Avoiding fisheries collapse: Can robustness frameworks capture and navigate uncertain harvest trade-offs?


Barracuda swimming (iStock)

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Multi-Objective Robust Decision Making for fisheries

1. Quantify and analyze **tradeoffs** of managing a simple **fishery** with a **predator-prey** relationship

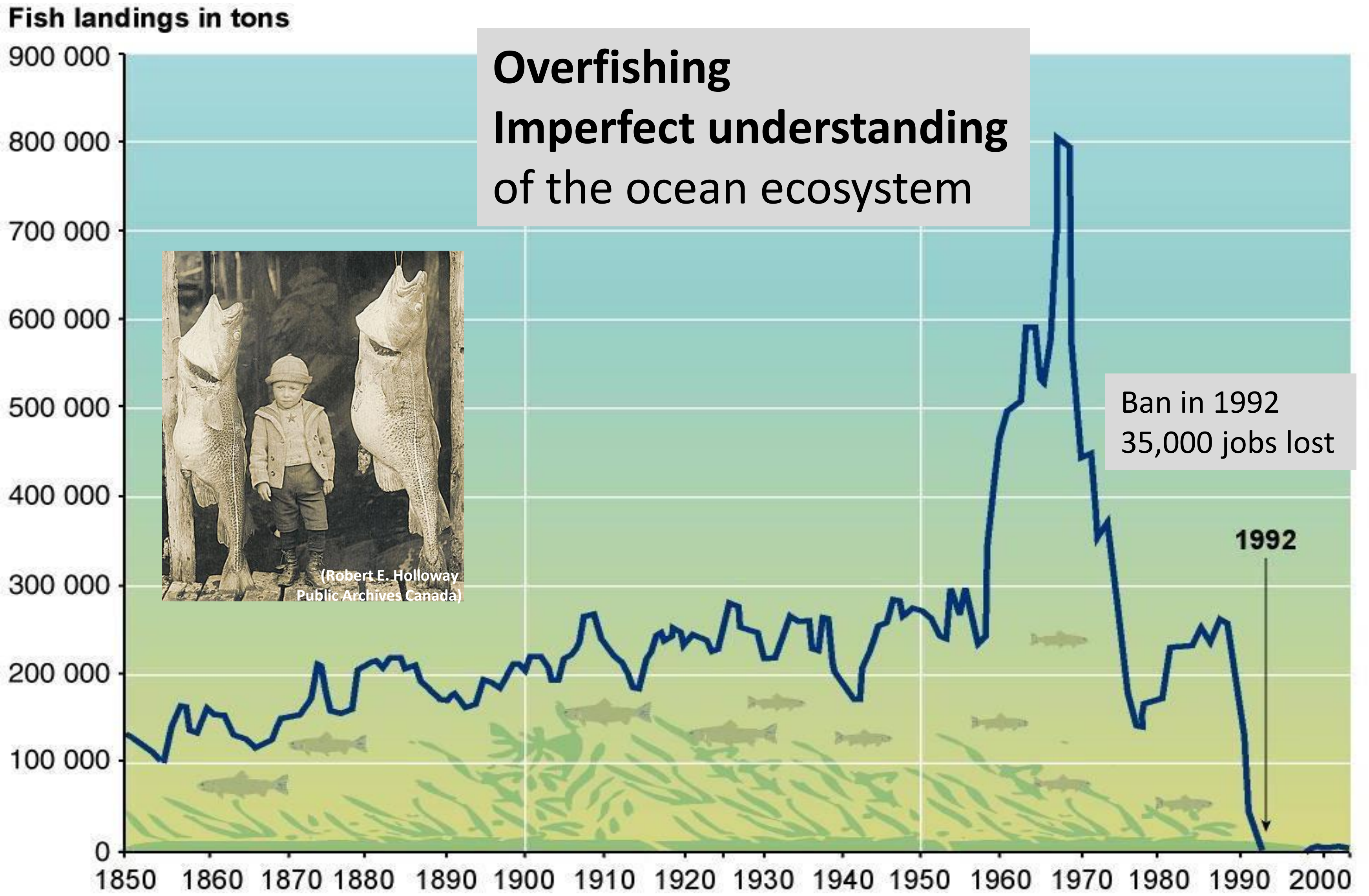
2. Assess the impacts of **deeply uncertain** parameters and relationships on system dynamics and tradeoffs

3. Explore formulations of harvesting **policies** to avoid potential **catastrophic consequences**

Northatlantic cod fishery collapse

Overfishing
Imperfect understanding
of the ocean ecosystem

Ban in 1992
35,000 jobs lost

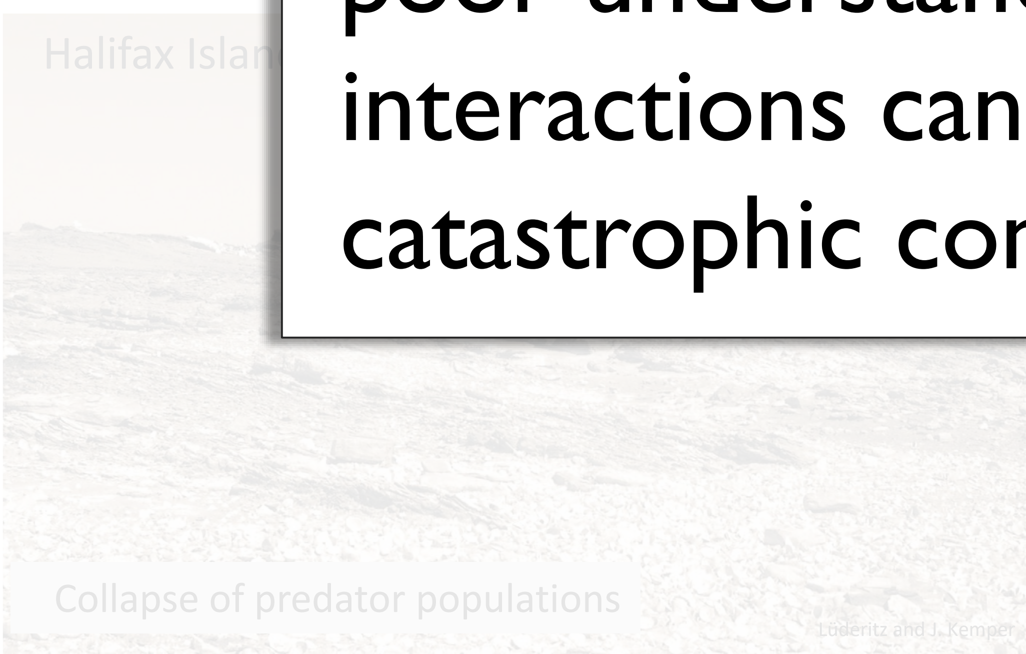


Source: Millennium Ecosystem Assessment

Northern Benguela ecosystem

Combination of **overfishing** and **changing environmental conditions**

Imprudent human action and poor understanding of system interactions can have catastrophic consequences!



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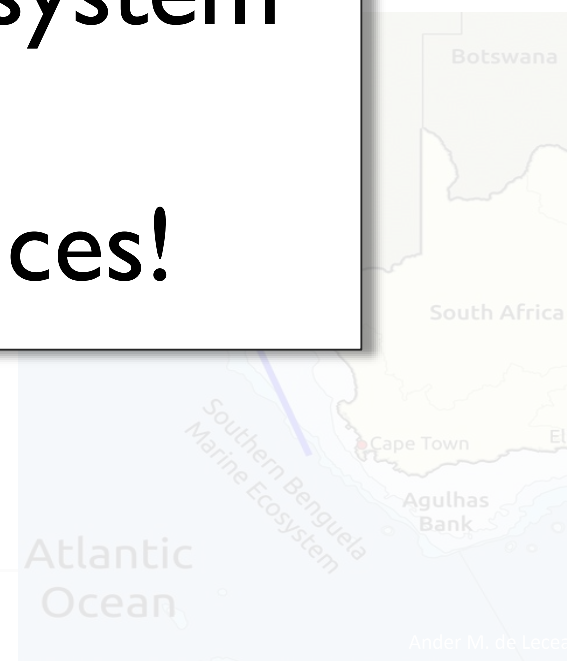
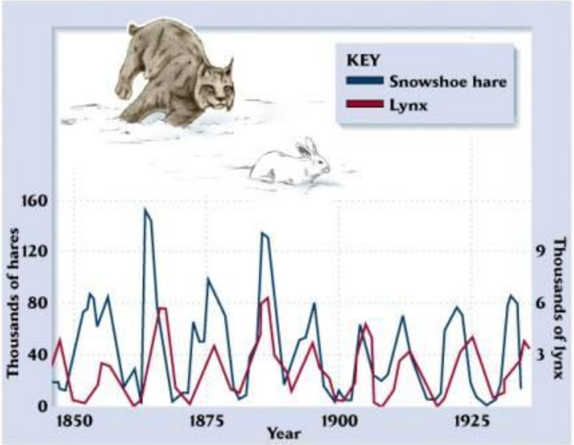


Modeling predator-prey systems

The classic system

Lotka-Volterra equations



x: prey $$\frac{dx}{dt} = bx - axy$$

y: predator $$\frac{dy}{dt} = caxy - dy$$

b: prey growth rate

d: predator death rate

c: rate with which consumed prey is converted to predator

a: rate with which prey is killed by a predator per unit of time

Modeling predator-prey systems

Prey growth

Exponential growth in the absence of a predator

$$\frac{dx}{dt} = \boxed{bx} - axy$$

$$\frac{dy}{dt} = caxy - dy$$

$$\boxed{f(x) = bx\left(1 - \frac{x}{K}\right)}$$

Replaced with:

Density-dependent function (logistic model)

K: prey carrying capacity given its environmental conditions

Modeling predator-prey systems

Trophic function

Most important and debated element

$$\frac{dx}{dt} = bx - axy$$

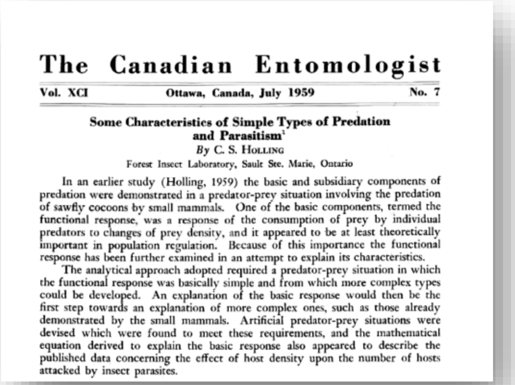
$$\frac{dy}{dt} = caxy - dy$$

$$g(x) = \frac{ax}{1 + ahx}$$

Replaced with:

Holling's generalized functional response

h is the handling time



The Canadian Entomologist

Vol. XCI Ottawa, Canada, July 1959 No. 7

Some Characteristics of Simple Types of Predation and Parasitism[1]

By C. S. Holling

Forest Insect Laboratory, Sault Ste. Marie, Ontario

In an earlier study (Holling, 1959) the basic and subsidiary components of predation were demonstrated in a predator-prey situation involving the predation of sawfly cocoons by small mammals. One of the basic components, termed the functional response, was a response of the consumption of prey by individual predators to changes of prey density, and it appeared to be at least theoretically important in population regulation. Because of this importance the functional response has been further examined in an attempt to explain its characteristics.

The analytical approach adopted required a predator-prey situation in which the functional response was basically simple and from which more complex types could be developed. An explanation of the basic response would then be the first step towards an explanation of more complex ones, such as those already demonstrated by the small mammals. Artificial predator-prey situations were devised which were found to meet these requirements, and the mathematical equation derived to explain the basic response also appeared to describe the published data concerning the effect of host density upon the number of hosts attacked by insect parasites.

Holling (1959); Can. Entomol.

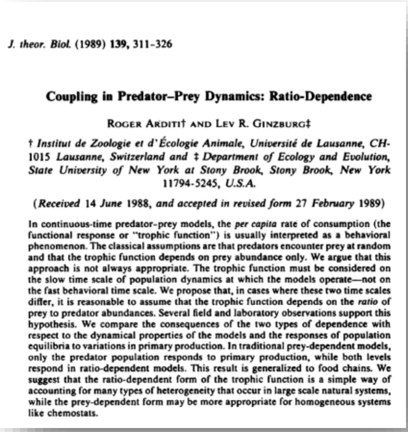
Modeling predator-prey systems

Trophic function

$$g(x) = \frac{ax}{1 + ahx}$$

Independent of predator density

$$\frac{dx}{dt} = f(x) - g(x)y$$
$$\frac{dy}{dt} = cg(x)y - dy$$



J. theor. Biol. (1989) **139**, 311–326

Coupling in Predator–Prey Dynamics: Ratio-Dependence

Roger Arditi† and Lev R. Ginzburg‡

† *Institut de Zoologie et d'Écologie Animale, Université de Lausanne, CH-1015 Lausanne, Switzerland and* ‡ *Department of Ecology and Evolution, State University of New York at Stony Brook, Stony Brook, New York 11794-5245, U.S.A.*

(*Received* 14 *June* 1988, *and accepted in revised form* 27 *February* 1989)

In continuous-time predator–prey models, the *per capita* rate of consumption (the functional response or "trophic function") is usually interpreted as a behavioral phenomenon. The classical assumptions are that predators encounter prey at random and that the trophic function depends on prey abundance only. We argue that this approach is not always appropriate. The trophic function must be considered on the slow time scale of population dynamics at which the models operate—not on the fast behavioral time scale. We propose that, in cases where these two time scales differ, it is reasonable to assume that the trophic function depends on the *ratio* of prey to predator abundances. Several field and laboratory observations support this hypothesis. We compare the consequences of the two types of dependence with respect to the dynamical properties of the models and the responses of population equilibria to variations in primary production. In traditional prey-dependent models, only the predator population responds to primary production, while both levels respond in ratio-dependent models. This result is generalized to food chains. We suggest that the ratio-dependent form of the trophic function is a simple way of accounting for many types of heterogeneity that occur in large scale natural systems, while the prey-dependent form may be more appropriate for homogeneous systems like chemostats.

Arditi and Ginzburg (1989); J. Theor. Biol.

Arditi & Ginzburg:
Ratio-dependent trophic function
Available prey shared among predators

$$g\left(\frac{x}{y}\right) = \frac{\alpha \frac{x}{y}}{1 + \alpha \frac{x}{y}} = \frac{\alpha x}{y + \alpha h x}$$

Note: a is defined as the rate with which prey is killed by a predator per unit of time (1/(mass·time)), α is defined as the rate at which the prey is available to the predator (1/time).

Modeling predator-prey systems

Trophic function

J. theor. Biol. (1989) 139, 311-326

Coupling in Predator–Prey Dynamics: Ratio-Dependence

Roger Arditi† and Lev R. Ginzburg‡

Arditi & Ginzburg (1989); J. T

The interpretation of tests for ratio-dependence

Ruxton & Gurney (1992); Oikos

Scale invariance is a reasonable approximation in predation models – reply to Ruxton and Gurney

Arditi et

DAPHNIA-PHYTOPLANKTON INTERACTIONS IN LAKES: IS THERE A NEED FOR RATIO-DEPENDENT CONSUMER-RESOURCE MODELS?

“This idea would set predator-p
- Abrams (1994)

THE FALLACIES OF “RATIO-DEPENDENT” PREDATION

Abrams (1994); Ecology

Sarnelle (1994); Ecology

The nature of predation: prey dependent, ratio dependent or neither?

Peter A. Abrams and Lev R. Ginzburg

To describe a predator–prey relationship, it is necessary to specify the rate of prey consumption by an average predator. This functional response largely determines dynamic stability, responses to environmental influences and the nature of indirect effects in the food web containing the predator–prey pair. Nevertheless, measurements of functional responses in nature are quite rare. Recently, much work has been devoted to comparing two idealized forms of the functional response: prey dependent and ratio dependent. Although we agree that predator abundance often affects the consumption rate of individual predators, this phenomenon requires more attention. Disagreement remains over which of the two idealized responses serves as a better starting point in building models when data on predator dependence are absent.

Peter Abrams is at the Dept of Zoology, University of Toronto, 25 Harbord Street, Toronto, Ontario, Canada M5S 3G5 (abrams@zoo.utoronto.ca); and Lev Ginzburg is at the Dept of Ecology and Evolution, State University of New York at Stony Brook, Stony Brook, NY 11794-5245, USA (lev@ramas.com).

Abrams & Ginzburg (2000); Trends Ecol. Evol.

Modeling predator-prey systems

Lotka-Volterra & Arditi-Ginzurg models extremes of a spectrum of predator dependence

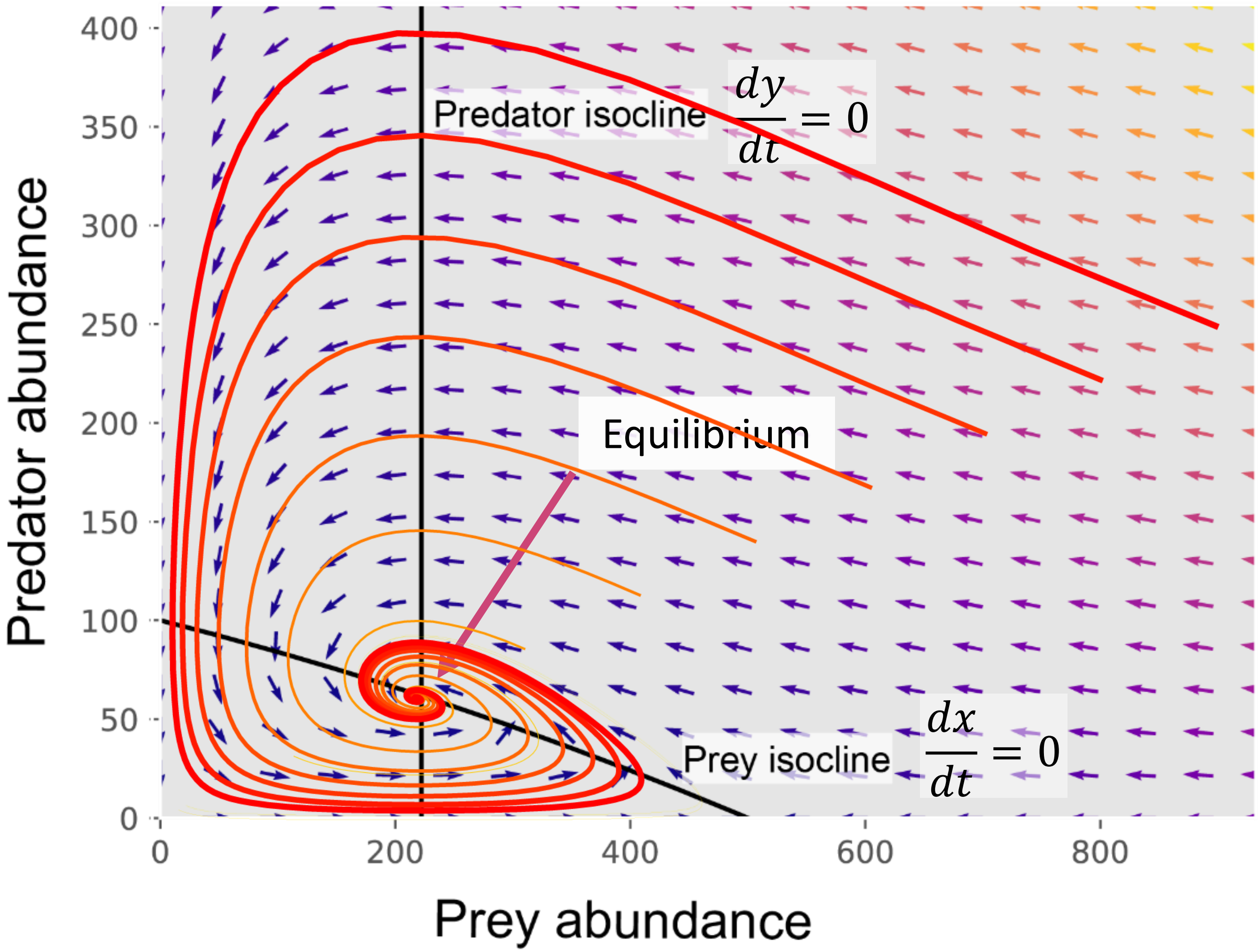
What does this uncertainty in interference imply for the system?

$$g(x) = \frac{\;}{1 + ahx} \leftarrow g\left(\frac{\;}{y^m}\right) = \frac{\;}{y^m + \alpha hx} \rightarrow g\left(\frac{\;}{y}\right) = \frac{\;}{y + \alpha hx}$$

m: predator interference parameter, on a sliding scale of 0 to 1

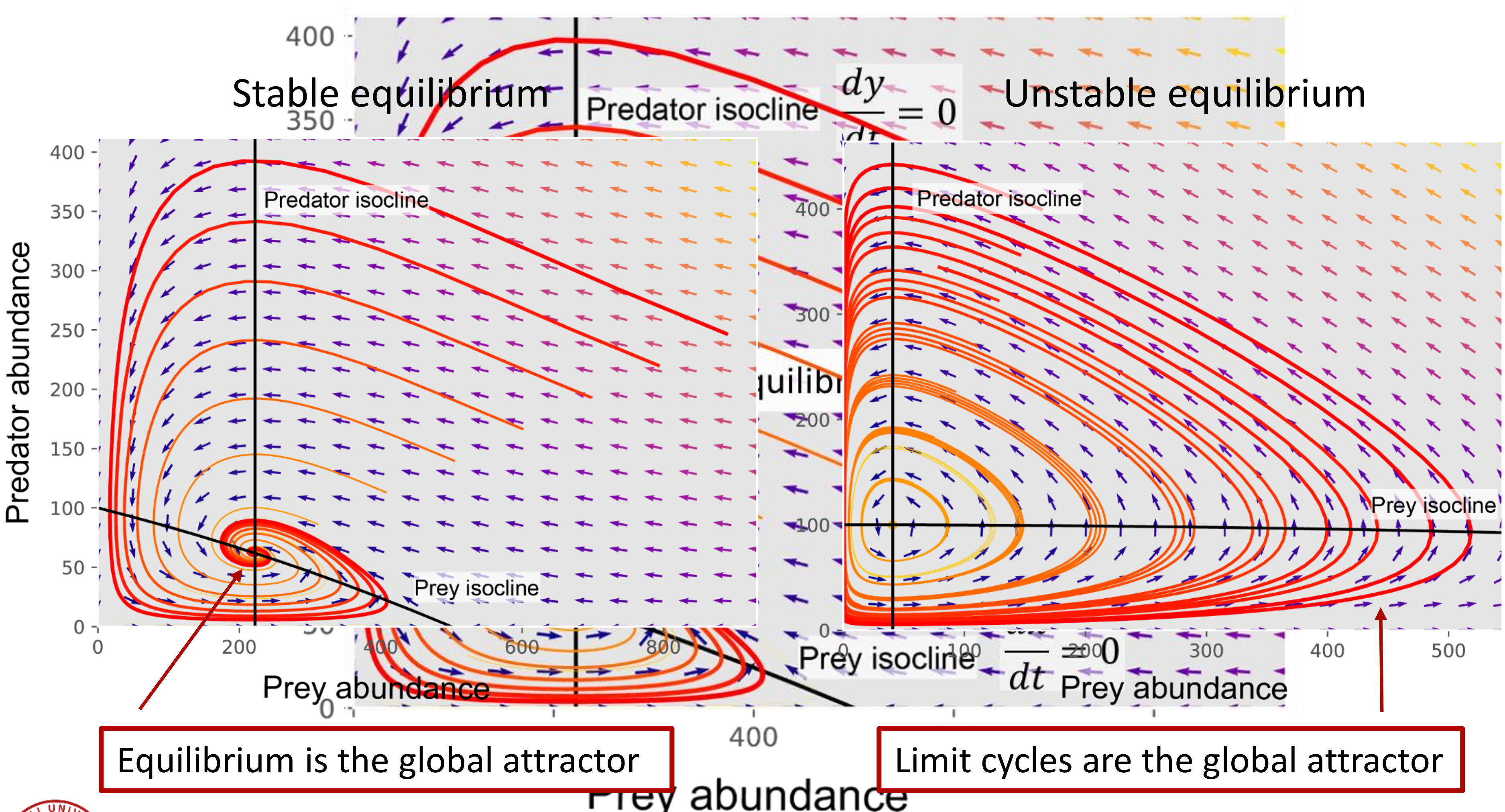
System dynamics

Classic ratio-dependent model



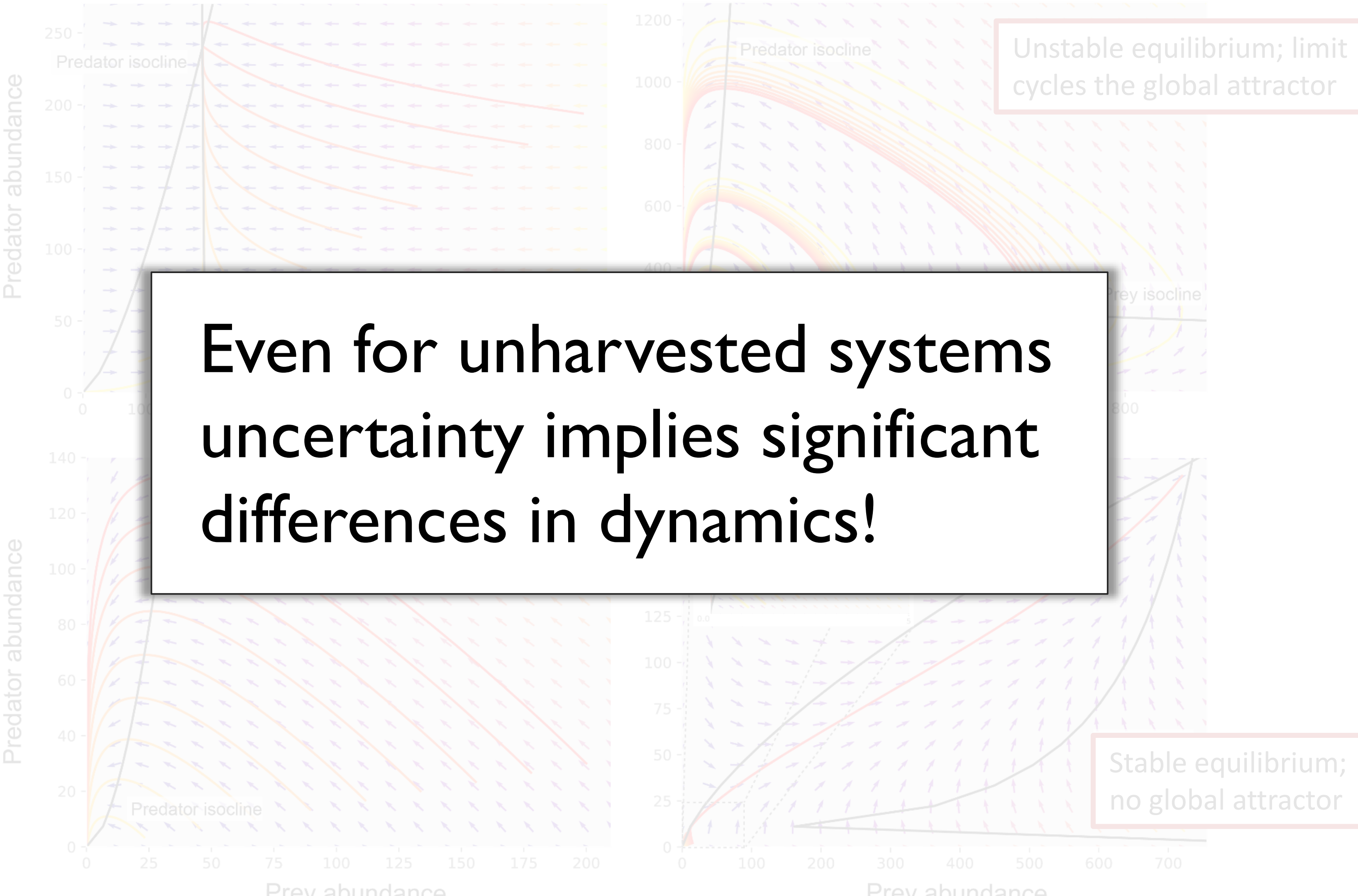
System dynamics

Classic ratio-dependent model



System dynamics

Predator-dependent model



Even for unharvested systems uncertainty implies significant differences in dynamics!

Harvesting the system

Continuous-time model

$$\frac{dx}{dt} = bx\left(1 - \frac{x}{K}\right) - \frac{\alpha xy}{y^m + \alpha hx} - z \cdot x$$

$$\frac{dy}{dt} = \frac{c\alpha xy}{y^m + \alpha hx} - dy$$

Harvesting effort

Harvested fish

Harvesting the system

Discrete-time model

$$x_{t+1} = x_t + bx_t\left(1 - \frac{x_t}{K}\right) - \frac{\alpha x_t y_t}{{y_t}^m + \alpha h x_t} - z_t \cdot x_t - \varepsilon_x$$

$$y_{t+1} = y_t + \frac{c\alpha x_t y_t}{{y_t}^m + \alpha h x_t} - dy_t - \varepsilon_y$$

Set of T decisions described by a policy

Environmental stochasticity

$\varepsilon_i \sim L.N(0, \sigma_i)$

Parameter	α	b	c	d	h	K	m	σ_x	σ_y
Value	0.005	0.5	0.5	0.1	0.1	2000	0.7	0.004	0.004

Multi-Objective Robust Decision Making for fisheries

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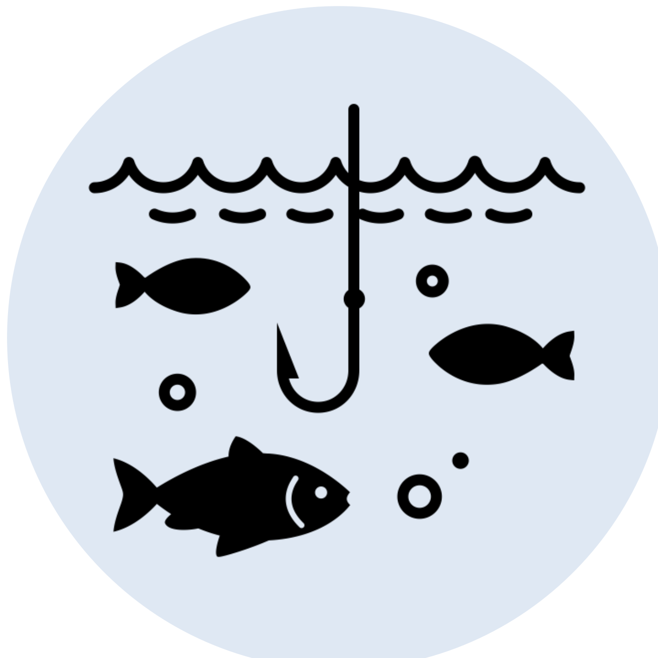
3. Explore formulations of harvesting **policies** to avoid potential **catastrophic consequences**

Four objectives and a constraint

Averaged over 100 realizations of well-characterized environmental stochasticity

Net Present Value
Total discounted profits

Consecutive low harvest duration
Harvest below 5% of population



Prey deficit
Deficit from population capacity

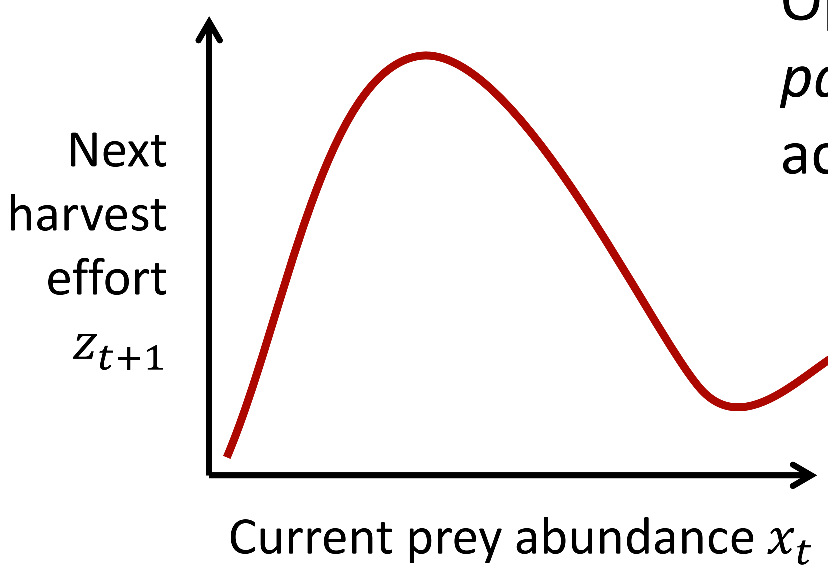
Worst harvest instance
1^{st} percentile of harvest

No predator population collapse

Identifying harvesting policies

Direct Policy Search:

Optimize a policy describing z_{t+1} as a function of prey abundance, x_t



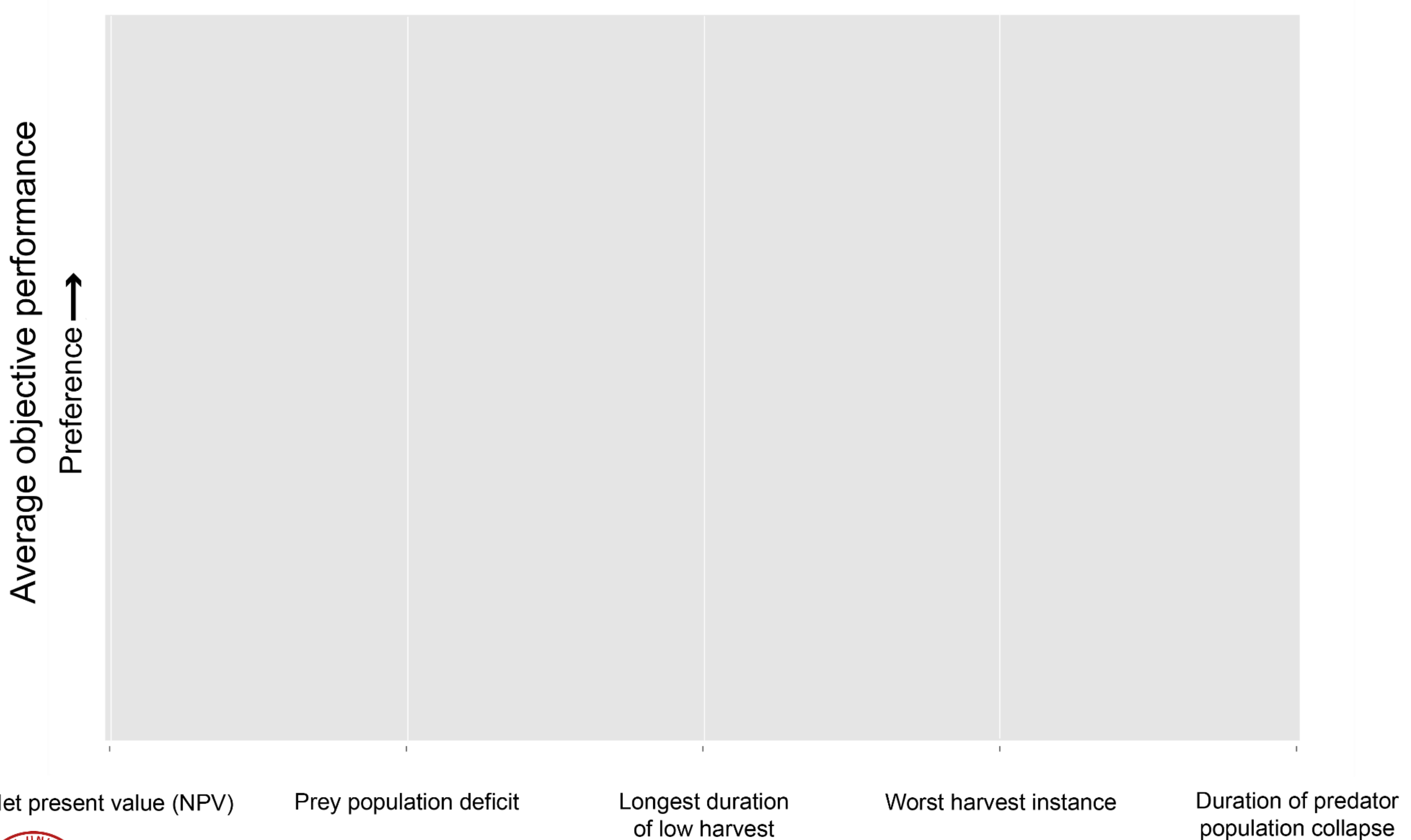
Optimize function *parameters*, rather than actual decision

Borg MOEA - borgmoea.org/

Giuliani et al. (2016); https://doi.org/10.1061/(ASCE)WR.1943-5452.0000570

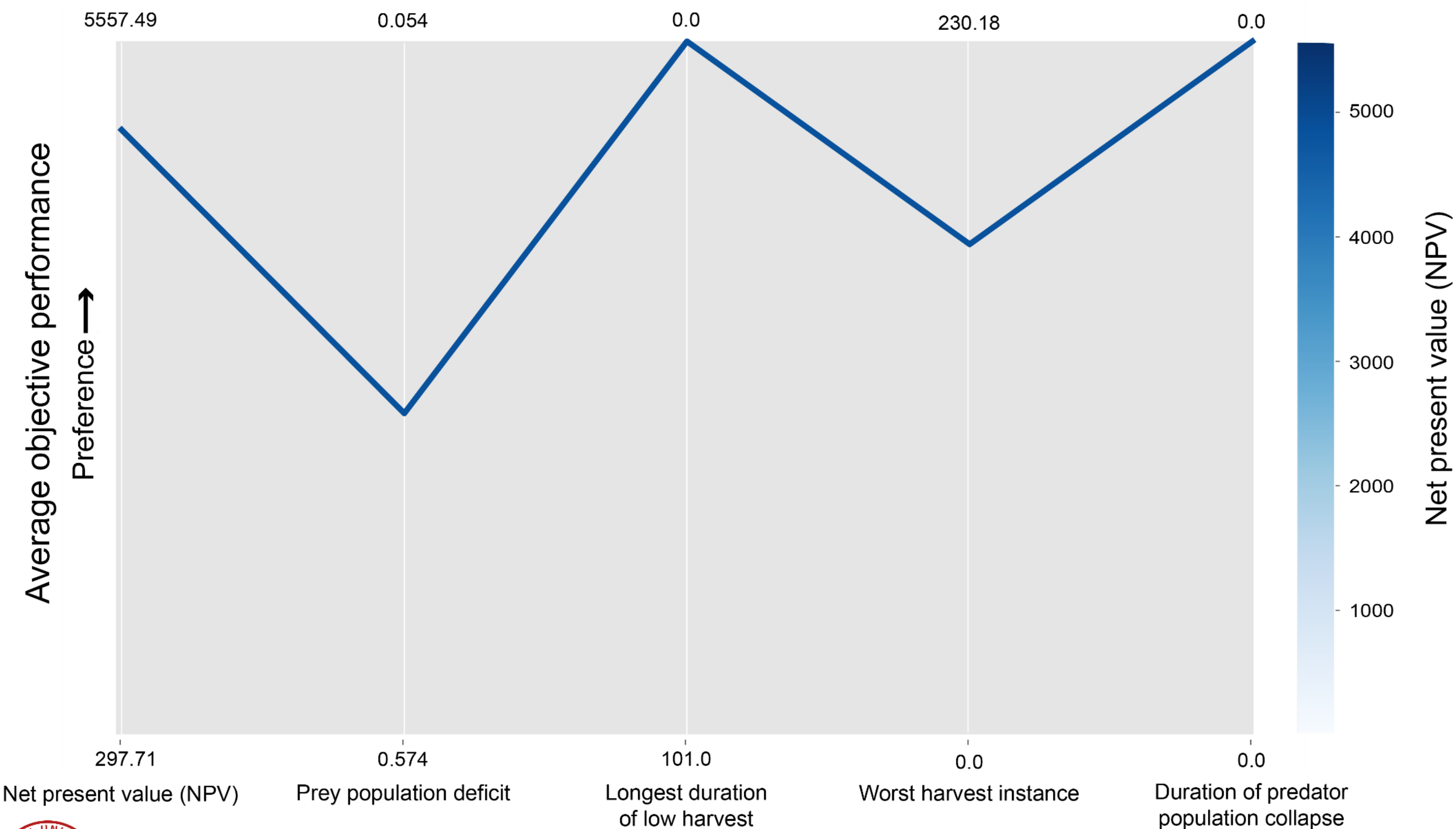
Identified tradeoffs

Parallel axis



Identified tradeoffs

Parallel axis



Identified tradeoffs

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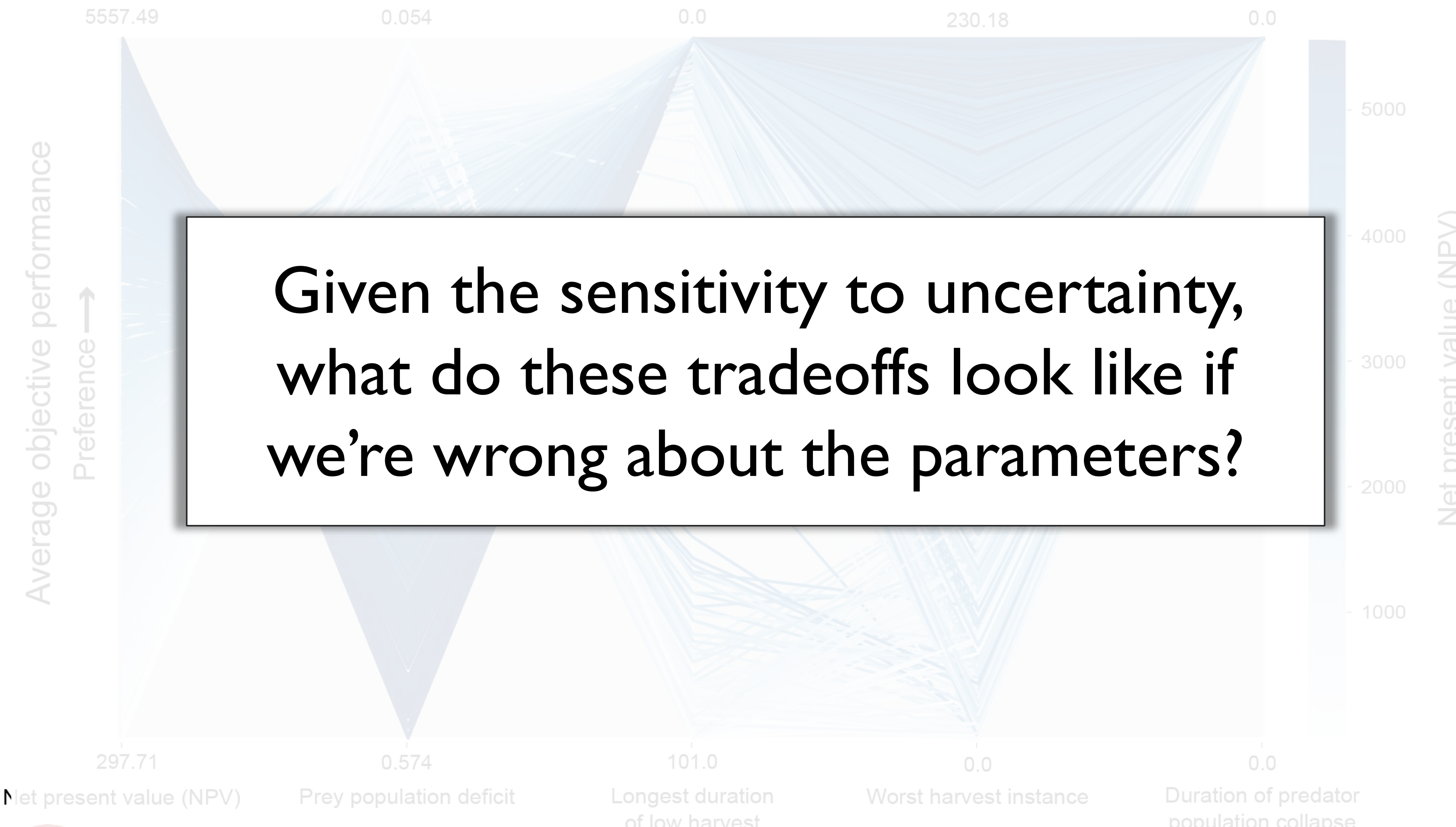
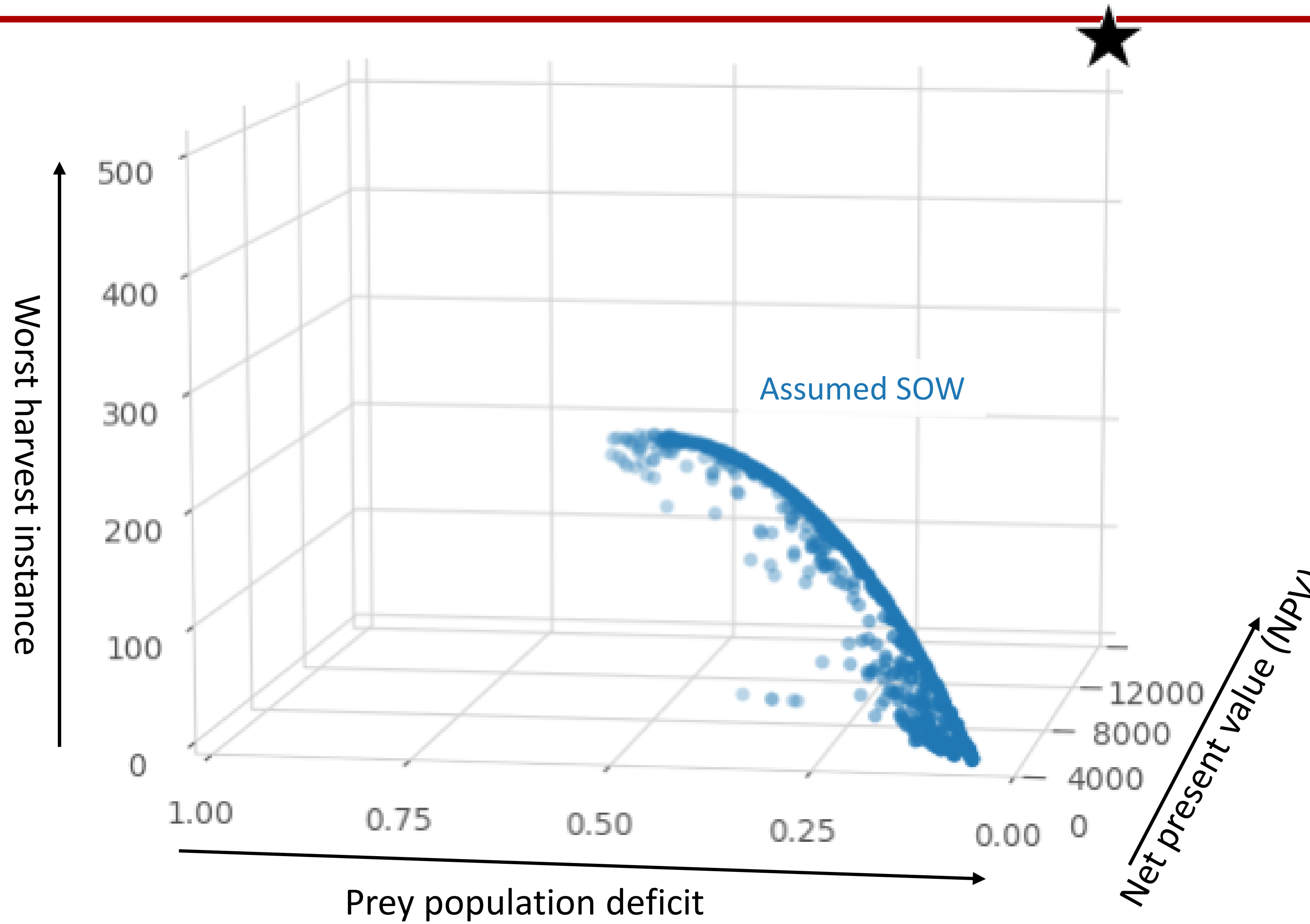


Given the sensitivity to uncertainty, what do these tradeoffs look like if we're wrong about the parameters?

What do the tradeoffs look like in other SOW?



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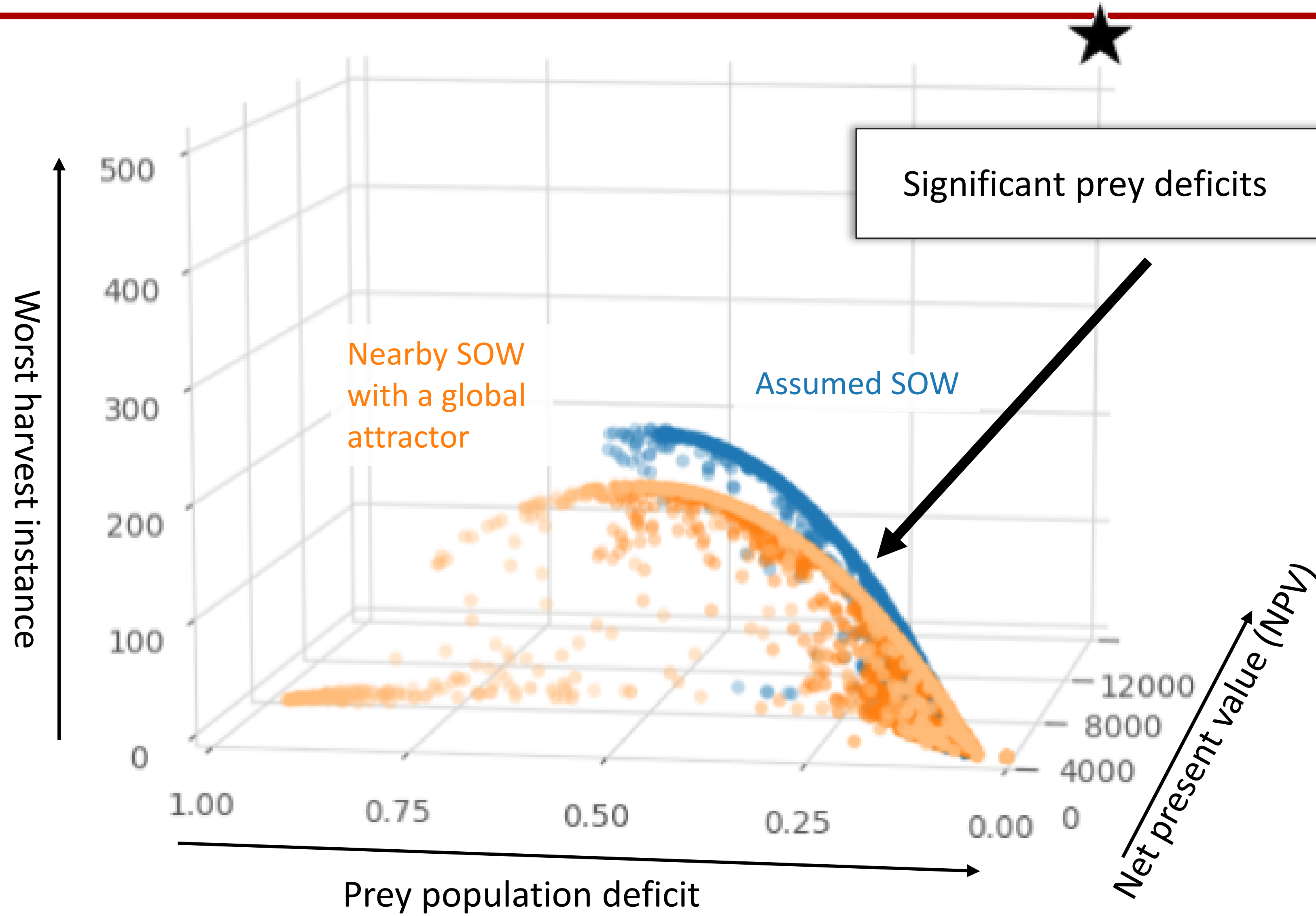

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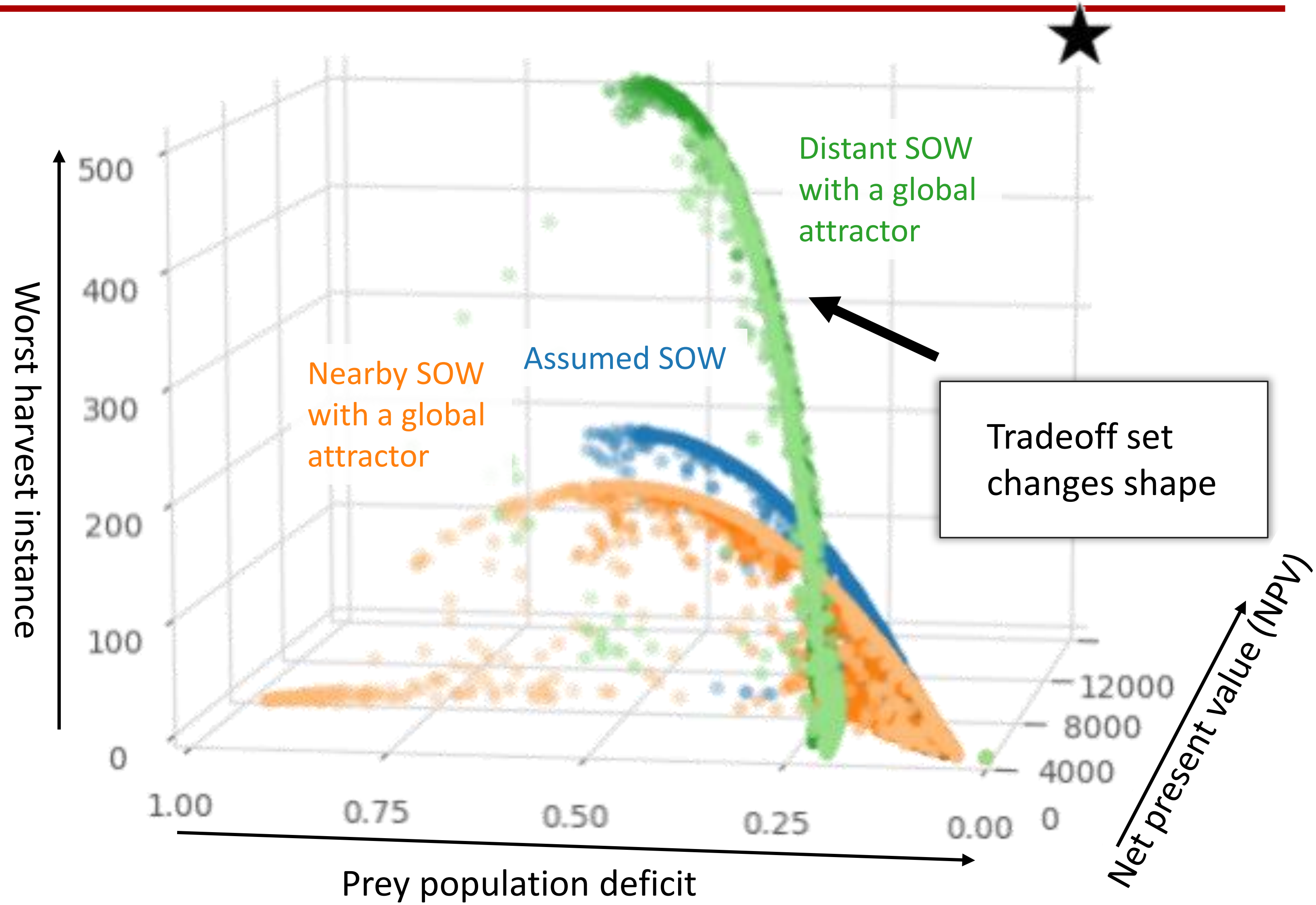
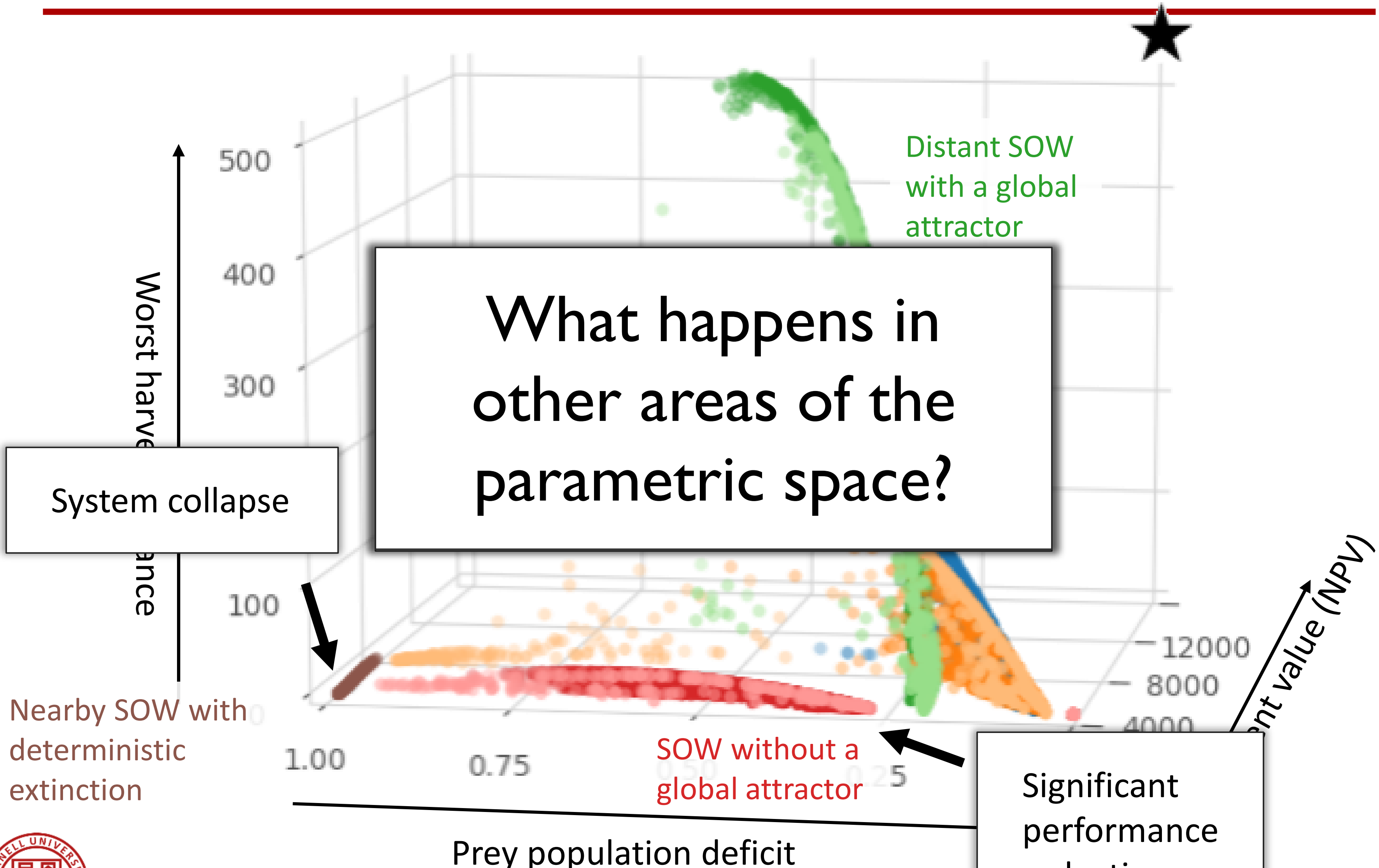
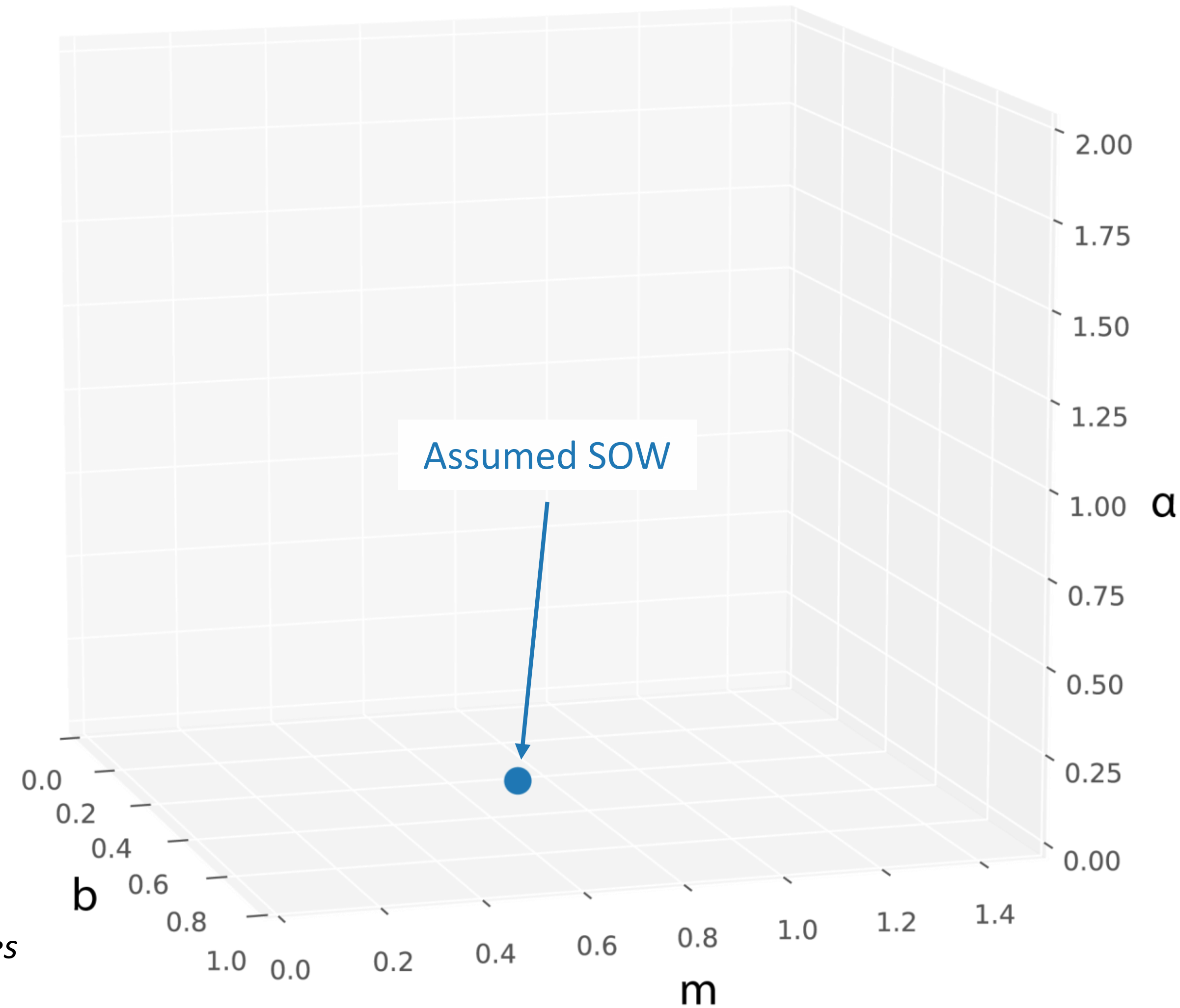


Tradeoff set changes shape

What do the tradeoffs look like in other SOW?

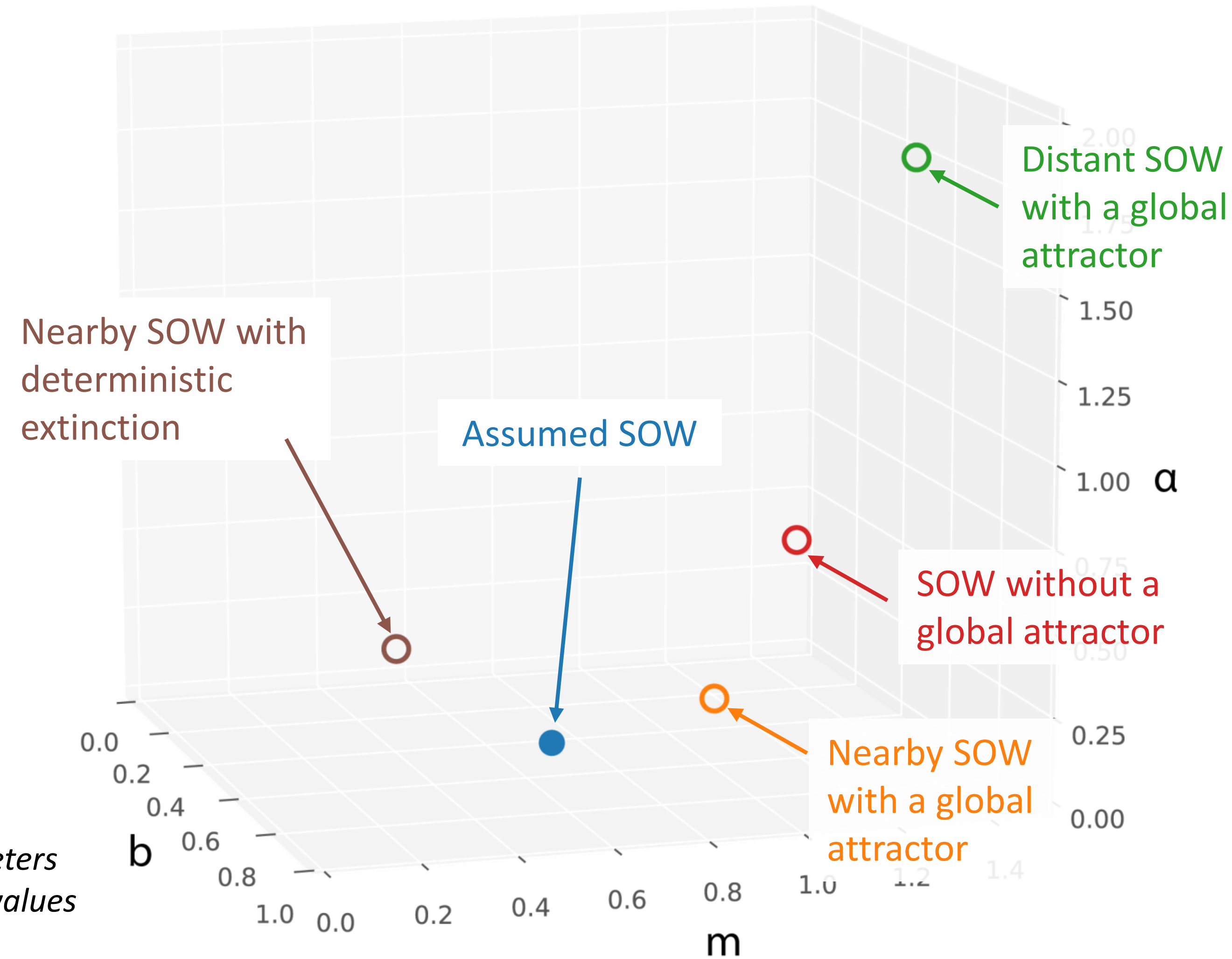


What happens in other areas of the parametric space?



All other parameters fixed to default values

What happens in other areas of the parametric space?



All other parameters fixed to default values

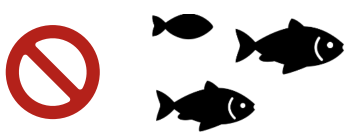
What happens in other areas of the parametric space?

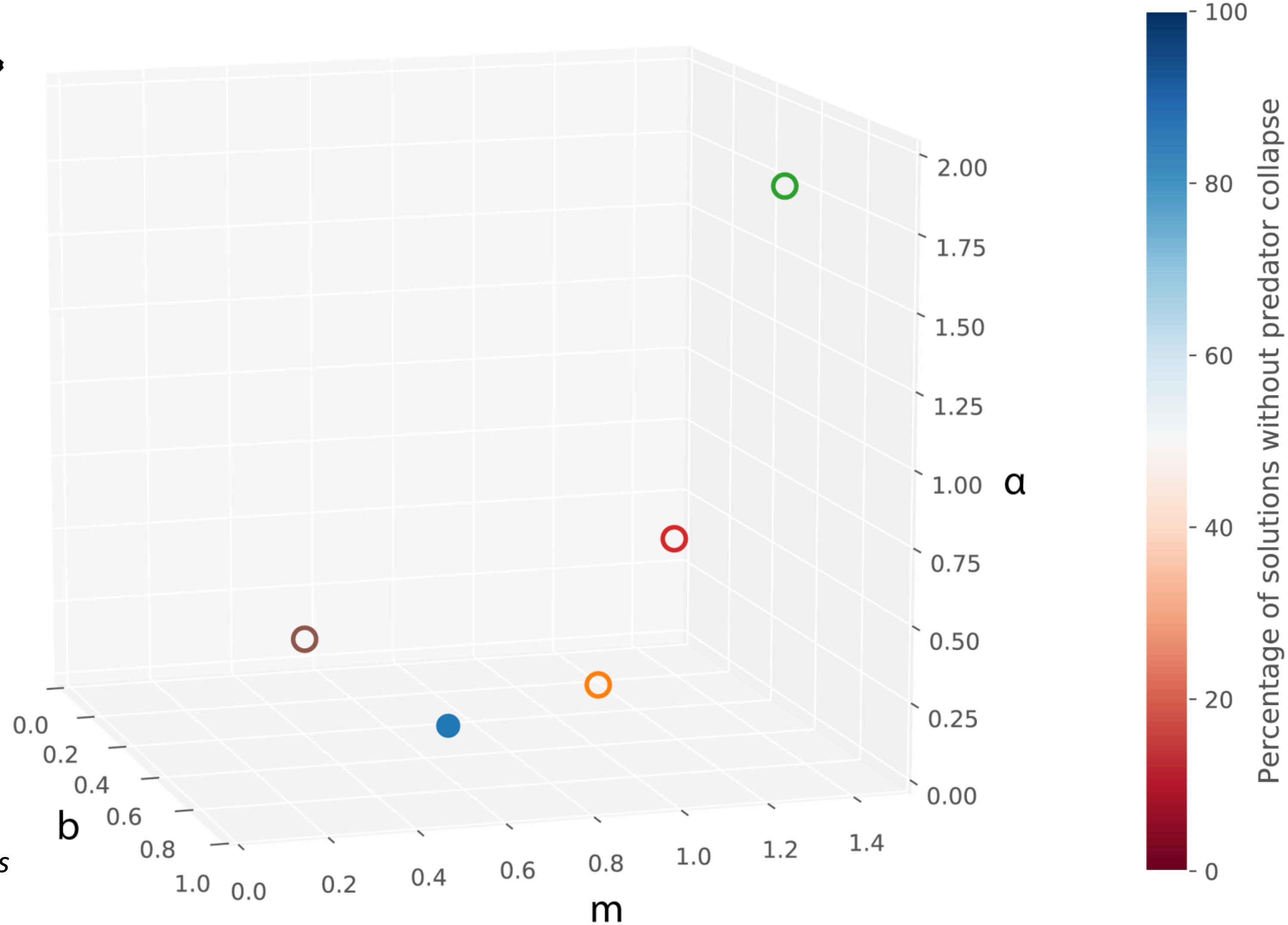
Latin Hypercube Sampling: 4,000 combinations

Parameter	Min	Default	Max
K	100	**2000**	5000
m	0.1	**0.7**	1.5
σ_x	0.001	**0.004**	1
σ_y	0.001	**0.004**	1

How is performance affected when found in any of these SOW?

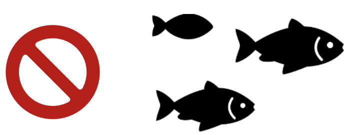
How is performance affected when in other SOW?

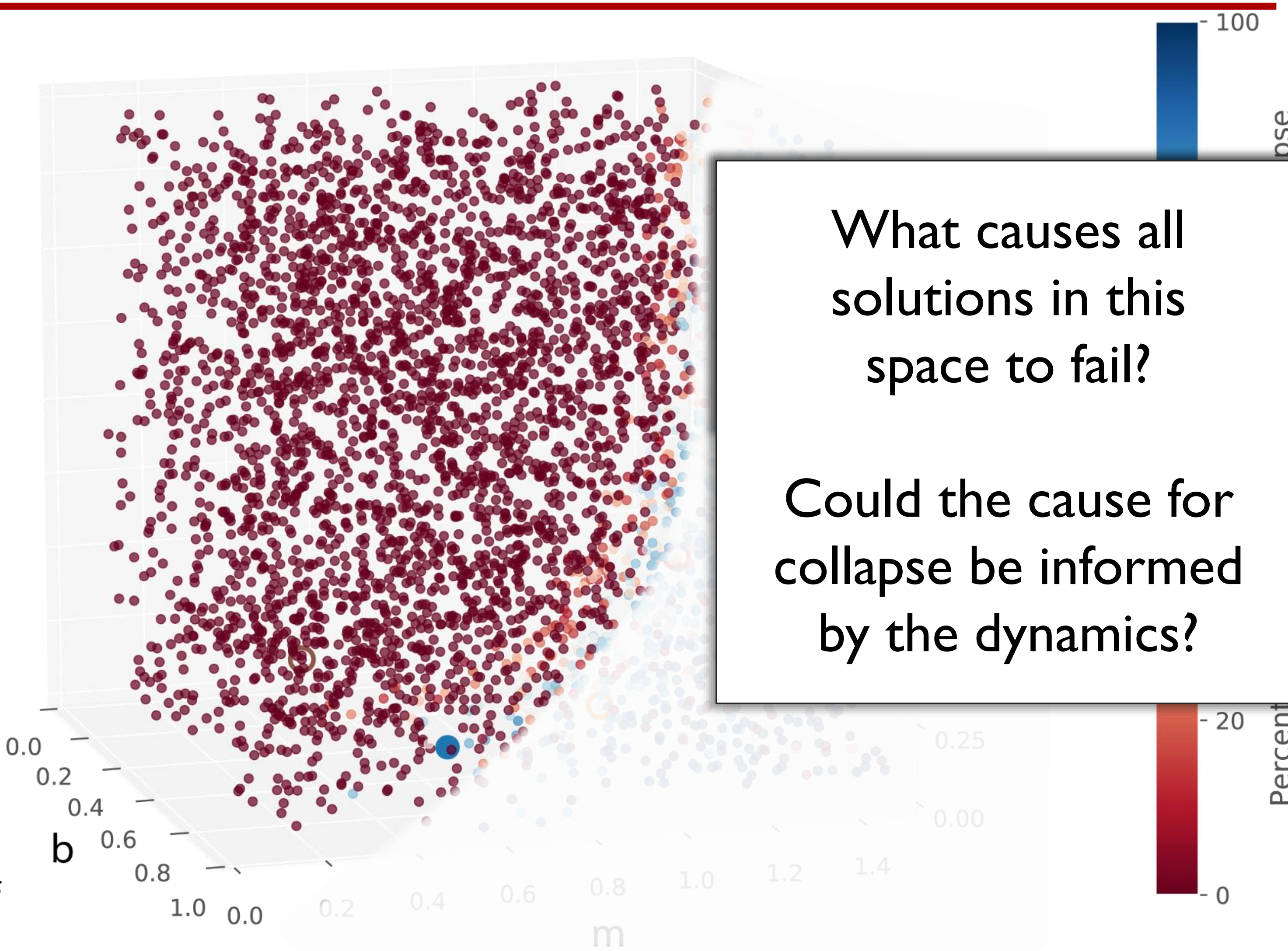




All other parameters fixed to default values

How is performance affected when in other SOW?





What causes all solutions in this space to fail?

Could the cause for collapse be informed by the dynamics?

All other parameters fixed to default values

How is performance affected when in other SOW?

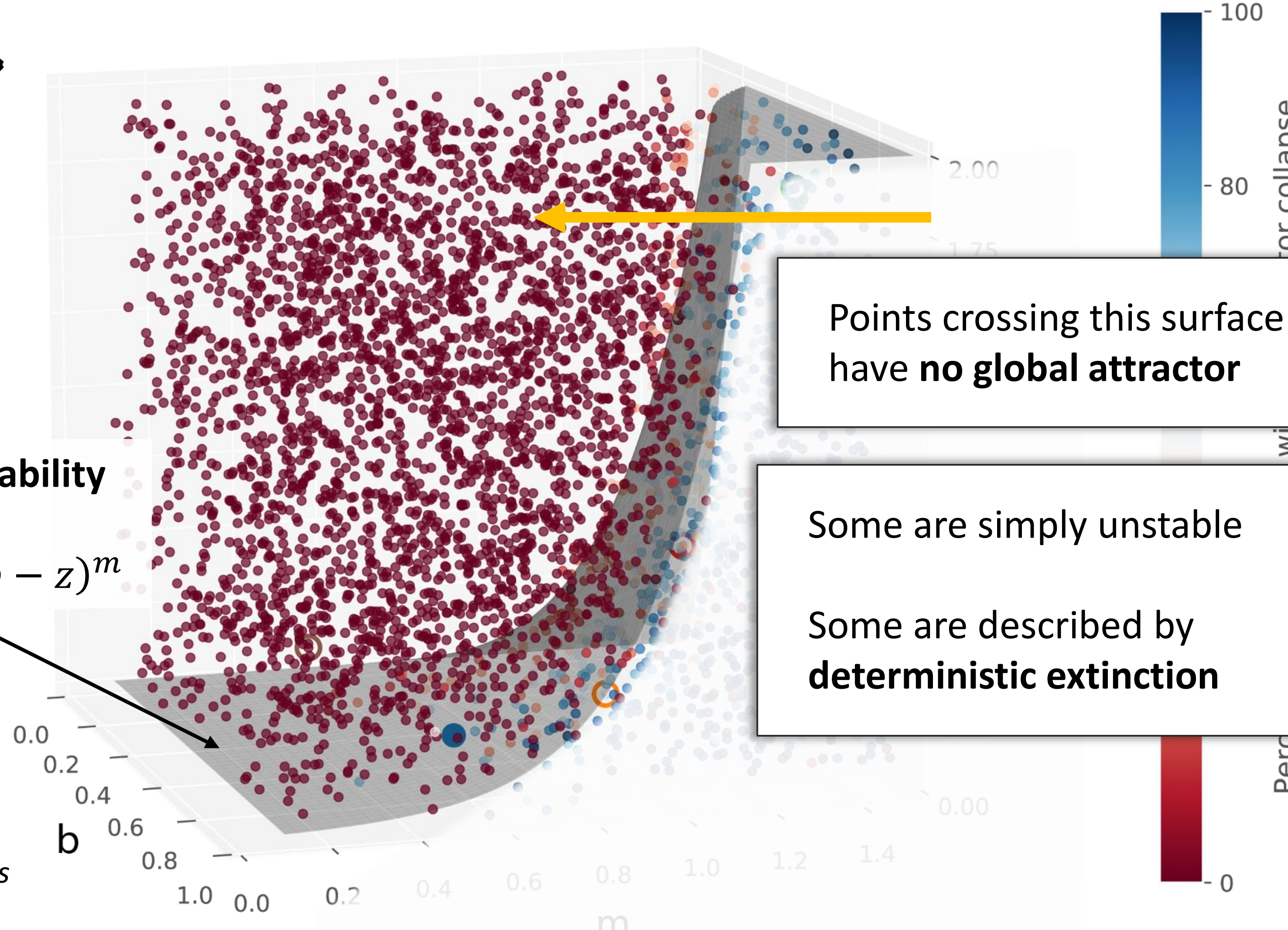
Could the cause for collapse be informed by the dynamics?

$$\frac{dx}{dt} = bx\left(1 - \frac{x}{K}\right) - \frac{\alpha xy}{y^m + \alpha hx} - z \cdot x$$
$$\frac{dy}{dt} = \frac{c\alpha xy}{y^m + \alpha hx} - dy$$

Derived inequality for stability

$$\alpha(hK)^{1-m} < (b-z)^m$$

How is performance affected when in other SOW?



Points crossing this surface have **no global attractor**

Some are simply unstable

Some are described by **deterministic extinction**

Inequality for stability

$$\alpha(hK)^{1-m} < (b-z)^{m}$$

All other parameters fixed to default values

How is performance affected when in other SOW?

How should our preference be informed to avoid failure?

All other parameters fixed to default values

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3. Explore formulations of harvesting **policies** to avoid potential **catastrophic consequences**

Robustness across criteria

Net Present Value (max)

Total discounted profits **> 1500**

Prey deficit (min)

Deficit from population capacity **< 0.2**

Duration of consecutive low harvest (min)

Duration of harvest below 5% of population **< 5**

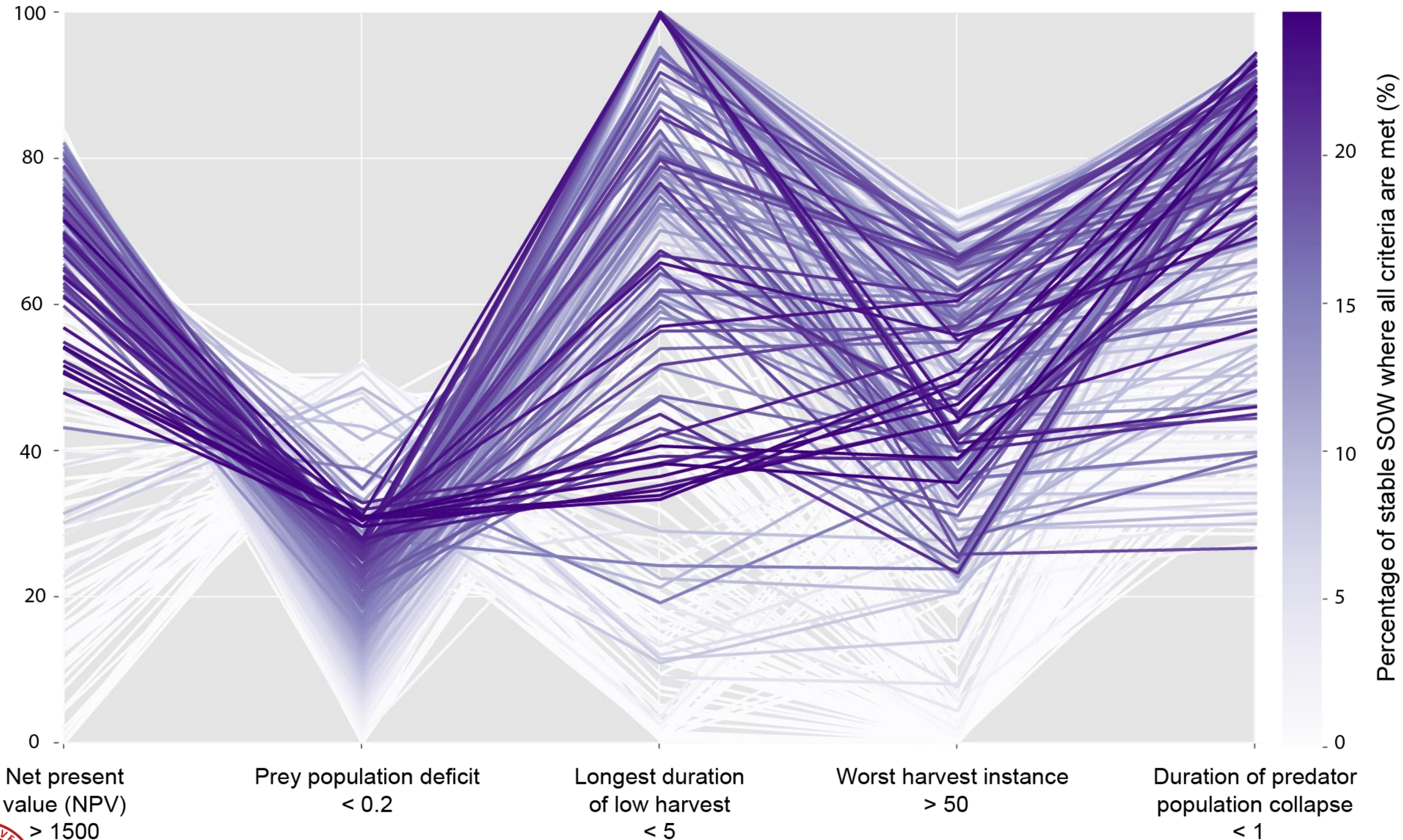
Worst harvest instance (max)

1st percentile of harvest **> 50**

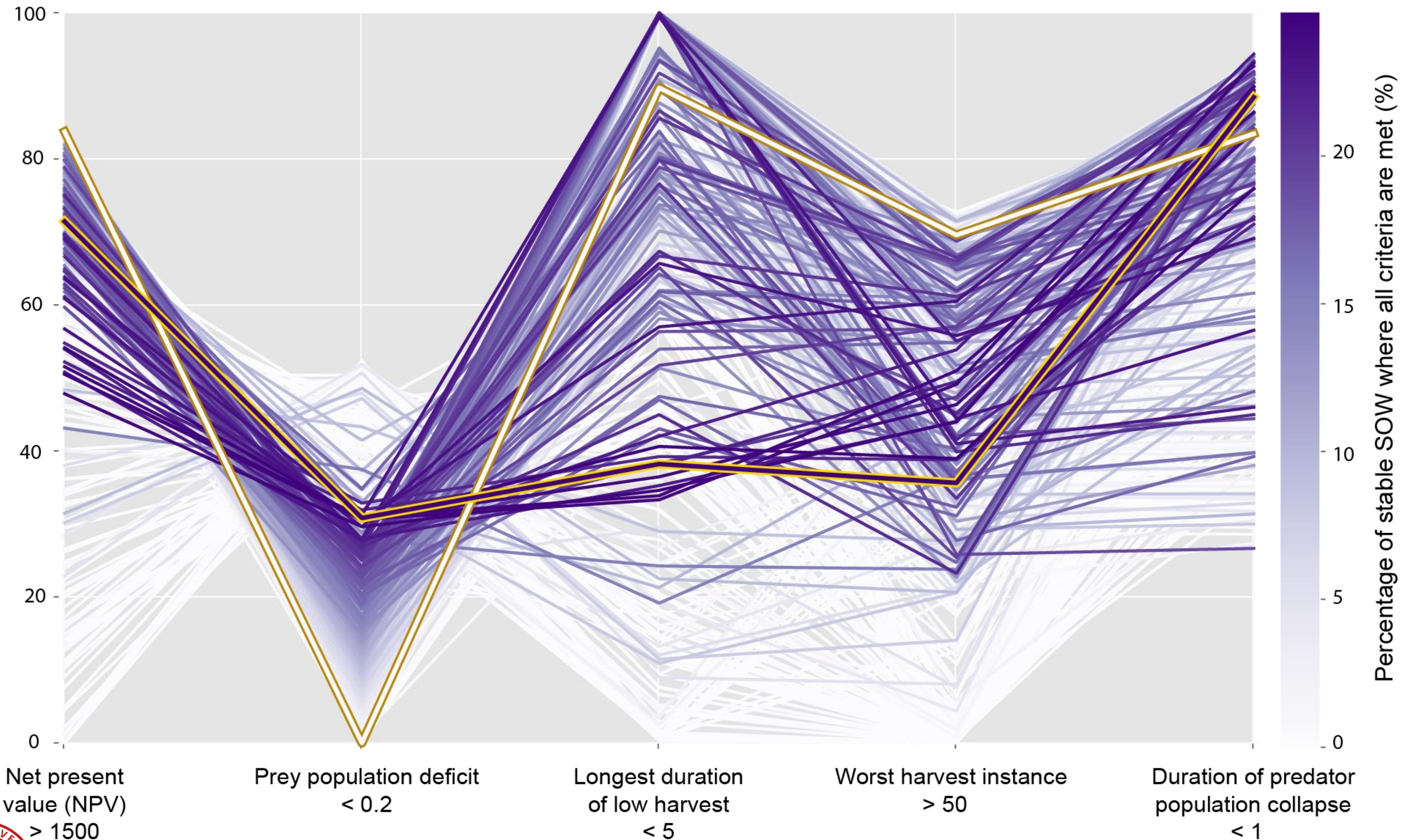
Avoid predator collapse

Duration of population collapse **< 1**

Percentage of SOW where each criterion is met (%)



Percentage of SOW where each criterion is met (%)



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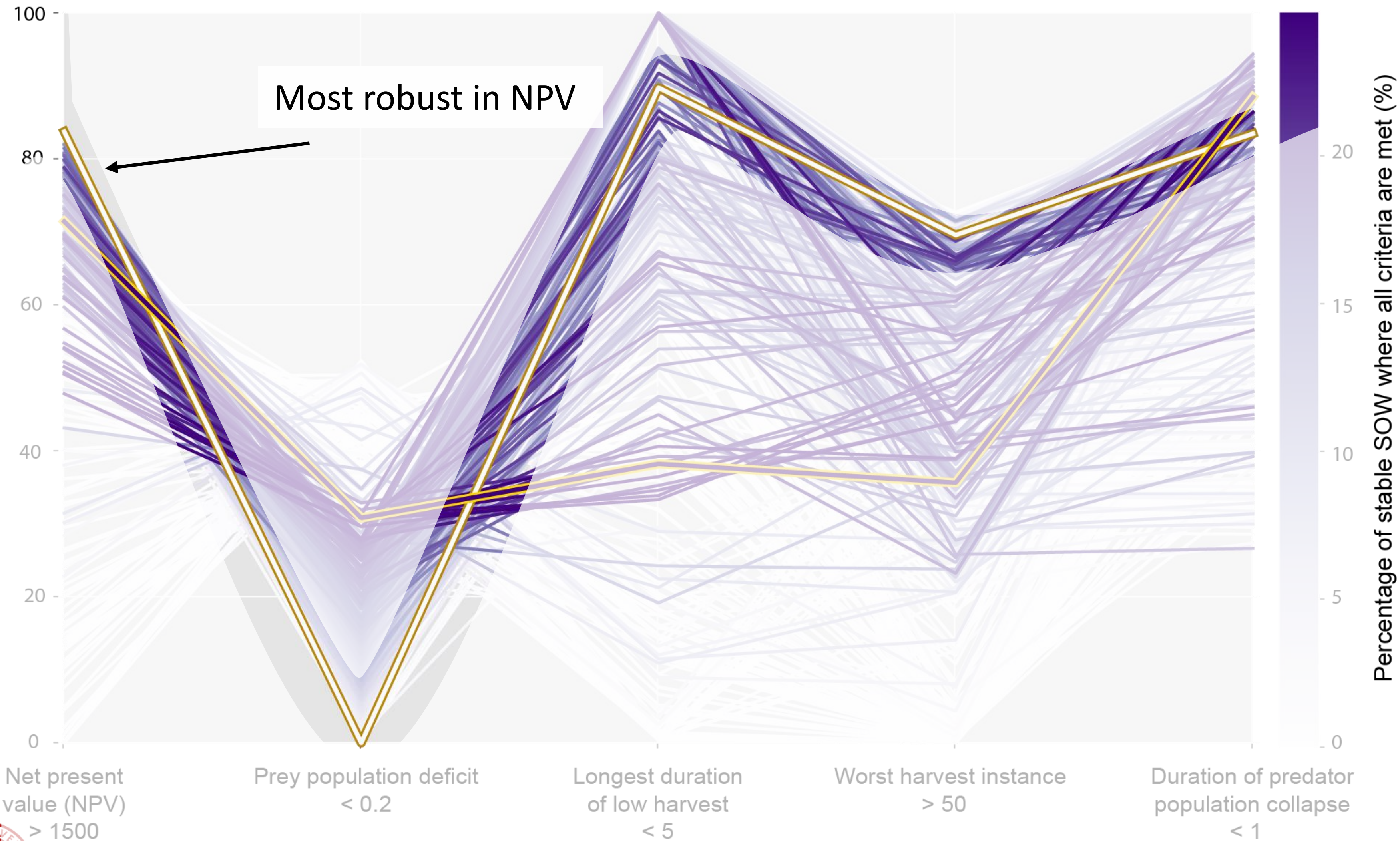
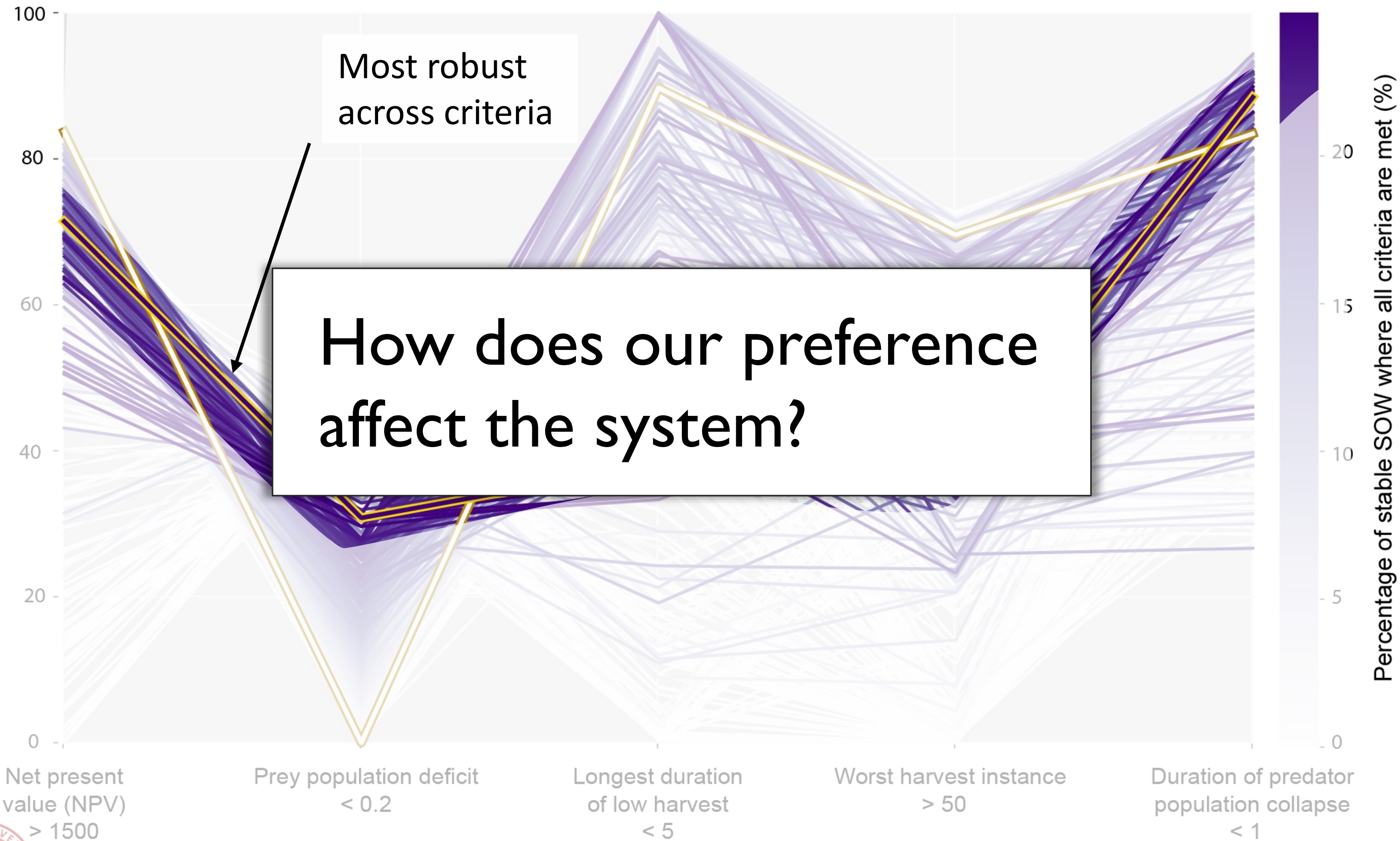
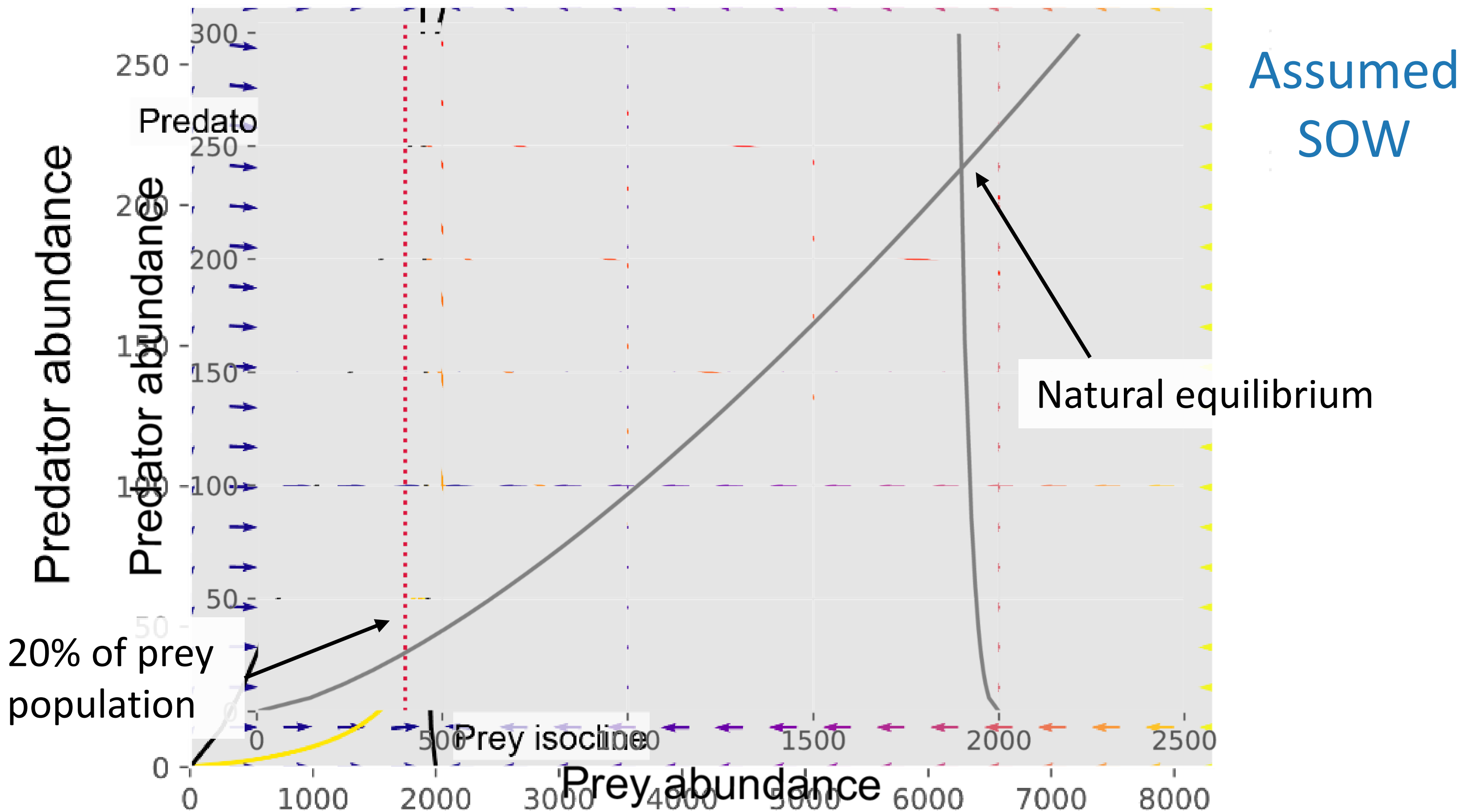


Percentage of SOW where each criterion is met (%)



How does our preference affect the system?



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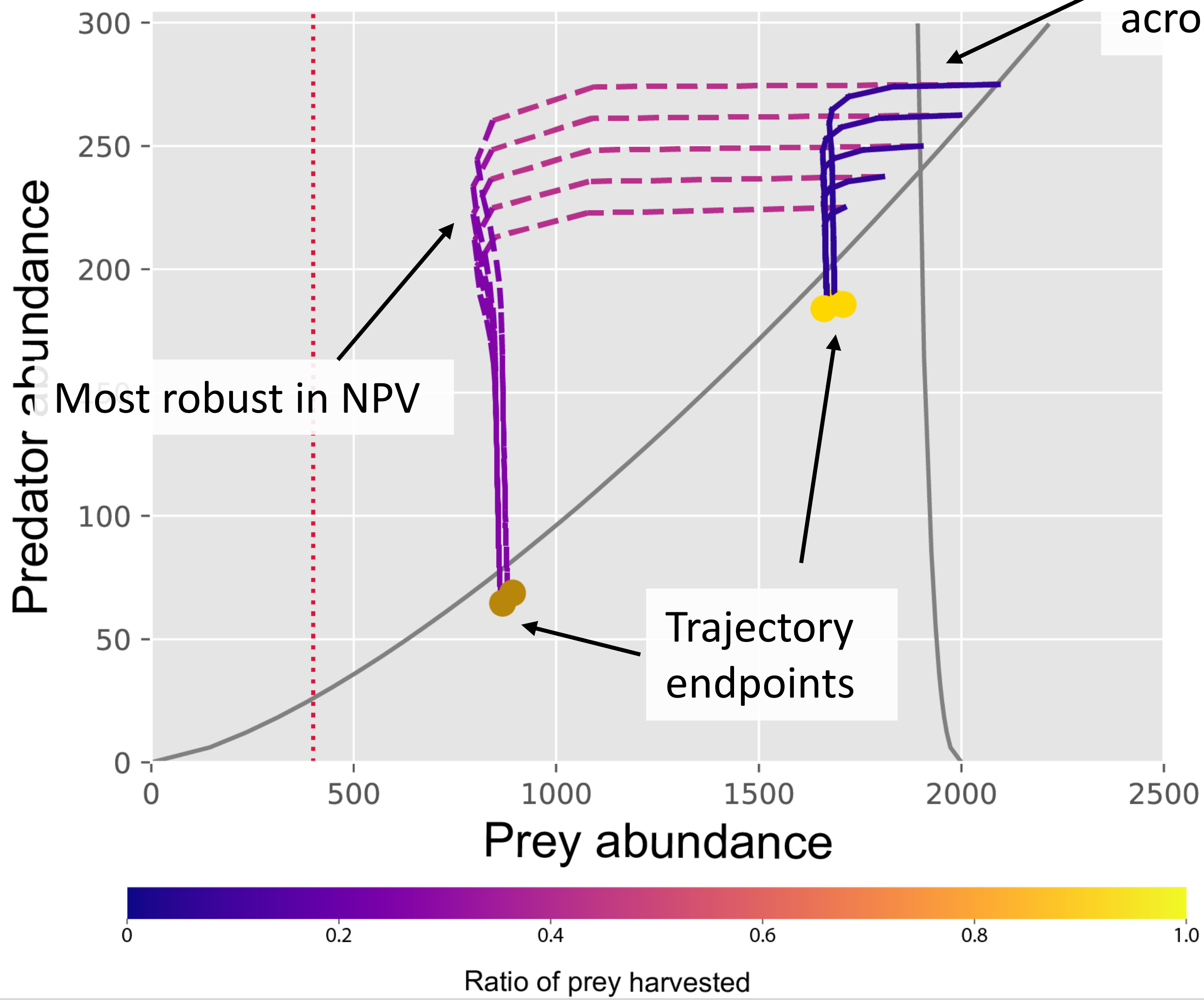

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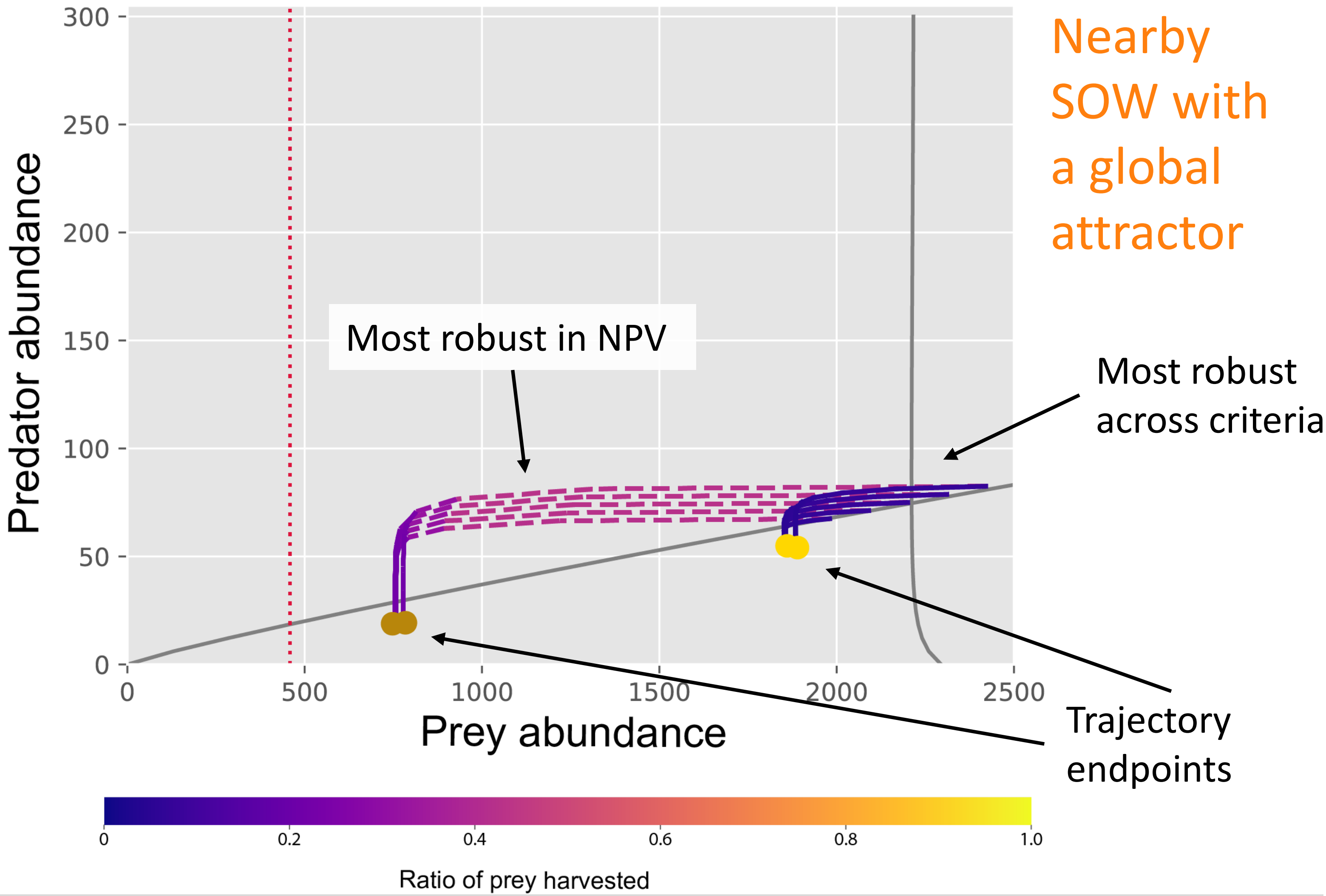
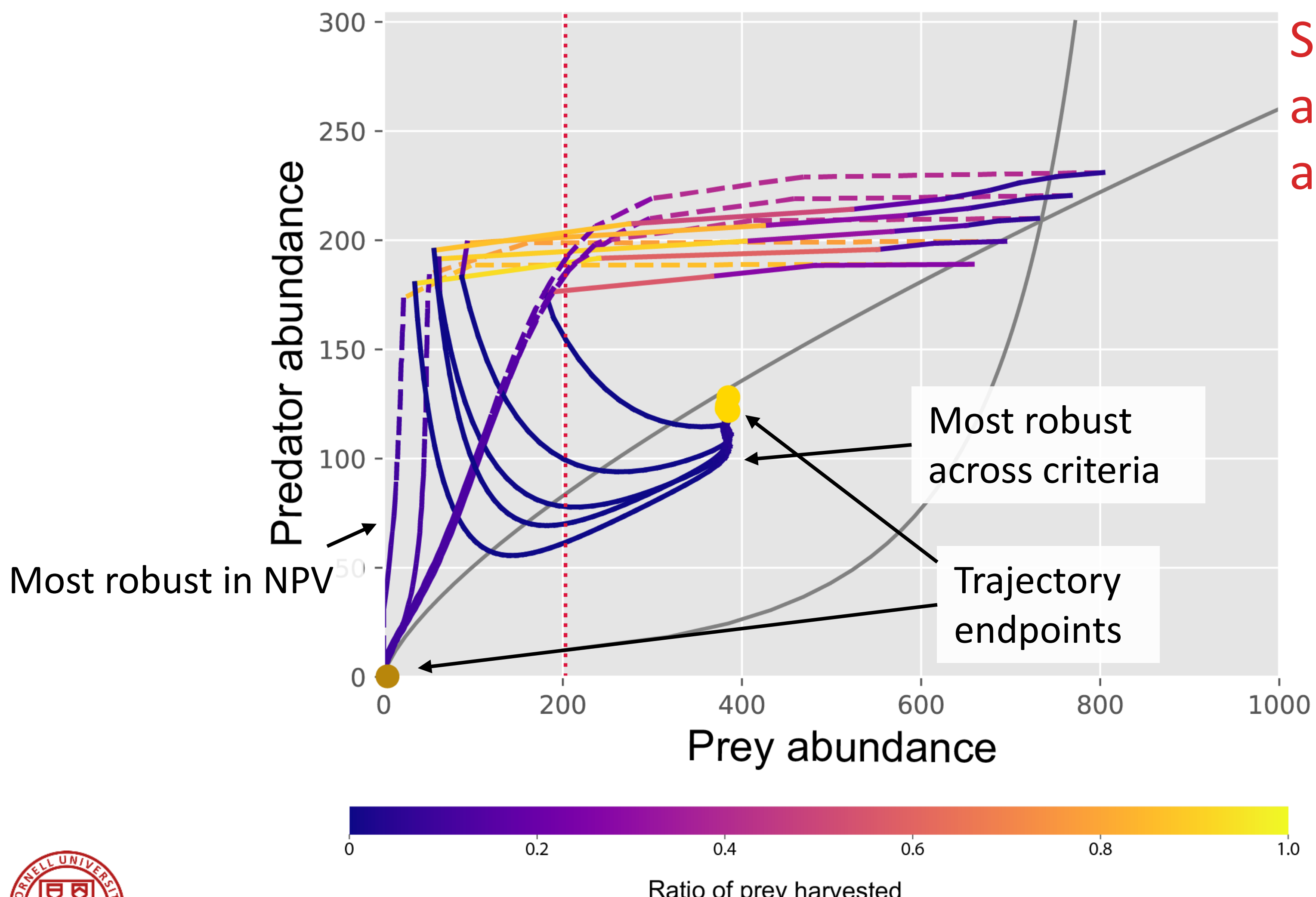


Nearby SOW with a global attractor

How does our preference affect the system?



SOW without a global attractor

Key Points and Implications

1. Generalized predator-prey system with harvest of prey and derived the isoclines, equilibria, and conditions for stability

2. Significant impacts of deep uncertainty; distinct basins of attraction can be present and shift even with marginal changes

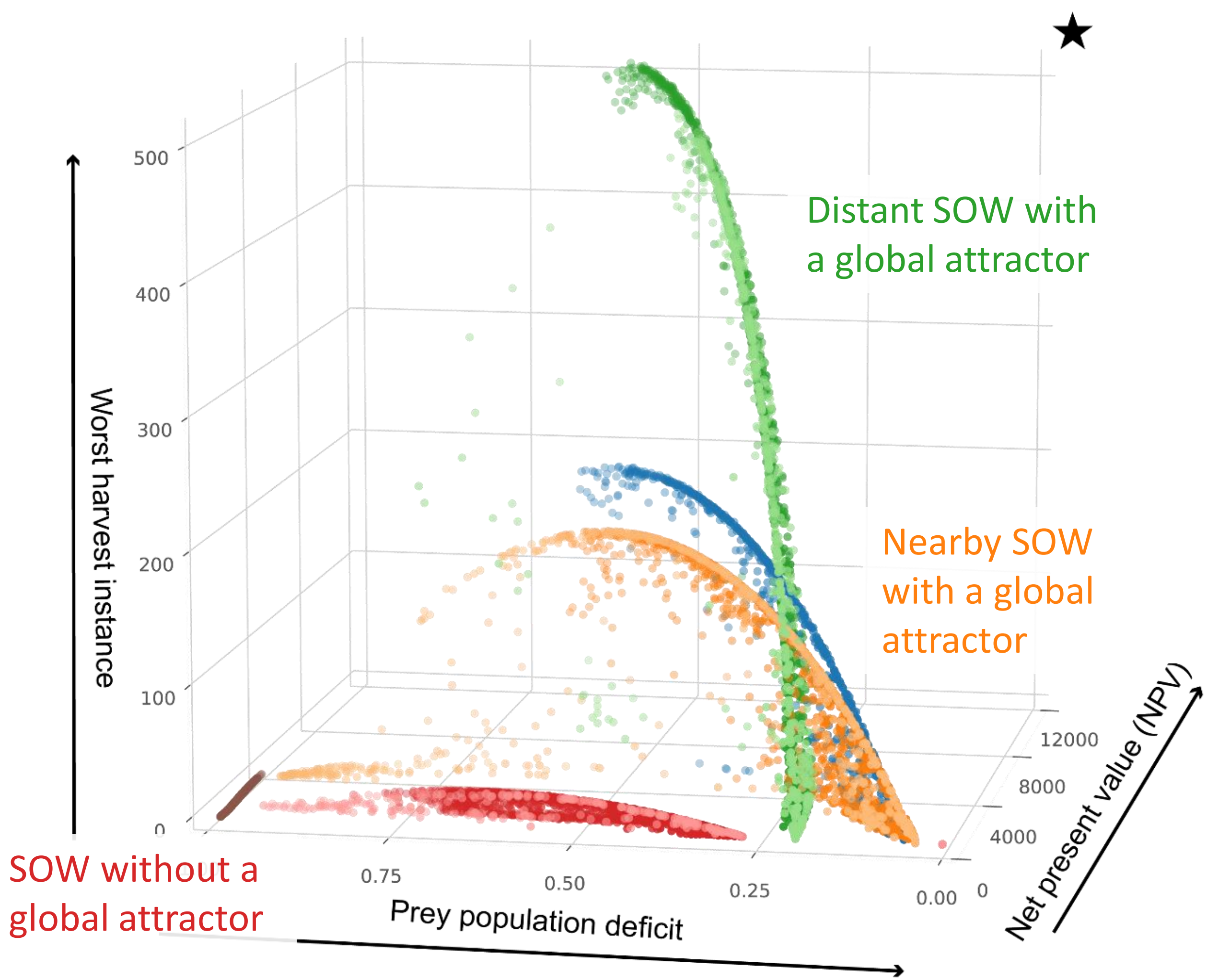
3. Significant differences in system dynamics and equilibria as a result of human preference and action

4. Robustness through compromise as a driver for harvest can help navigate deep uncertainties in parameters and relationships

Questions?

Appendix

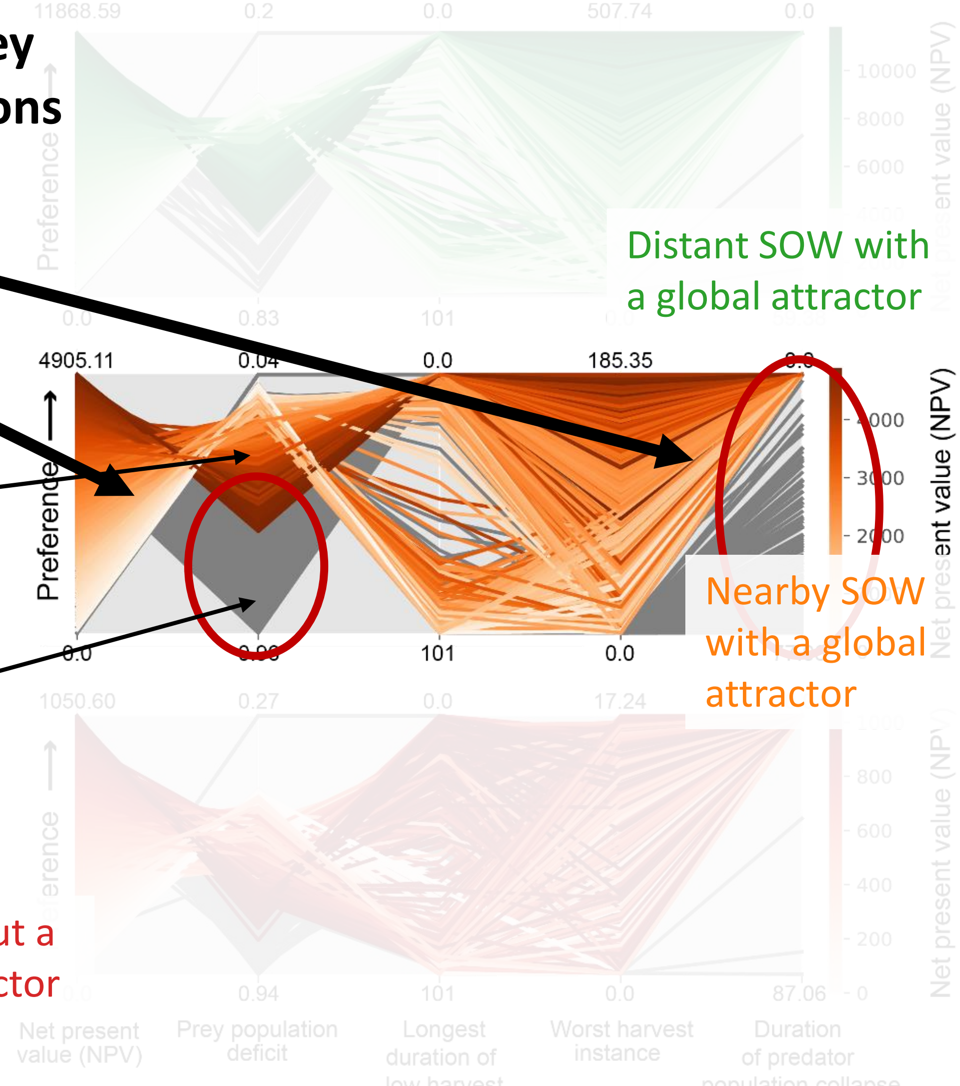
Regrets


Worst harvest instance
500
400
300
200
100
0
Prey population deficit
0.75
0.50
0.25
0.00
Net present value (NPV)
12000
8000
4000
0
Distant SOW with a global attractor
Nearby SOW with a global attractor
SOW without a global attractor

11868.59
0.2
Preference
0.0
0.83
4905.11
0.04
Preference
0.0
0.96
1050.60
0.27
Preference
0.0
0.94
Net present value (NPV)

Regrets

Significant losses in **prey and predator populations** as a result of being **uncertain** about SOW parameters



Solutions optimized to this SOW

Solutions from assumed SOW re-evaluated in this SOW

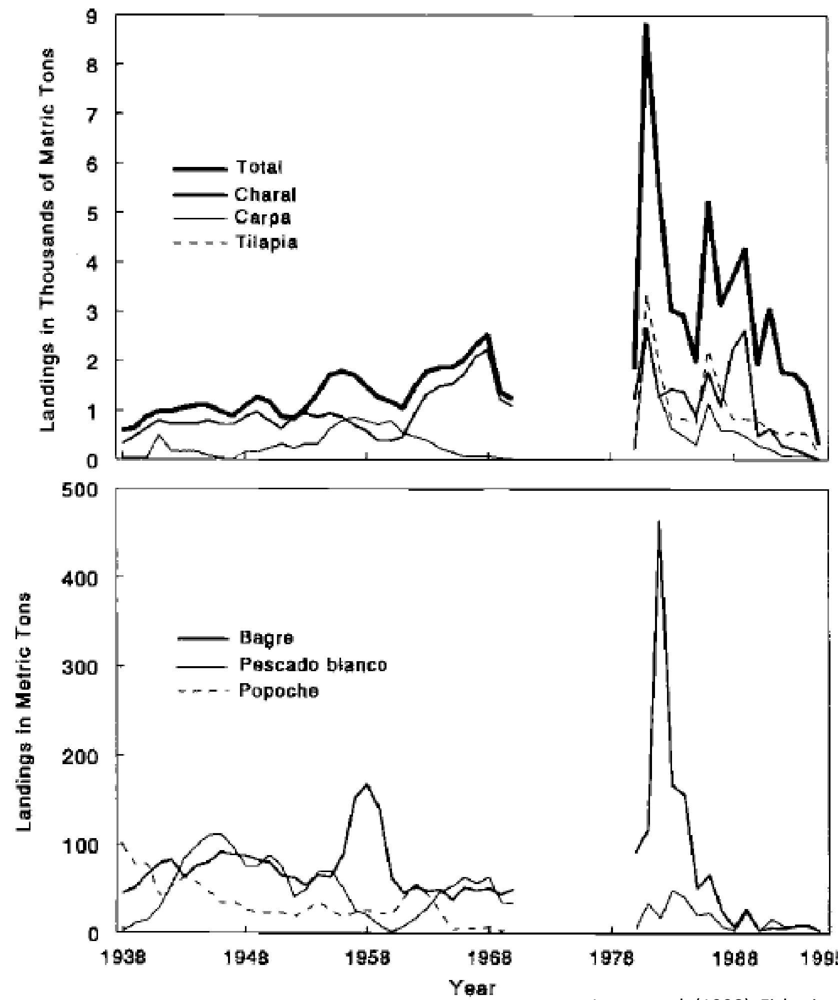
SOW without a global attractor

Collapse in freshwater fisheries

Great Slave Lake (Canada): Trout **collapse** due to **overexploitation**

Volga River (Russia): Nelma, beluga, herring **collapse** due to **dam construction** (spawning ground loss) and **illegal fishing**

Lake Chapala (Mexico): Bagre, Popoche, Pescado blanco **collapse** due to **overfishing** and **habitat loss** from **agricultural activities**

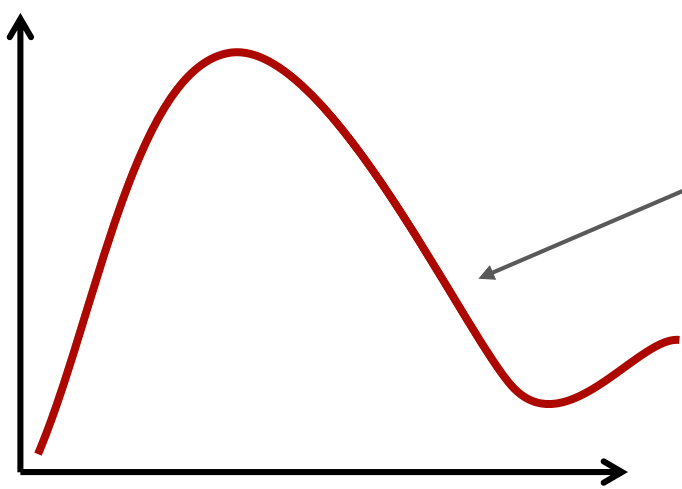


Lyons et al. (1998); Fisheries

Identifying harvesting policies

Direct Policy Search:

Optimize a policy describing z_{t+1} as a function of prey abundance, x_t



Gaussian radial basis functions (RBFs)

$$z_{t+1} = \sum_{i=1}^{R} w_i \left[exp \left[- \sum_{j=1}^{m} \left(\frac{(I_t)j - c_{j,i}}{b_{j,i}^2} \right)^2 \right] \right]$$

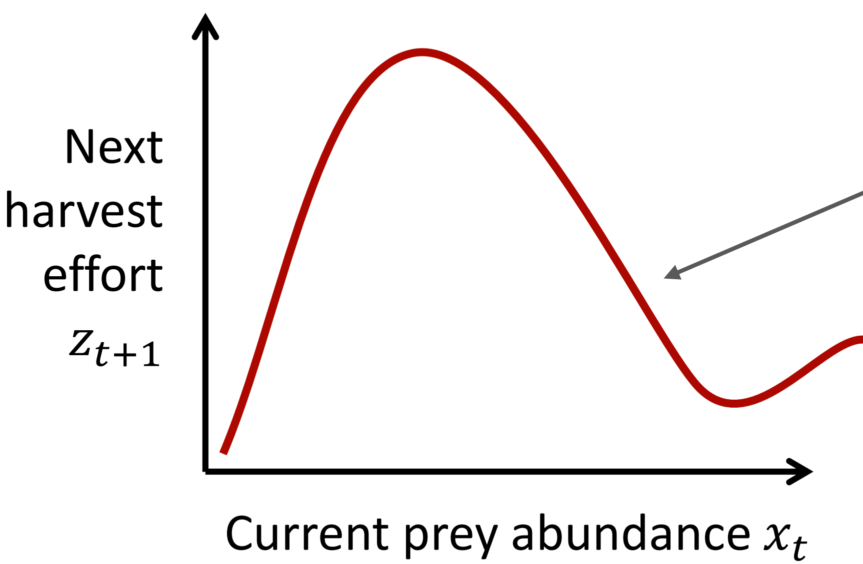
is the number of RBFs, in this case $n = 2$

Giuliani et al. (2016); https://doi.org/10.1061/(ASCE)WR.1943-5452.0000570

Identifying harvesting policies

Direct Policy Search:

Optimize a policy describing z_{t+1} as a function of prey abundance, x_t



$$z_{t+1} = \sum_{i=1}^{R} w_i \left[exp \left[- \sum_{j=1}^{m} \left(\frac{(I_t)j - c_{j,i}}{b_{j,i}^2} \right)^2 \right] \right]$$

Weight of the ith RBF
Formulated to be positive and sum to 1

$$w_i > 0 \ \forall i$$

$$\sum_{i=1}^{R} w_i = 1$$

Giuliani et al. (2016); https://doi.org/10.1061/(ASCE)WR.1943-5452.0000570

Identifying harvesting policies

Direct Policy Search

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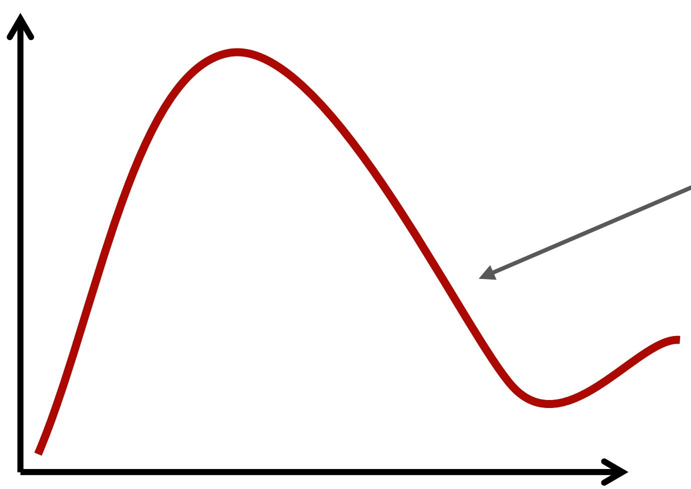

$$z_{t+1} = \sum_{i=1}^{R} w_i \left[exp \left[-\sum_{j=1}^{m} \left(\frac{(I_t)j - c_{j,i}}{b_{j,i}^2} \right)^2 \right] \right]$$

is the number of policy inputs, in this case current prey (x_t)

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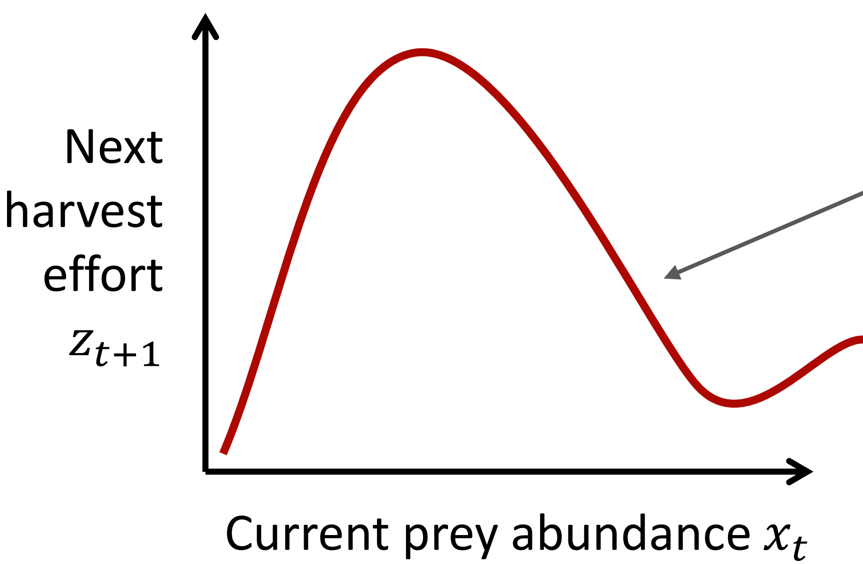

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Centers and radii of the ith RBF

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Identifying harvesting policies

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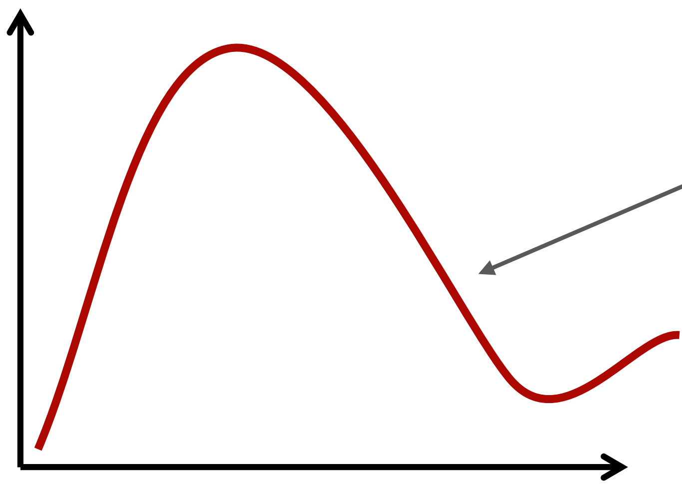

$$z_{t+1} = \sum_{i=1}^{R} w_i \left[exp \left[-\sum_{j=1}^{m} \left(\frac{(I_t)j - c_{j,i}}{b_{j,i}^2} \right)^2 \right] \right]$$

$$Minimize\ F(z) = (-\boldsymbol{O_1}, \boldsymbol{O_2}, \boldsymbol{O_3}, -\boldsymbol{O_4})$$

$$z = (z_1, z_2, \dots, z_T)$$

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