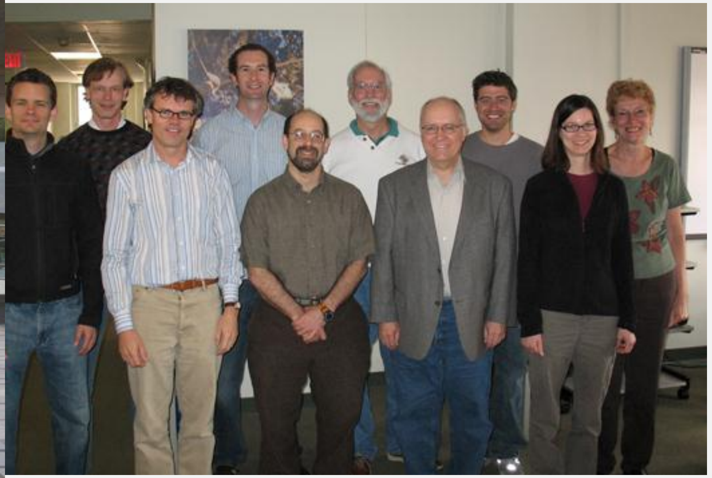

National Center for Ecological Analysis and Synthesis

$$\frac{\partial}{\partial t}(\nabla^2\phi) = \frac{\partial\psi}{\partial z}\frac{\partial}{\partial x}(\nabla^2\psi) - \frac{\partial\psi}{\partial x}\frac{\partial}{\partial z}(\nabla^2\psi) + \nu\nabla^2(\nabla^2\psi) + g\alpha\frac{dT}{dx}$$


cost
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CANADIAN AQUATIC INVASIVE SPECIES NETWORK