Sensitivity, Uncertainty, and Robustness Analysis

EES 4760/5760

Agent-Based and Individual-Based Computational Modeling

Jonathan Gilligan

Class #25: Monday, November 18 2024

Sensitivity, Uncertainty, Robustness

Sensitivity, Uncertainty, Robustness

- Starting point: You have a working model that achieves some goal:
  - Reproduces multiple observed patterns
  - Identifies policies that could produce a desired outcome
  - …
- How *trustworthy* and *reliable* are the model's predictions?
- **Sensitivity Analysis** focuses on how changing the model's parameters affects the outcome.
  - How important is it for a parameter to have some exact value?
    - For policymaking, do we need to work hard to *achieve* just that value?
    - For science, do we need to work hard to *measure* that parameter very accurately?
- **Uncertainty Analysis** focuses on how our uncertainty about the model's *parameters* affects our certainty about the model's *outputs* or *predictions*.
- **Robustness Analysis** looks at bigger changes:
  - What parts of the model can we change or eliminate and still get the desired results?
  - Can we simplify the model without losing the desired behavior?

Sensitivity Analysis

Is high sensitivity good or bad?

- **Bad:** If model is testing a general theory, but is very sensitive to parameter values, that may be evidence *against* the theory.
  - Does model work across the entire range of *observed values* for parameters?
    - If we don't know the values of the parameters, does the model work for the entire *plausible ranges* of the parameters?
    - **Exception**: Quantum field theory is one of the most successful theories of physics, but it is *very sensitive* to one parameter called the ***fine-structure constant***.
      - If the *fine-structure constant* were slightly larger or smaller than it actually is, the universe as we know it could not exist.
      - But this isn't evidence against the theory because we know the *fine-structure constant* very precisely.
- **Good:** If the model is being used to evaluate parameters we can't measure directly, then *higher sensitivity* can mean that we can infer the values of those parameters *more precisely*, with *less uncertainty*.

Challenges: Computational Complexity

- We would like to do *global sensitivity analysis:*
  - Vary all parameters over their entire ranges, in every combination.
  - Usually, we can't: computationally unfeasible.
    - A model has 10 parameters
    - Each parameter can take 10 possible values
    - Run the model 10 times for each combination of parameter values:
      - 100,000,000,000 runs.
  - There are strategies to make global sensitivity analysis feasible, but they are complicated.
    - Sampling parameter values
      - Random (Monte Carlo)
      - Systematic (e.g., Latin Hypercube)
- Instead: *local sensitiity analysis:*
  - Small variations around most likely values of parameters.
  - Vary one parameter at a time, or multiple parameters?
    - Interactions

Steps in Sensitivity Analysis

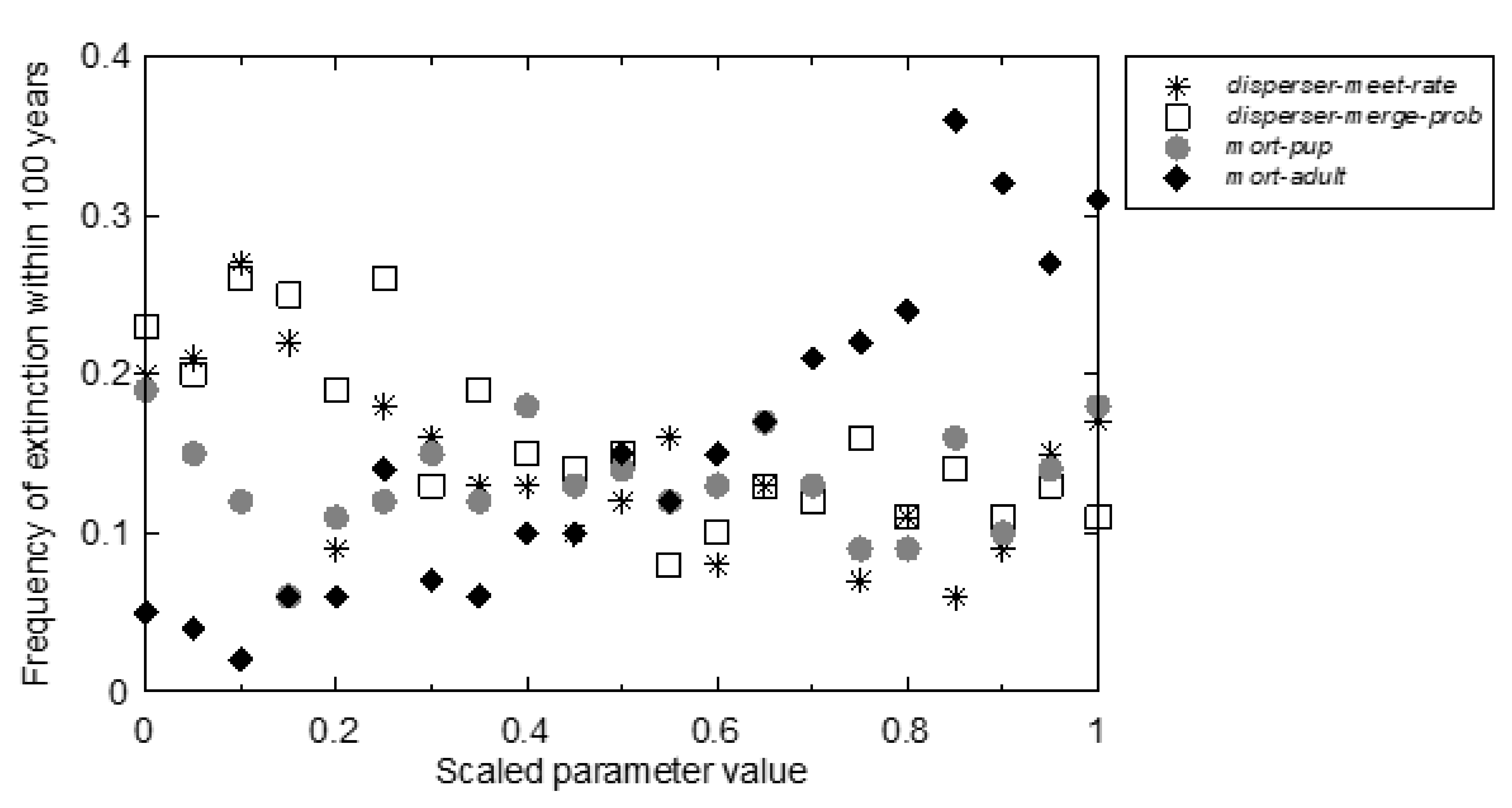
- Choose one or more **currencies** that we will use to evaluate the model (e.g., a pattern we want to reproduce).
- Single-Parameter analysis:
  - Vary each parameter one at a time with the others set to their nominal value
- Interactions:
  - Vary all the parameters simultaneous over a limited range

Example of Sensitivity Analysis

Example: Wild Dog Model

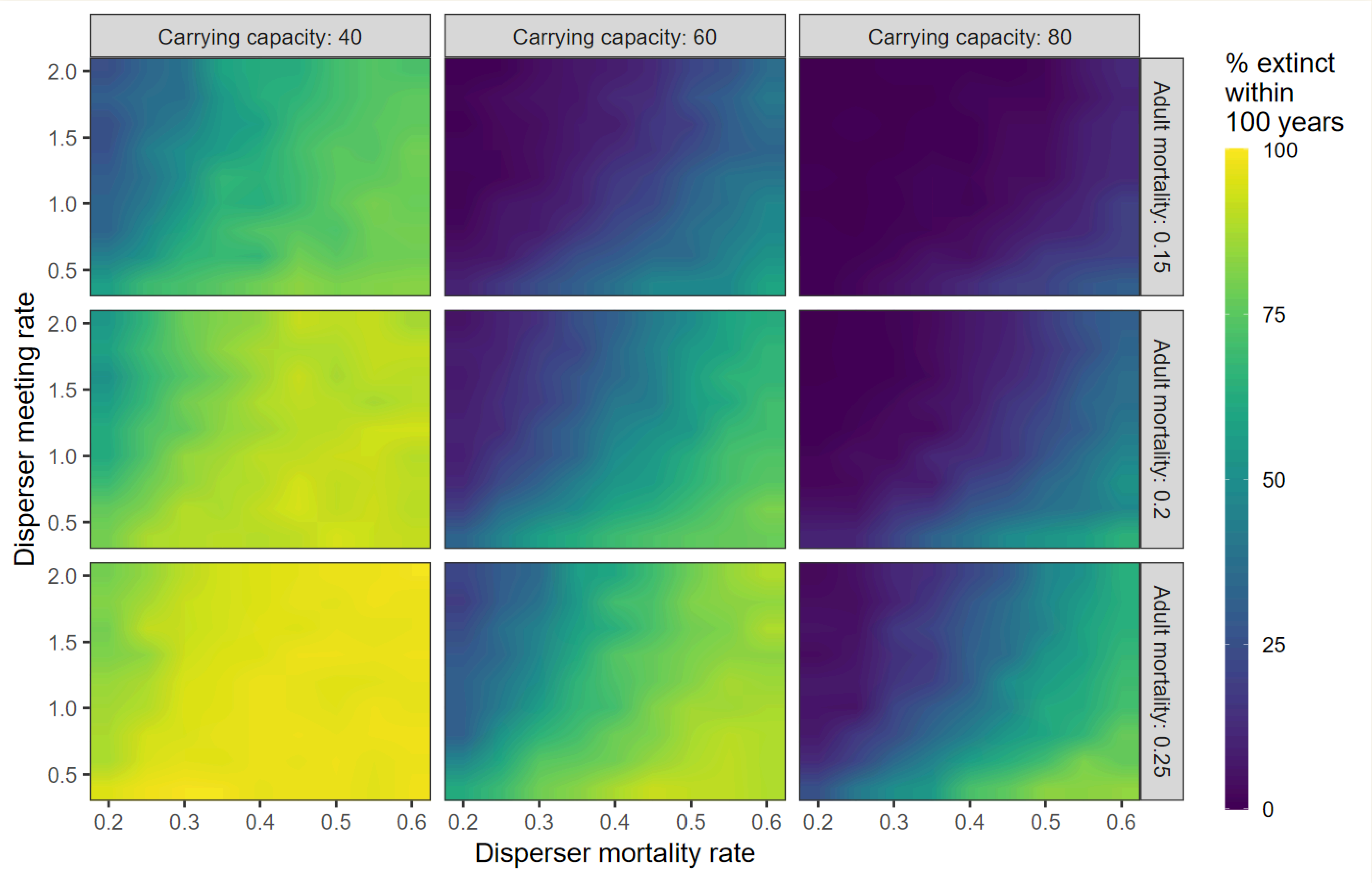
- Packs of wild dogs in nature preserve.
- Goal: Keep them from going extinct in next 100 years.
  - **Currency:** Fraction of runs in which dogs go extinct within 100 years.
- Vary parameters:
  - Mortality rate of adult dogs in pack
  - Mortality rate of dispersers
  - Meeting rate of disperser groups
  - Carrying capacity

Single-Parameter Analysis



Analyzing Interaction Data:

- Contour plots
- “Small multiple” plots
- Analyze a four-dimensional data set using a grid of nine plots.

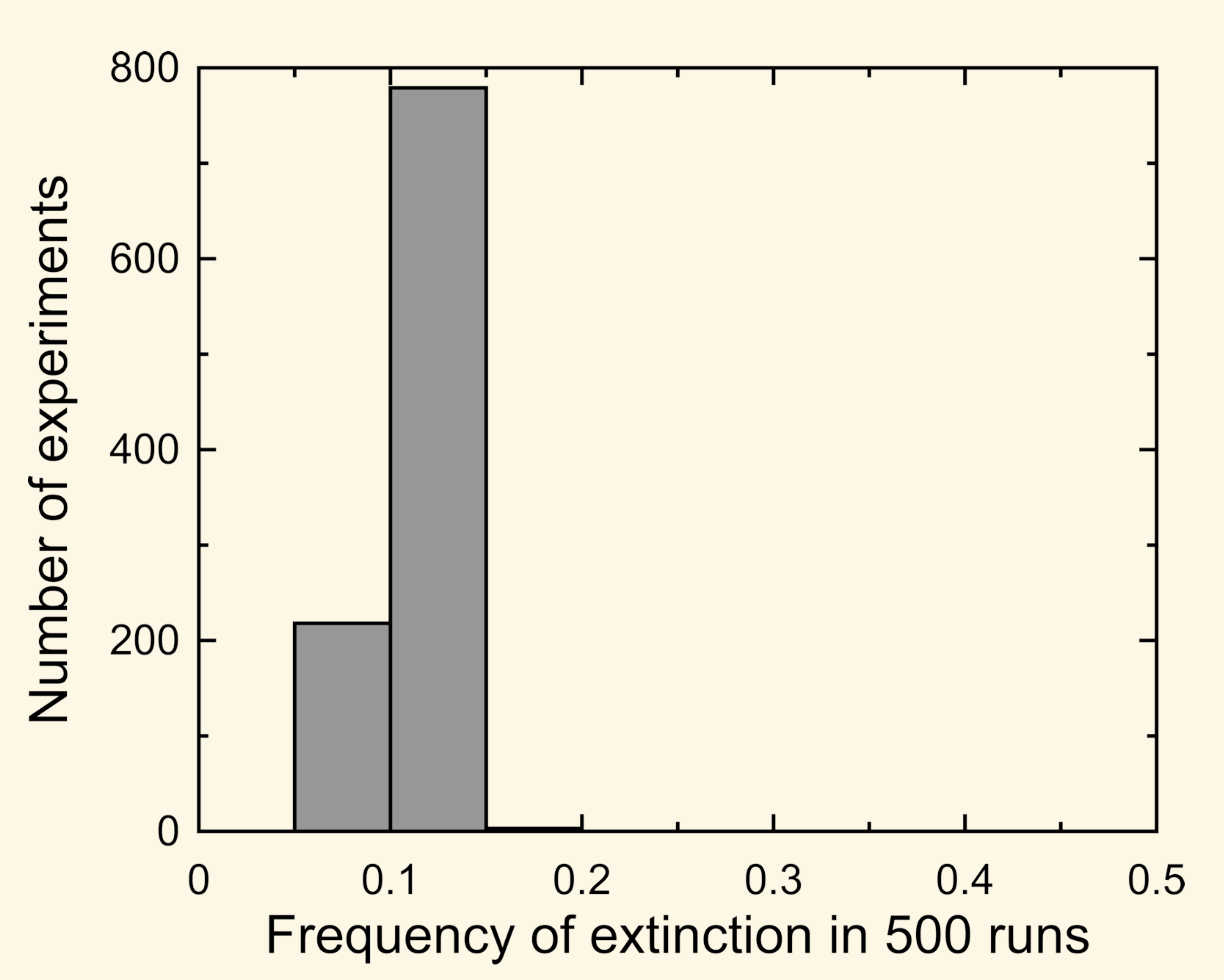

Carrying capacity: 40
Carrying capacity: 60
Carrying capacity: 80
Adult mortality: 0.15
Adult mortality: 0.2
Adult mortality: 0.25
Disperser meeting rate
2.0
1.5
1.0
0.5
Disperser mortality rate
0.2
0.3
0.4
0.5
0.6
% extinct within 100 years
100
75
50
25
0

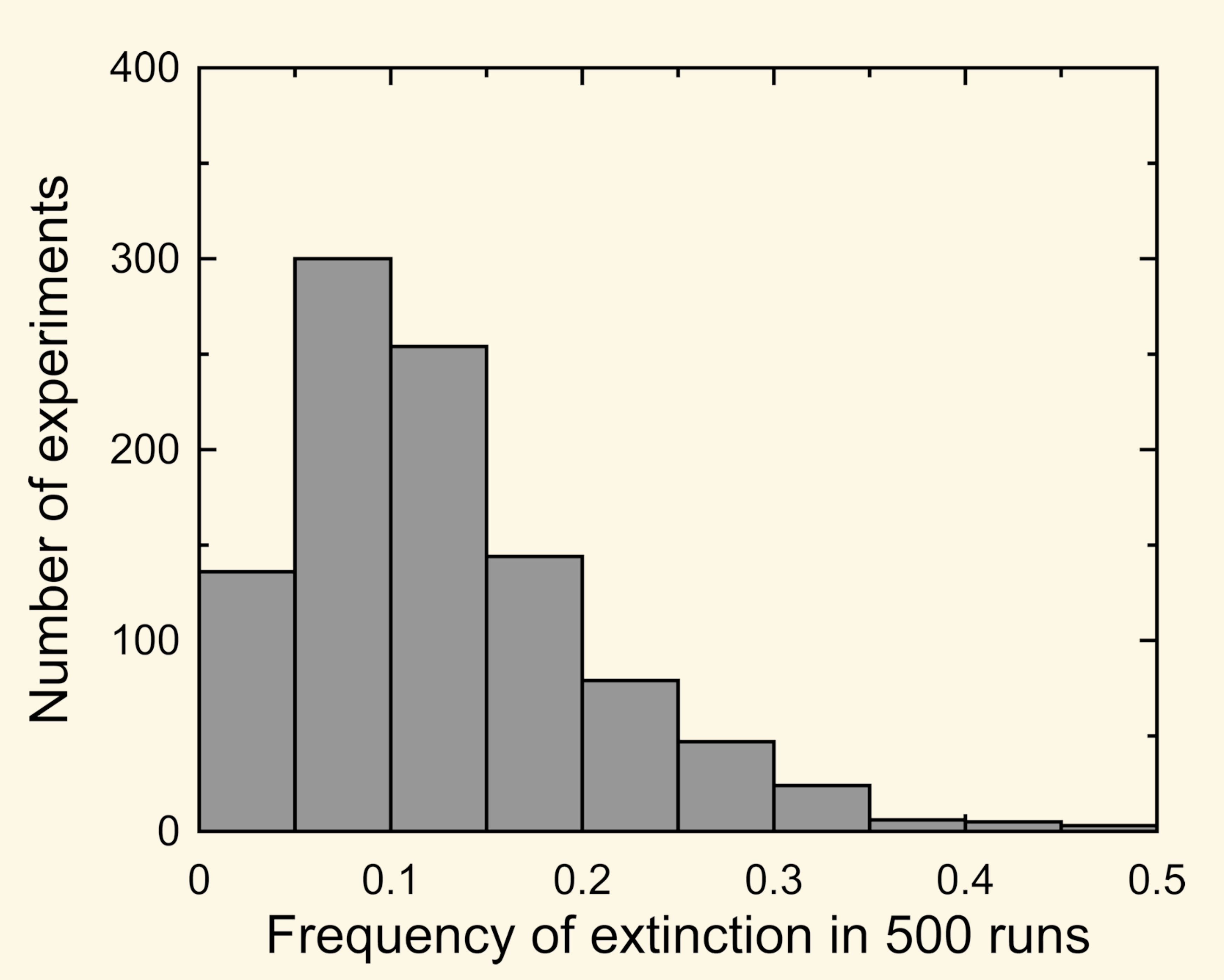
Uncertainty Analysis

Uncertainty Analysis

- We usually don't know the exact values of parameters.
- How much does our uncertainty about the parameters' values affect our certainty about the model's predictions?
- Starting point:
  - Choose one or more **currencies**.
  - What parameters do we want to analyze?
  - Define a probability distribution for each parameter that represents our uncertainty about its value.
- Run the model many times, each time drawing a different random value for each parameter from the distributions.
- Analyze the output:
  - Probability distribution of the currency

Uncertainty in Wild Dog Model





Parameters at nominal (default) values.

Parameters randomly sampled from uncertainty distribution.

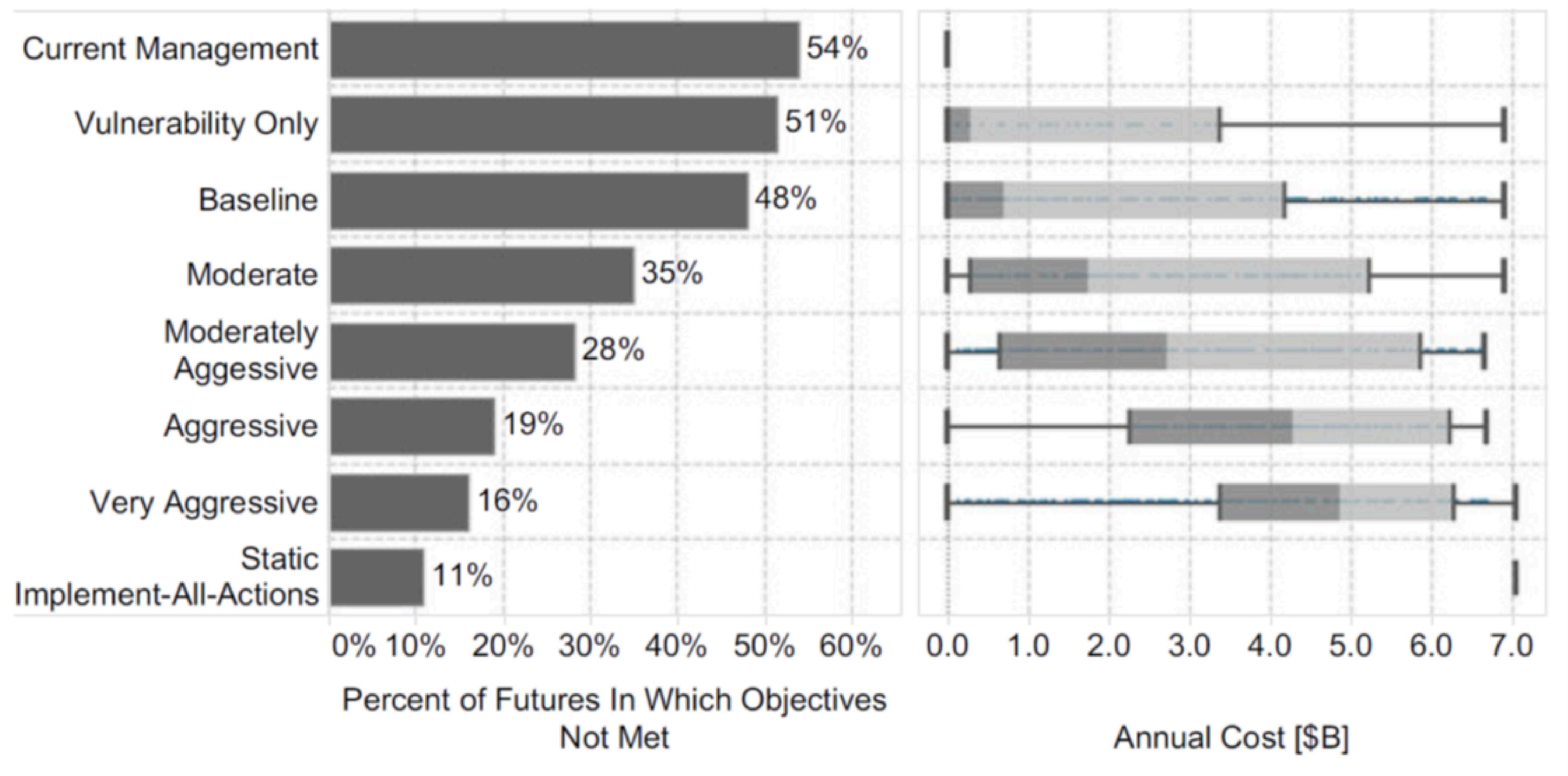
Robustness Analysis

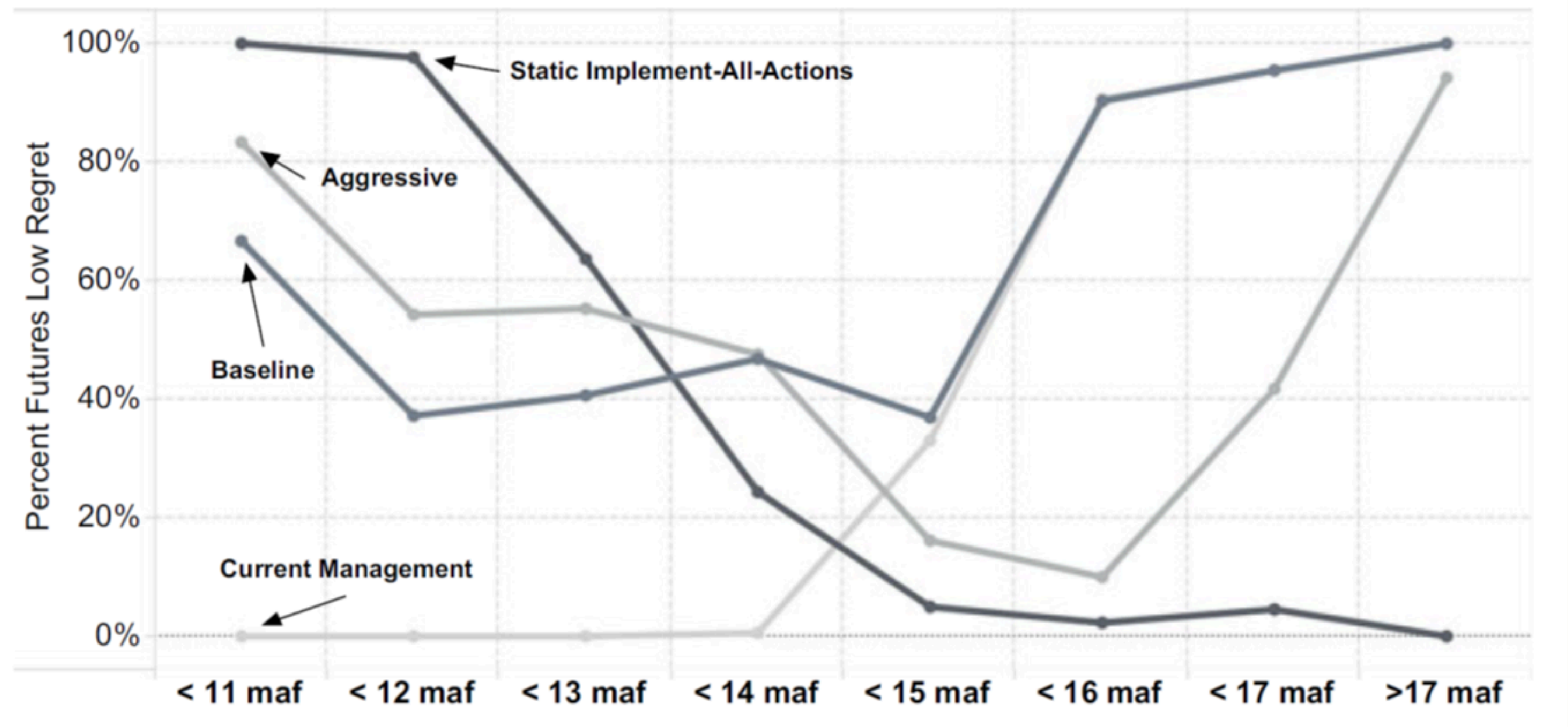
Robustness Analysis

- *Sensitivity analysis* and *uncertainty analysis* mostly made small changes to parameters and kept them within realistic limits
- ***Robustness analysis*** tries to break the model:
  - What happens when parameters take unrealistic values?
  - What happens when we change remove different parts of the model?
  - Identify which parts of the model are necessary, and which are unnecessary.

Robust Decision Making

- Robust Decision-Making under Deep Uncertainty
- Problem:
  - Manage water in Colorado River
  - Allocate water to users under drought conditions
- Compare 7 policy optionss
- Vary streamflow, demand, management parameters
- Measure:
  - Success at meeting objectives
  - Cost of policy
- Robust policies meet objectives over a wide range of uncertainties
- D.G. Groves *et al.*, “Robust Decision Making (RDM): Application to Water Planning and Climate Policy,” in V.A.W.J. Marchau *et al.* (eds.) *Decision Making Under Deep Uncertainty* (Springer, 2019).





Summary

General ideas about agent-based modeling

- Model interactions between individuals
  - Direct: individual-individual
  - Indirect: individual-environment, environment-individual
- Focus on emergent properties
  - Patterns or phenomena that were not deliberately programmed in, but arise spontaneously from interactions of agents with each other and with environment.
- Pattern-oriented modeling:
  - Start simple, but aim to build in enough complexity to produce multiple patterns seen in nature, or predicted in theory.
  - As you design model think about what kinds of “currency” you will use to assess its value.