IDENTIFYING NONLINEARITIES, THRESHOLDS, AND INDICATORS OF MARINE ECOSYSTEM SHIFTS

Mary Hunsicker
NOAA Fisheries
Northwest Fisheries Science Center

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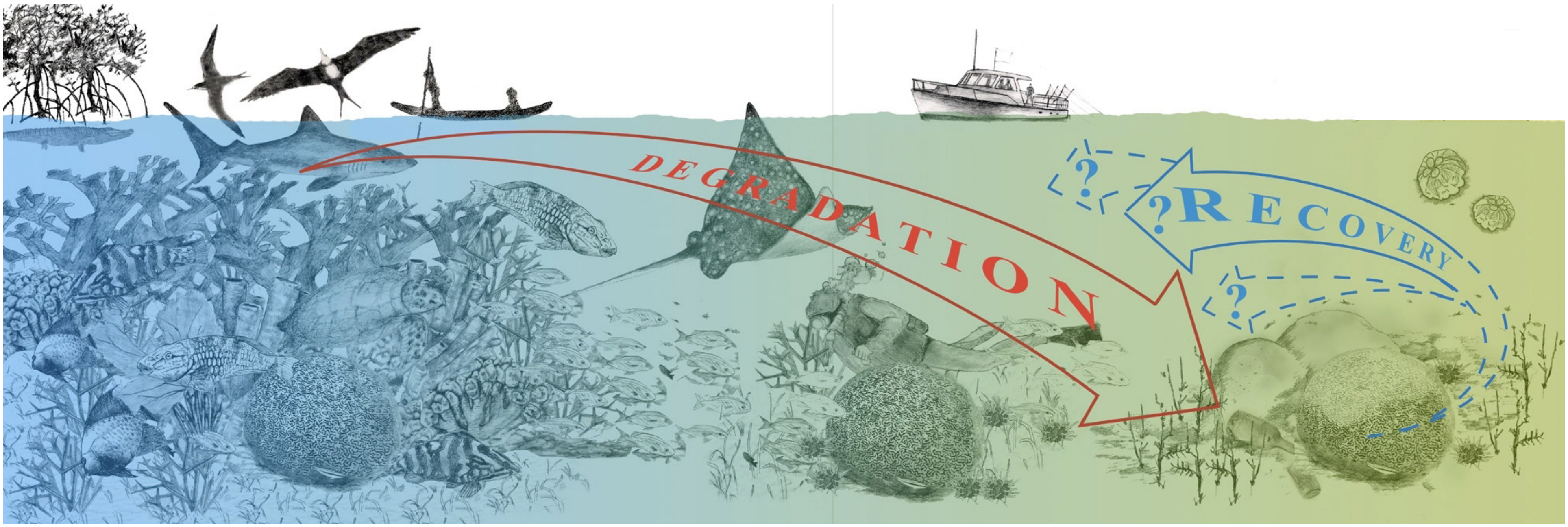
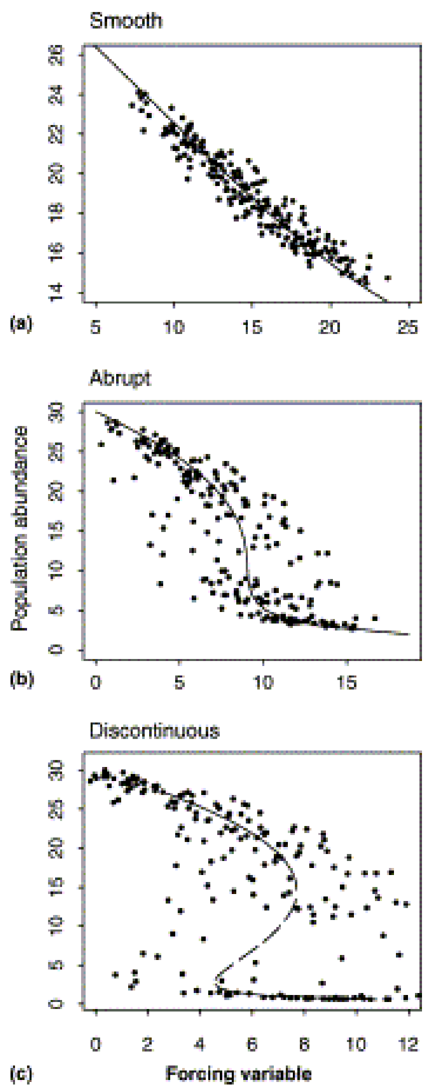
Ocean Tipping Points

When incremental changes in human use or environmental conditions can result in large, and sometimes abrupt, changes in ecosystem structure, function, and benefits to people



Tipping points in marine ecosystems



Linear

Underlying driver exhibits threshold behavior that is tracked by the ecosystem response

Nonlinear

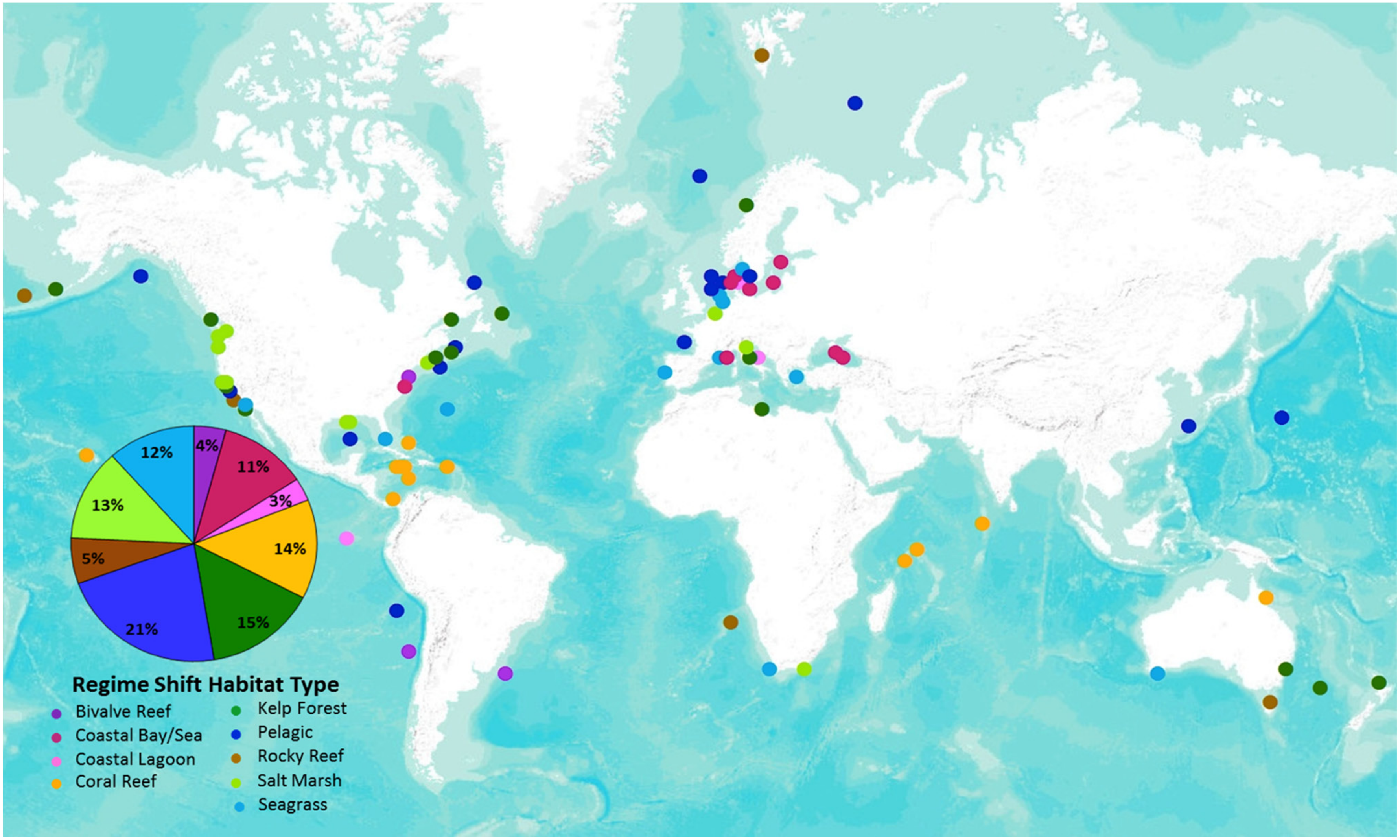
Relationship between driver and response variable is nonlinear

Nonlinear with hysteresis

Relationship between driver and response variable is different before and after shift

Collie et al. 2004 Progress in Oceanography

A wide range of marine habitats across the globe have experienced ecosystem shifts from the intertidal to the open ocean.



Kappel et al. in prep.

A wide range of marine habitats across the globe have experienced ecosystem shifts from the intertidal to the open ocean.

REPORT

Climate-driven regime shift of a temperate marine ecosystem

Thomas Wernberg[1,*,†], Scott Bennett[1,2,3,†], Russell C. Babcock[1,4], Thibaut de Bettignies[1,5], Katherine Cure[1,6], Martial Depczynski[6], Francois Dufois[7], Jane Fromont[8], Christopher J. Fulton[9], Renae K. Hovey[1], Euan S. Harvey[2], Thomas H. Holmes[1,10], Gary A. Kendrick[1], Ben Radford[6,11], Julia Santana-Garcon[1,2,3], Benjamin J. Saunders[2], Dan A. Smale[1,11], Mads S. Thomsen[1,12], Chenae A. Tuckett[1], Fernando Tuya[13], Mathew A. Vanderklift[7], Shaun Wilson[1,10]

Ocean Tipping Points Project Goals

- Improve knowledge and understanding of ocean tipping points, their potential impacts, and their relevance to management
- Co-develop and disseminate a toolbox of approaches for management of ecosystems prone to tipping points

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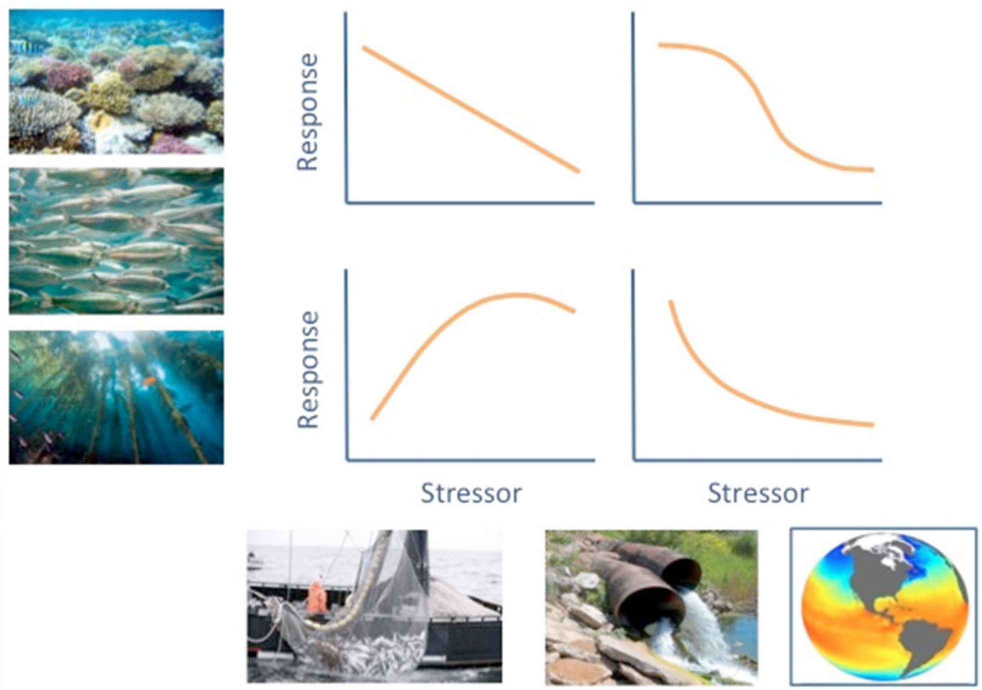
Identify the prevalence of strong nonlinearities, develop a framework to identify ecological thresholds, and test the utility of early warning indicators of abrupt change

Characterizing driver-response variables

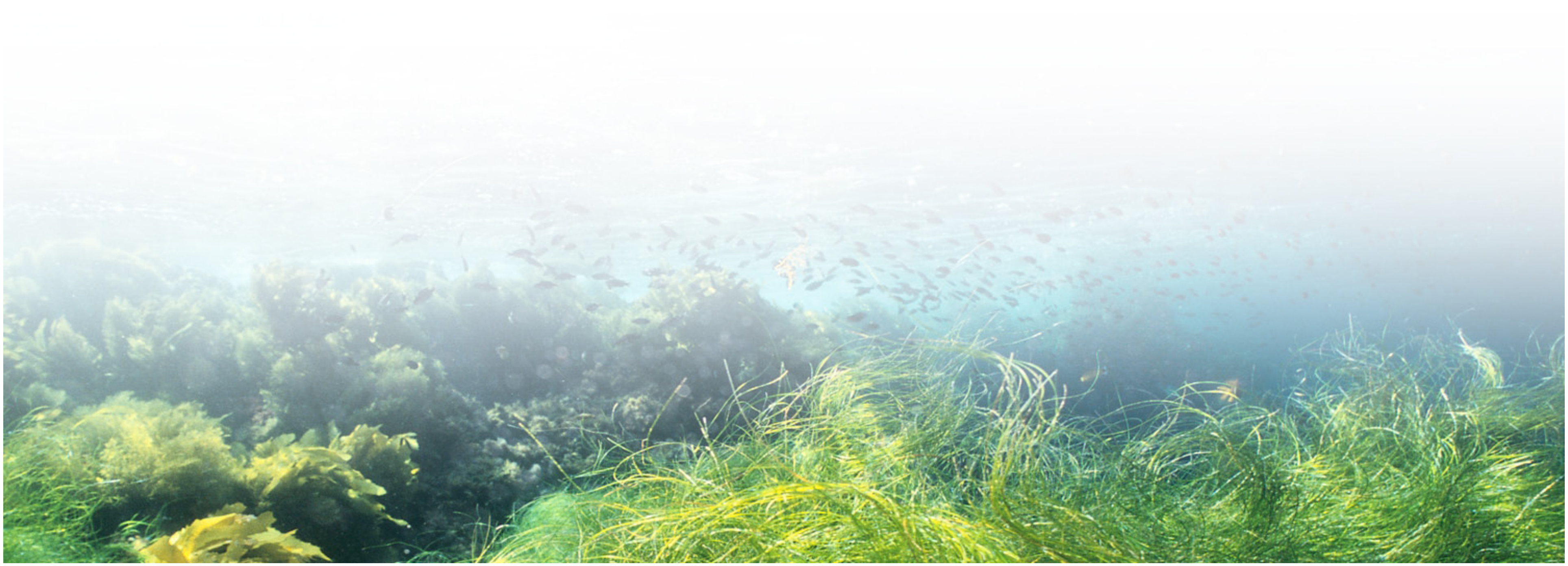
- To better understand the relationships between single stressors and ecosystem components

- To identify when nonlinearities and threshold responses are likely to exist



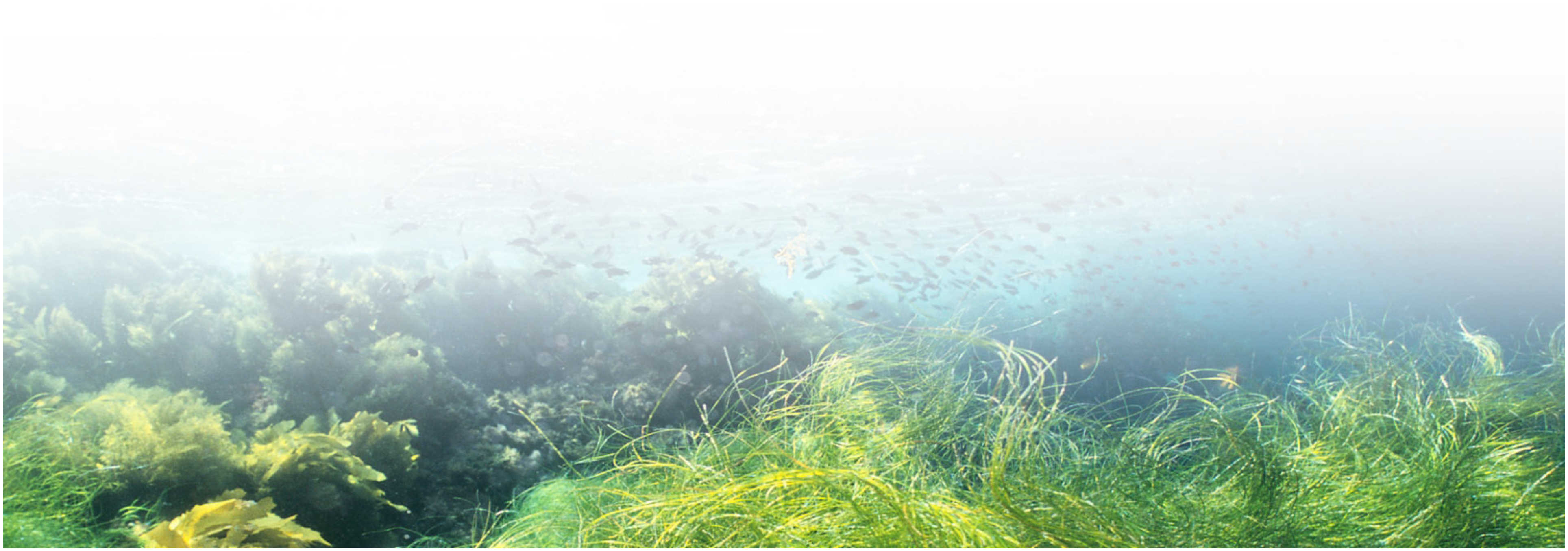
Motivation

- Default assumption of linearity



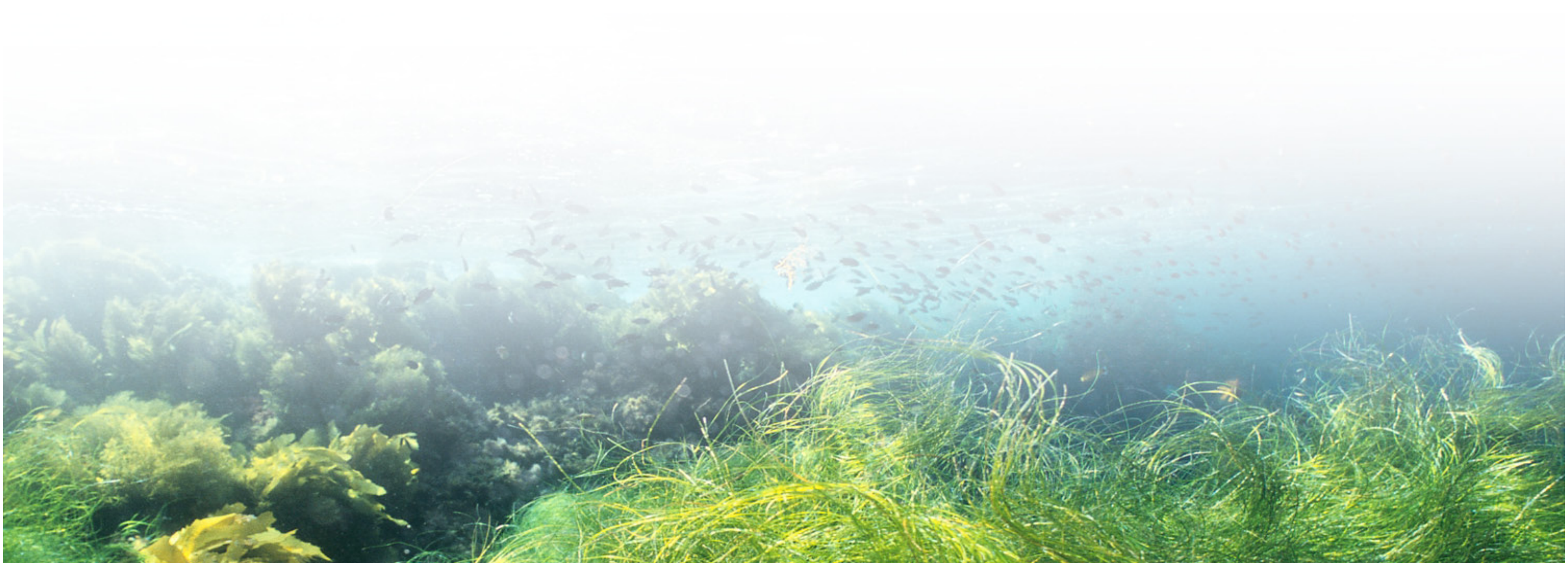
Motivation

- Default assumption of linearity
- When and where multiple stressors interact



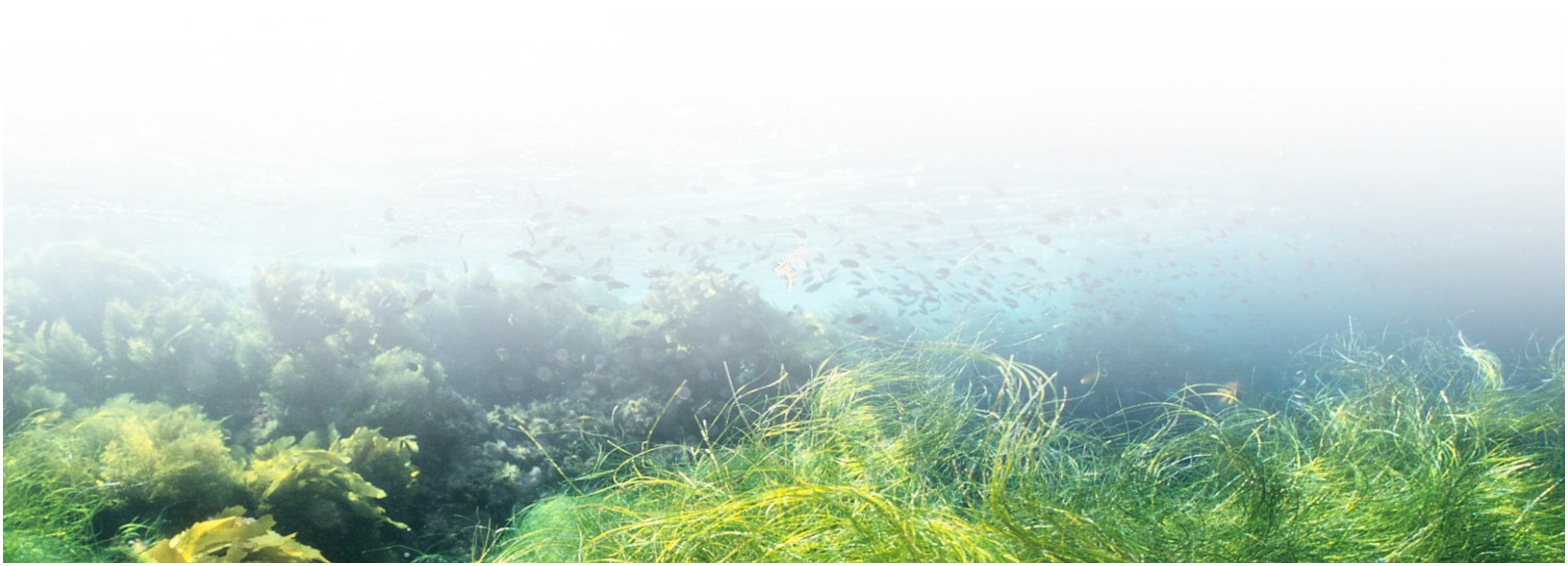
Motivation

- Default assumption of linearity
- When and where multiple stressors interact
- Reference points or safe zones for management



Approach

1) Literature search



Approach

1) Literature search

2) Selection criteria

- Field study in pelagic marine ecosystem
- Statistical analysis (regression, correlation) used to identify the relationship between stressor and response
- Sign. relationships identified by p-value and model selection
- Extract data from paper

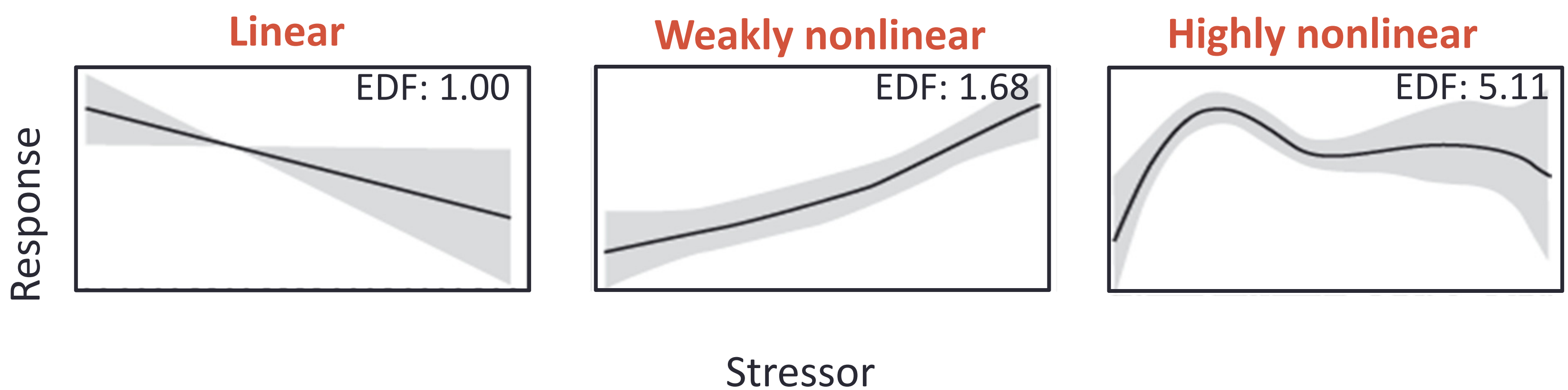
➢ 75 papers; 728 relationships

Approach

1) Literature search

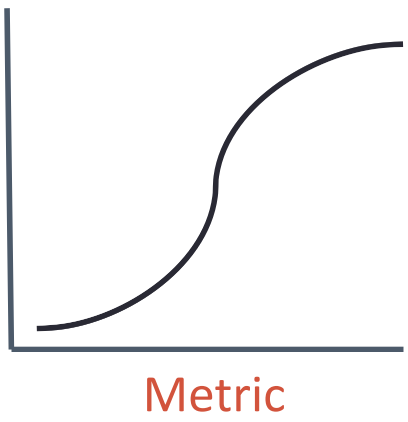
2) Selection criteria

3) Published or derived effective degrees of freedom (EDF) from GAMs are a measure of degree of nonlinearity



Outcome of literature search

Driver / Stressor	Examples of metrics
Climate	- Temperature - Large-scale climate pattern - Salinity
Exploitation	- Fishing effort - Catch/landings - Fishing mortality
Pollution	- Nutrient loading - Oxygen - Water clarity
Food web	- Predator/prey biomass, abundance - Primary production, nutrients - Density dependence



Outcome of literature search

Ecological Responses

Growth

Survival

Reproductive success

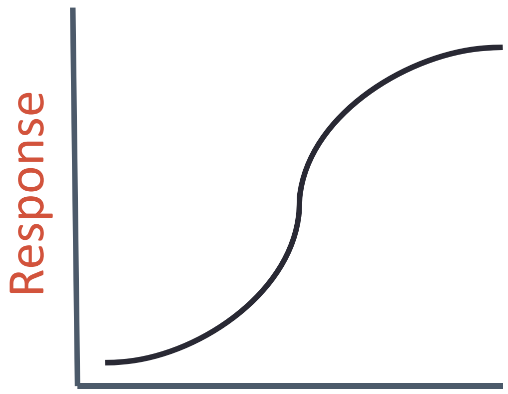
Recruitment

Species occurrence

Species biomass and abundance

Species richness

Community composition and diversity



Outcome of literature search

Ecological Responses

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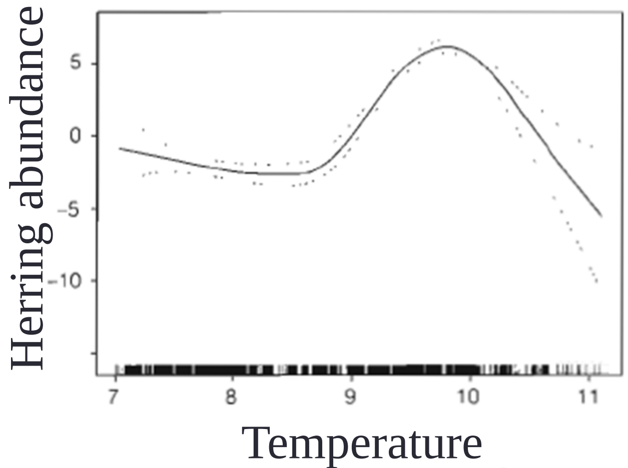
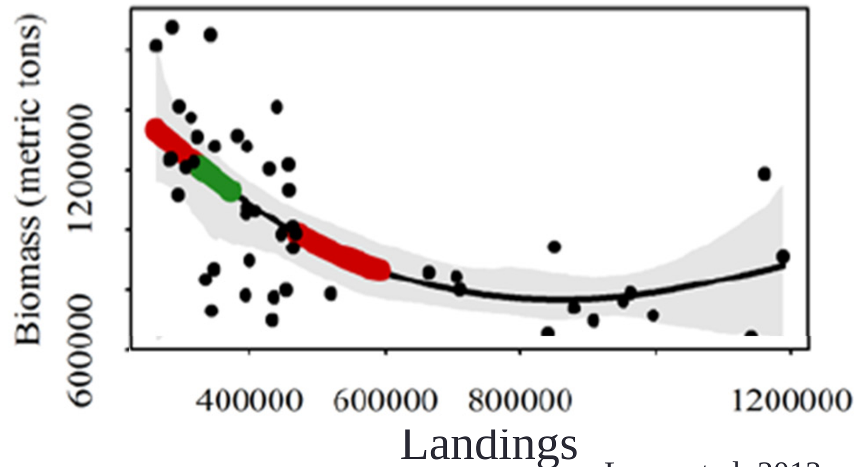
Examples of raw data

Climate



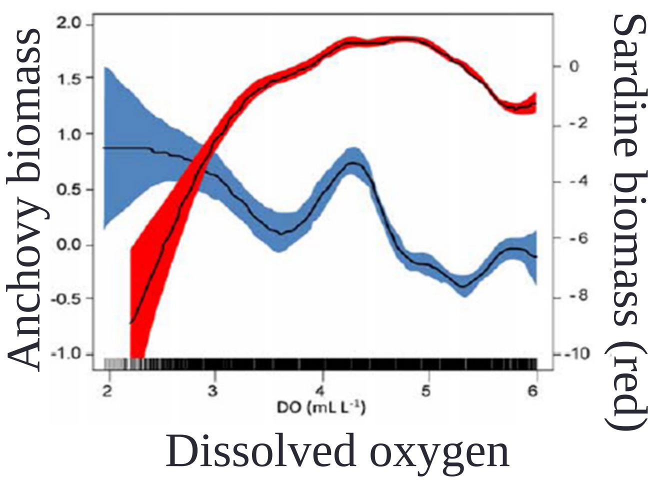
Maravelias & Reid 1997

Exploitation



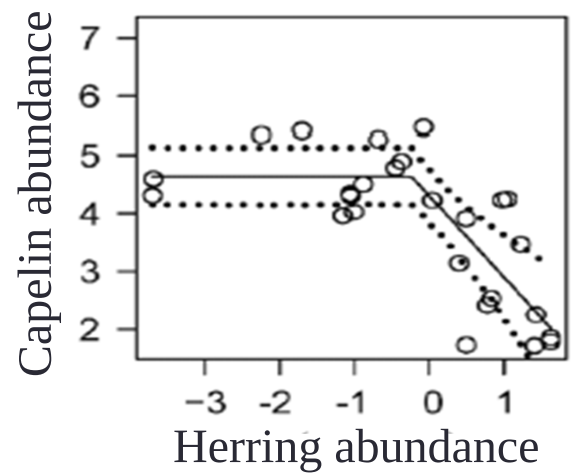
Large et al. 2013

Pollution



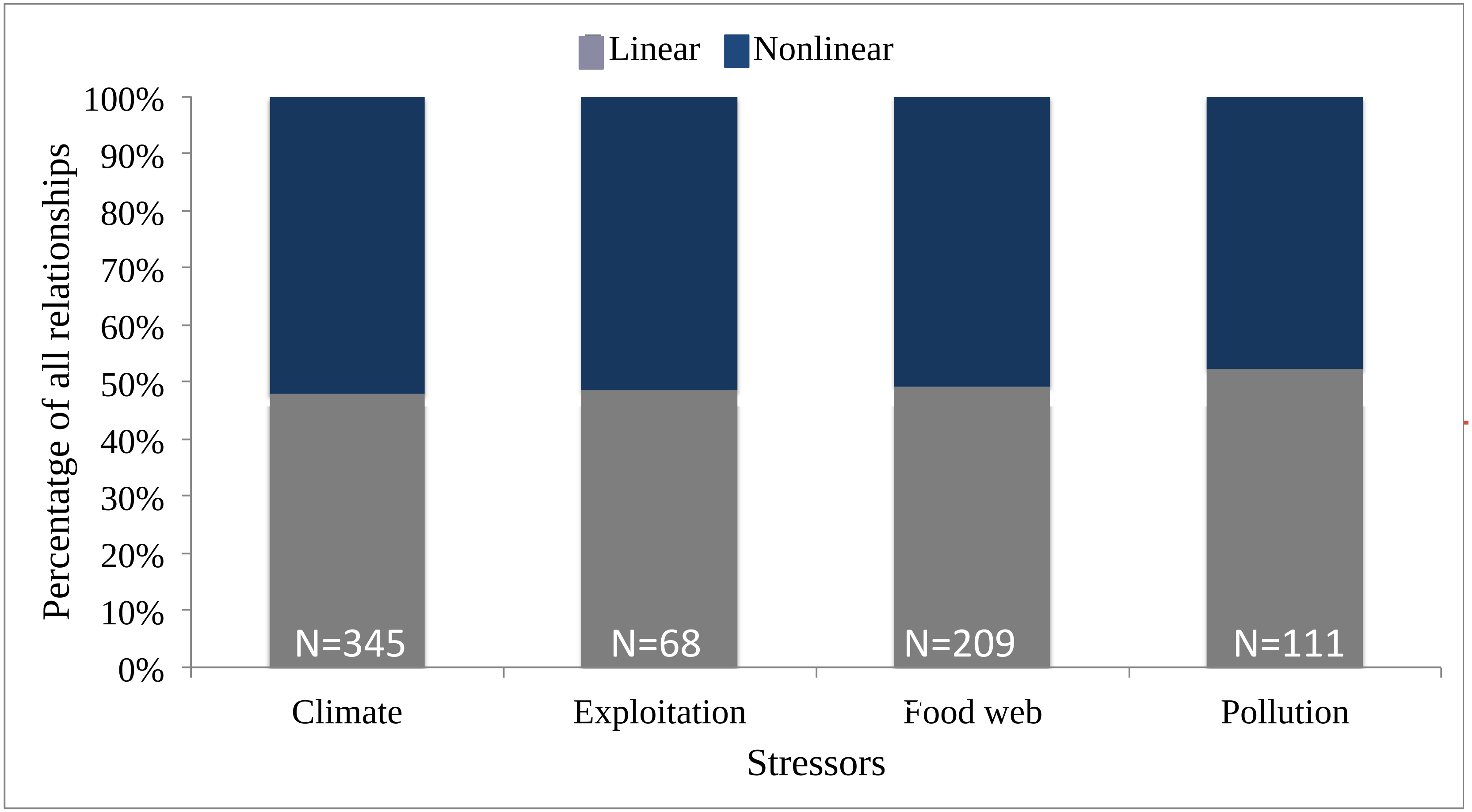
Bertrand et al. 2011

Food web



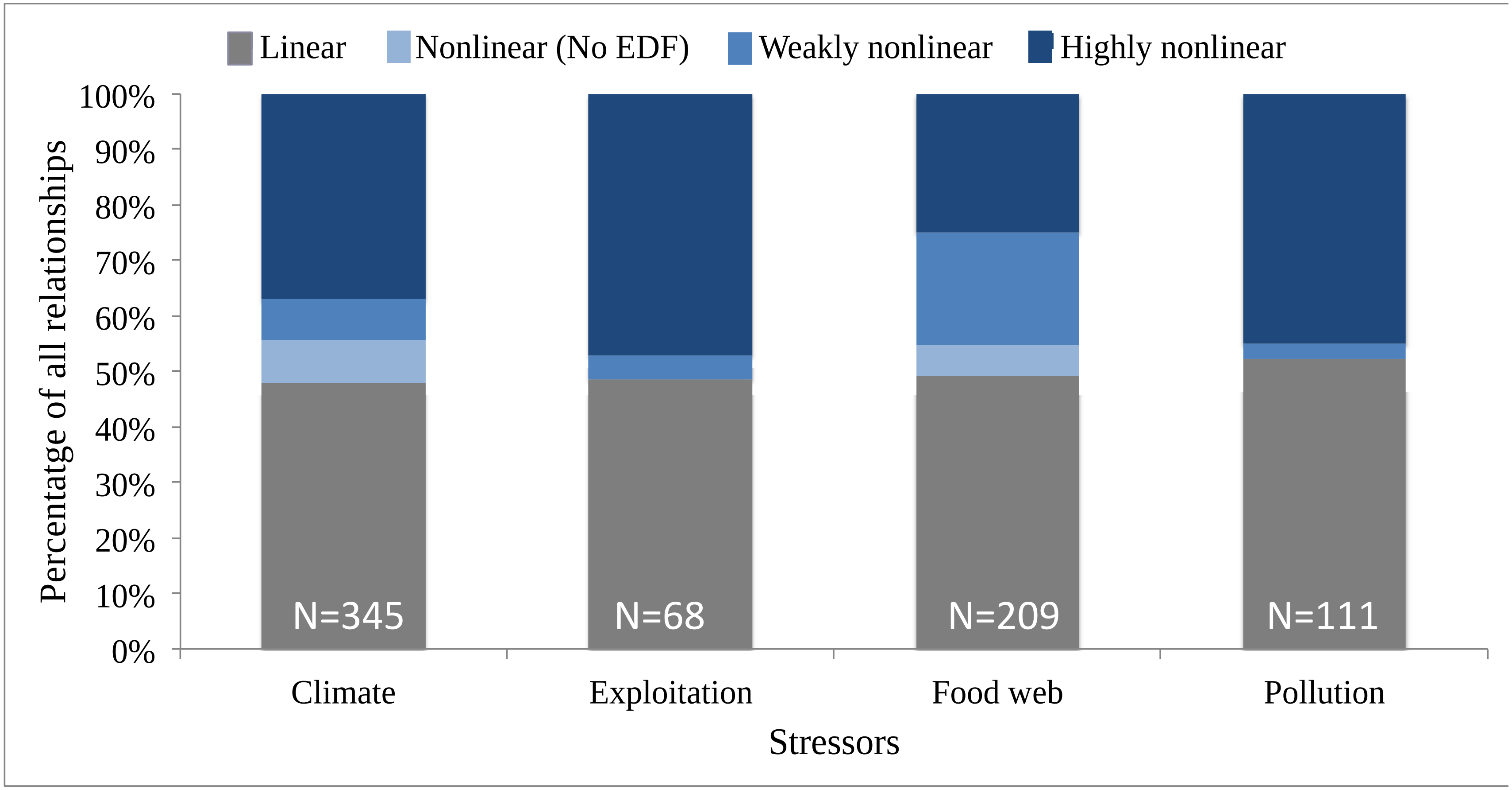
Hjermann 2010

Equal evidence for linear and nonlinear relationships



Hunsicker et al. 2016

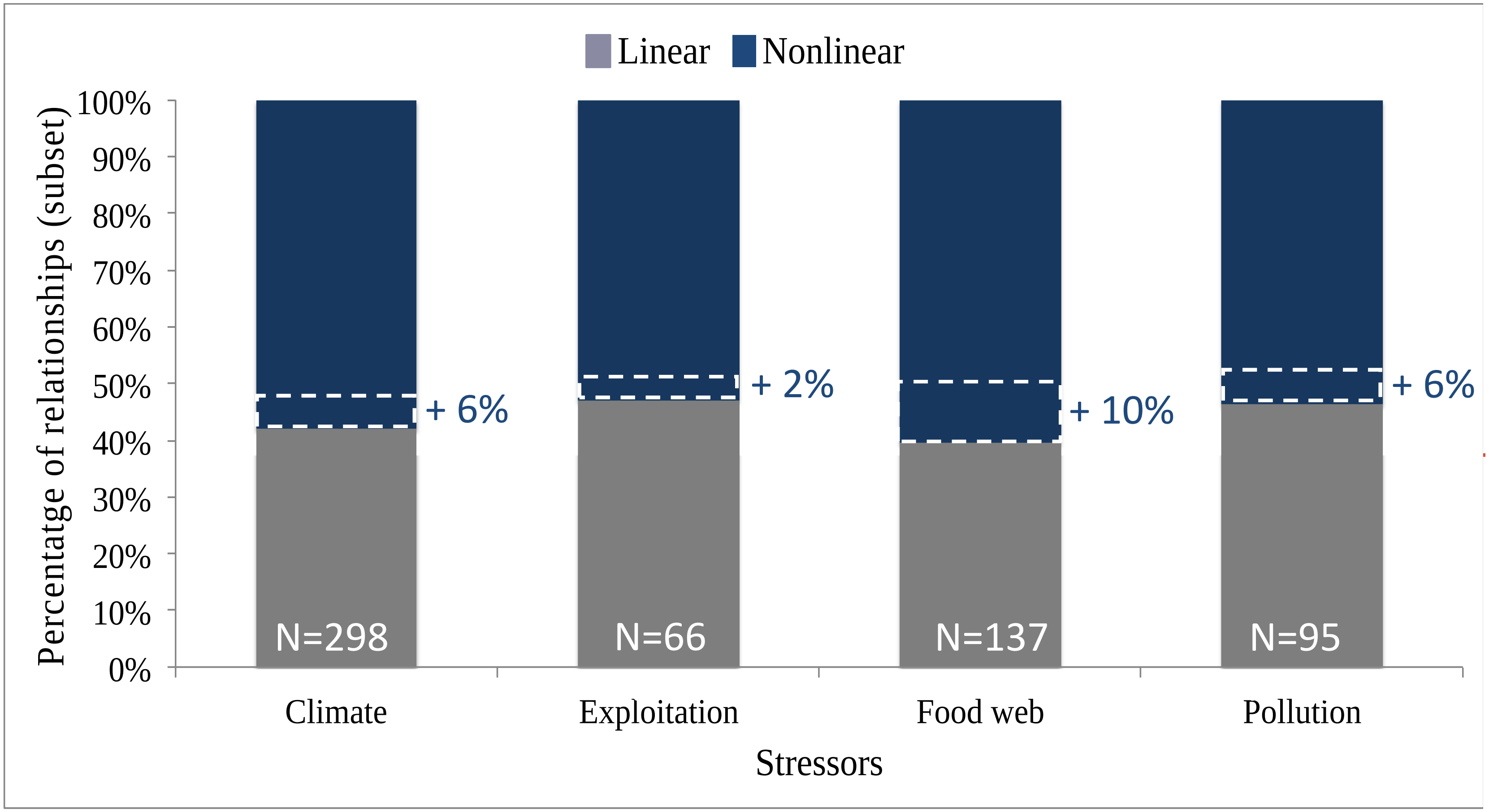
Highly nonlinear relationships are common



And thus may have detectable thresholds that could inform target-setting

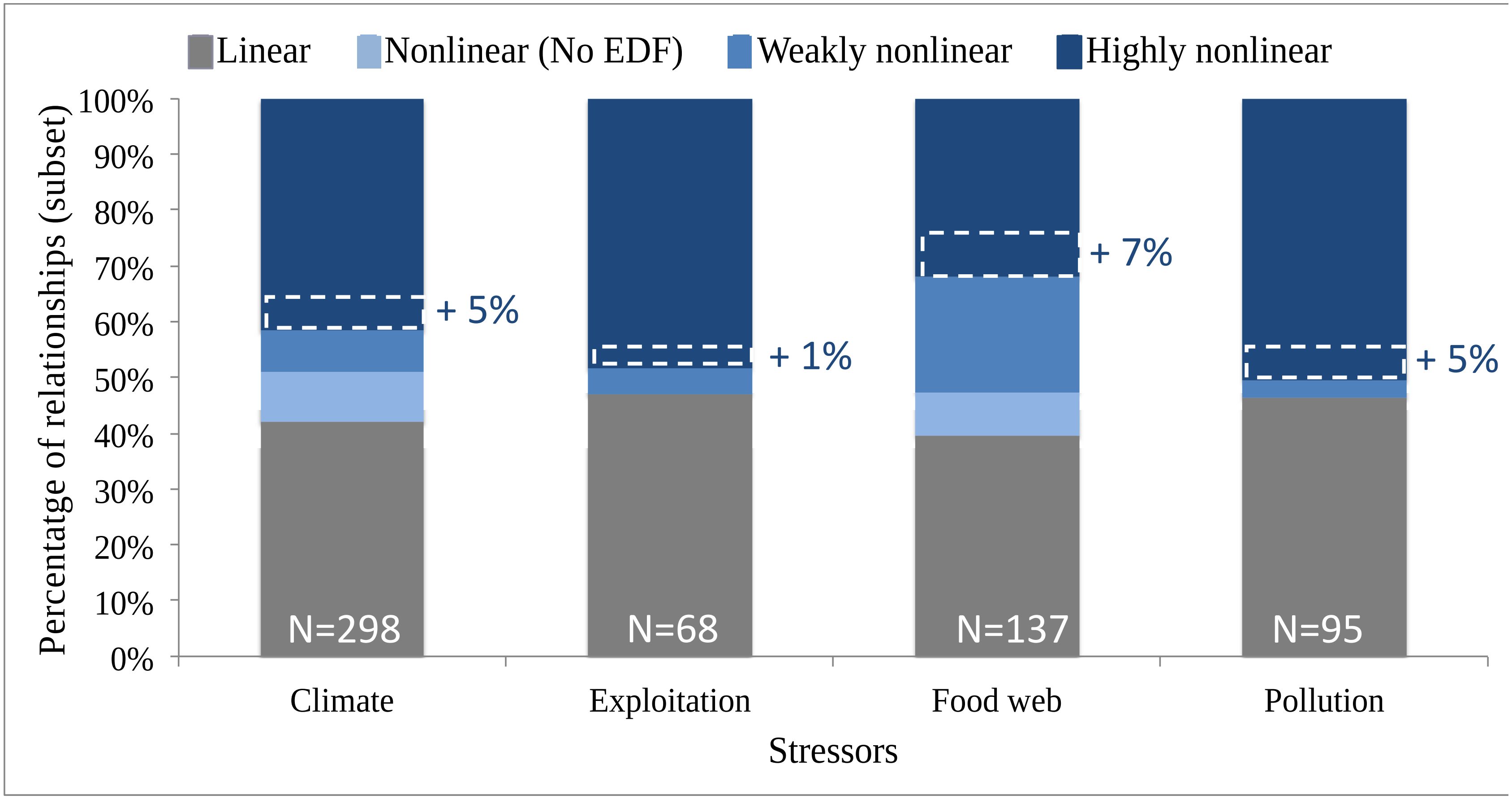
Hunsicker et al. 2016

Greater % of nonlinearities in robust set of papers



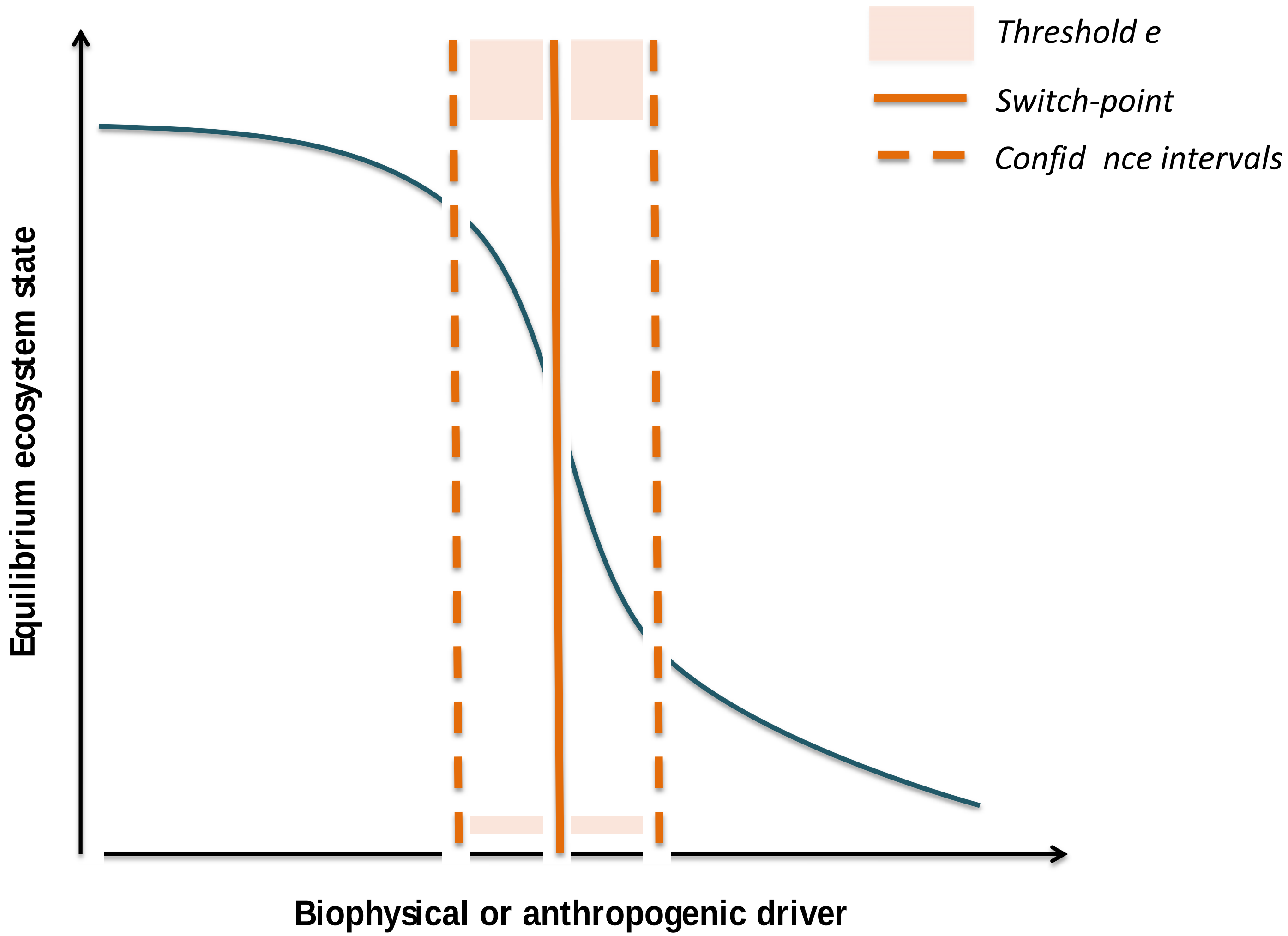
Hunsicker et al. 2016

Also, greater % of highly nonlinear relationships

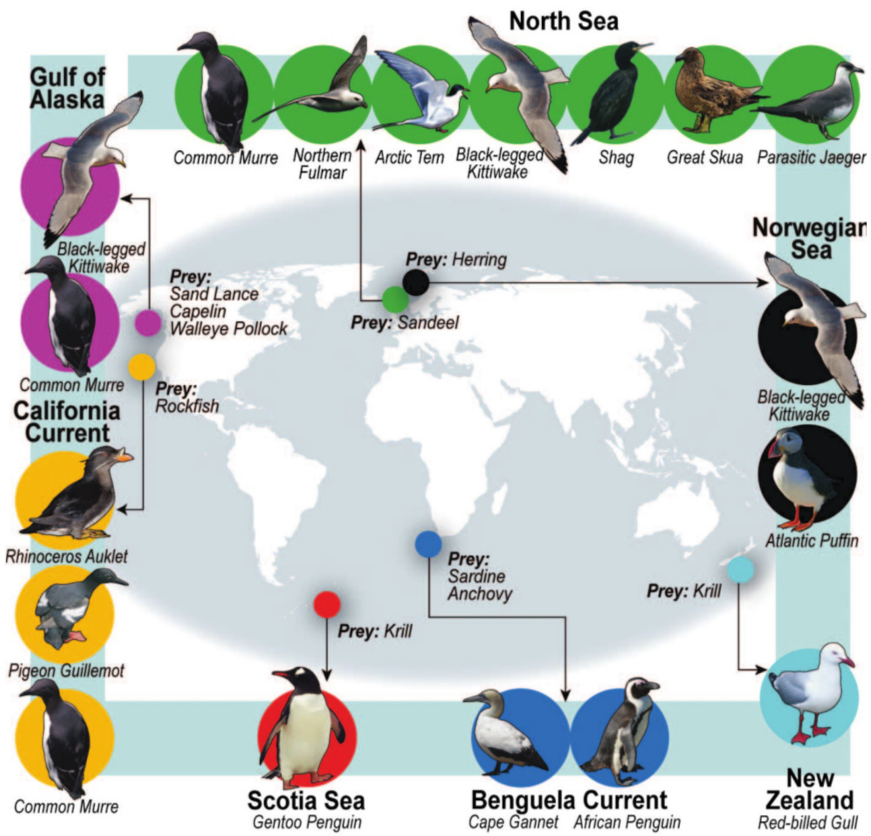


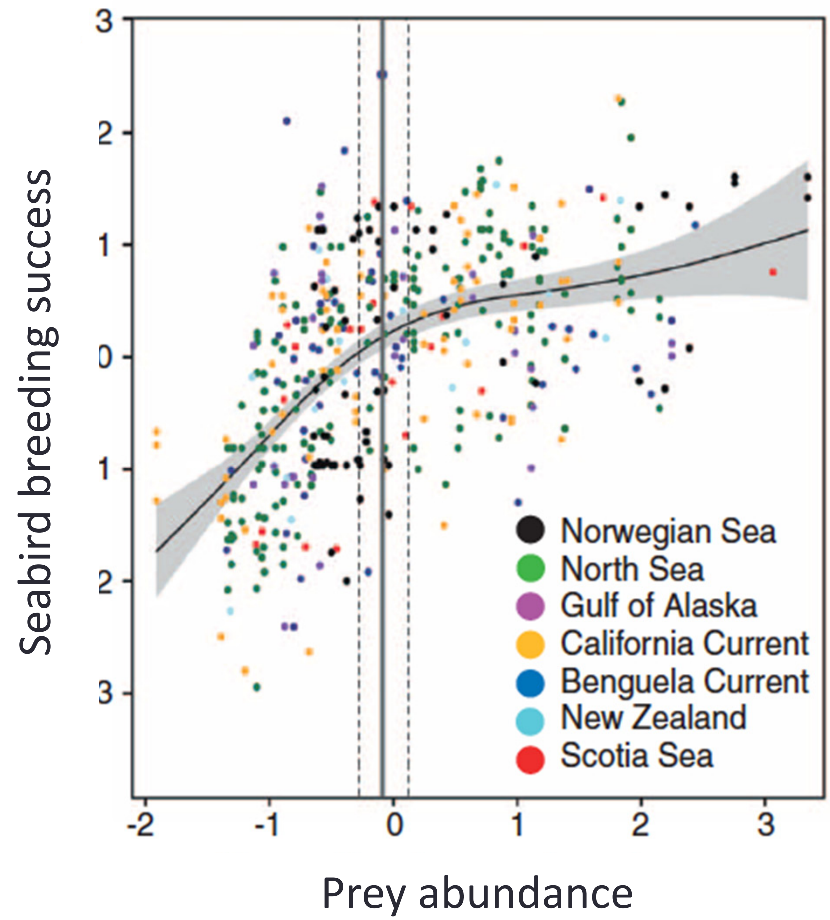
Hunsicker et al. 2016

What are the ecosystem thresholds that can inform target-setting?



Threshold effect of prey abundance on seabird breeding success





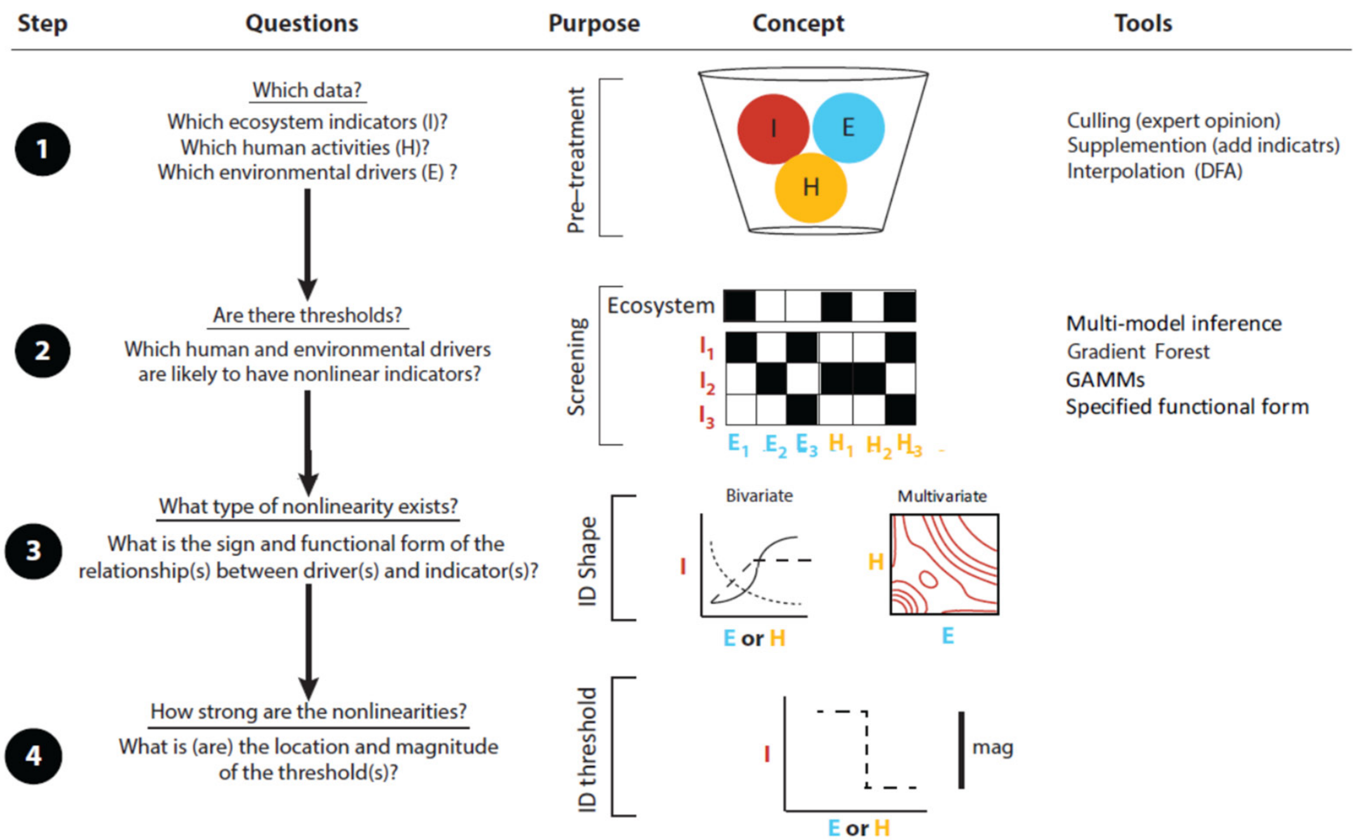
Cury et al. 2011

Challenges in our study

- Thresholds are more often identified in ecological time-series data than stressor-response relationships
- Only 8 papers quantified thresholds in single stressor relationships
- Precluded us from making generalizations about where thresholds are likely to exist

Ecosystem Thresholds

- Generalizable framework for identifying thresholds



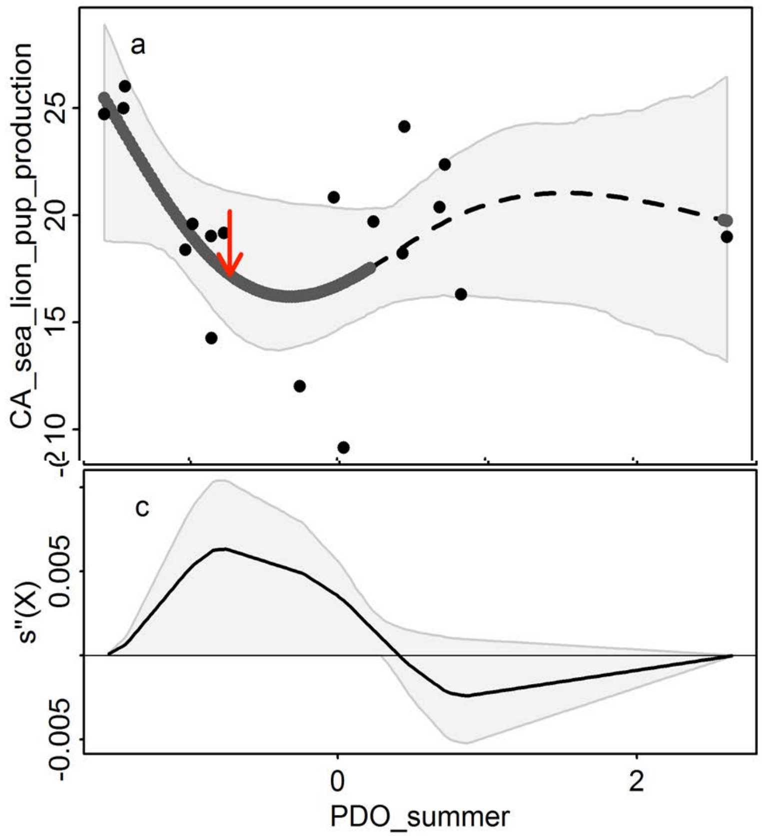
Samhouri et al. *In prep*

- Identify ecosystem thresholds for environmental drivers and human activities in the California Current ecosystem

Ecological Integrity Indicators: Northern copepod anomaly, groundfish mean TL and diversity, sea lion pup production and growth, scavenger biomass

Human Activities: Pollution, dredging, fishery removals, habitat modification, nutrient inputs, etc.

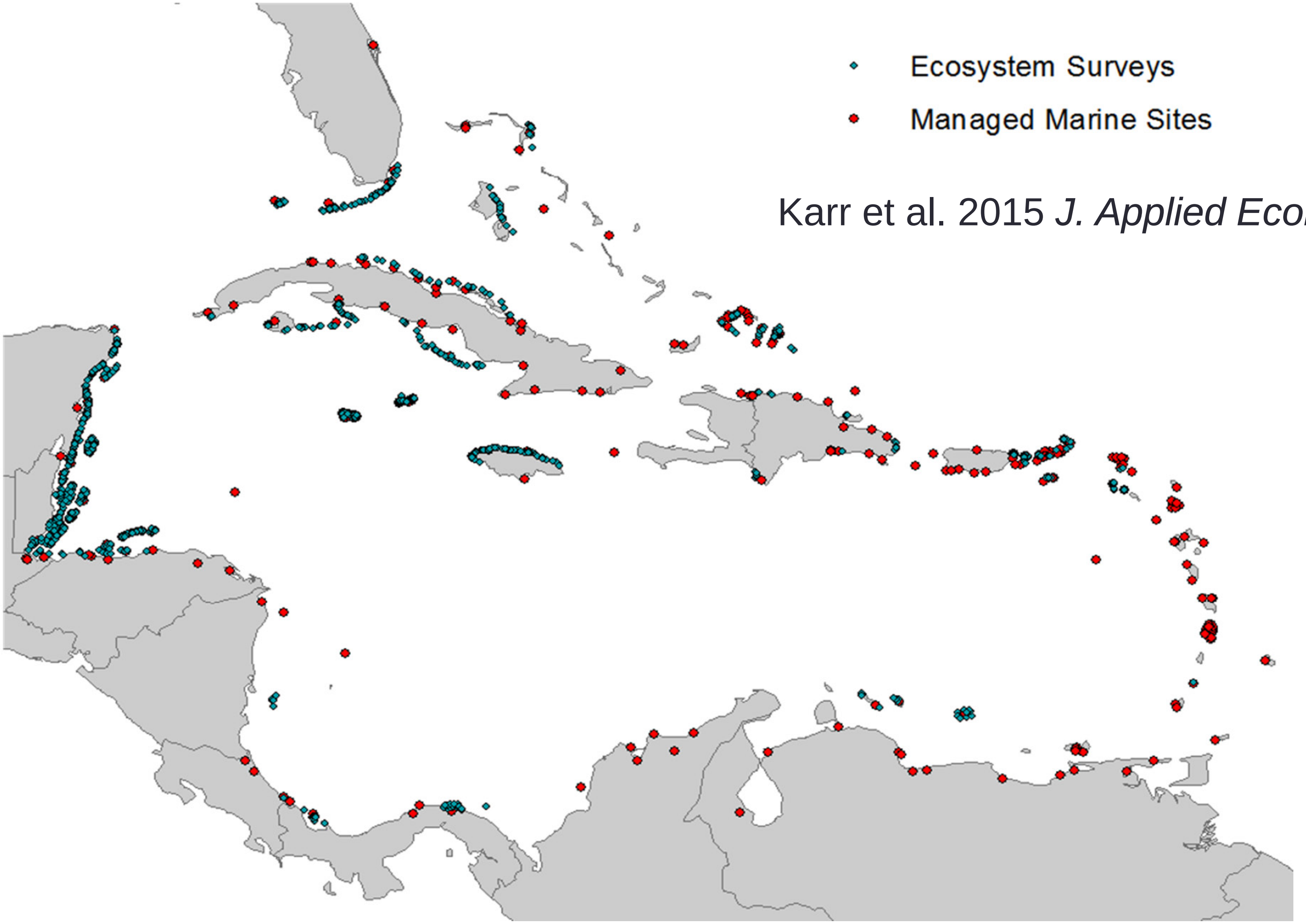
Environmental Drivers: PDO, NPGO



Leading indicators of ecosystem shifts

- Sudden transitions can have large impacts on ecosystem services
- Early warning signs provide ability to anticipate change and mitigate ecological and economic impacts

Leading indicators of Caribbean tipping points



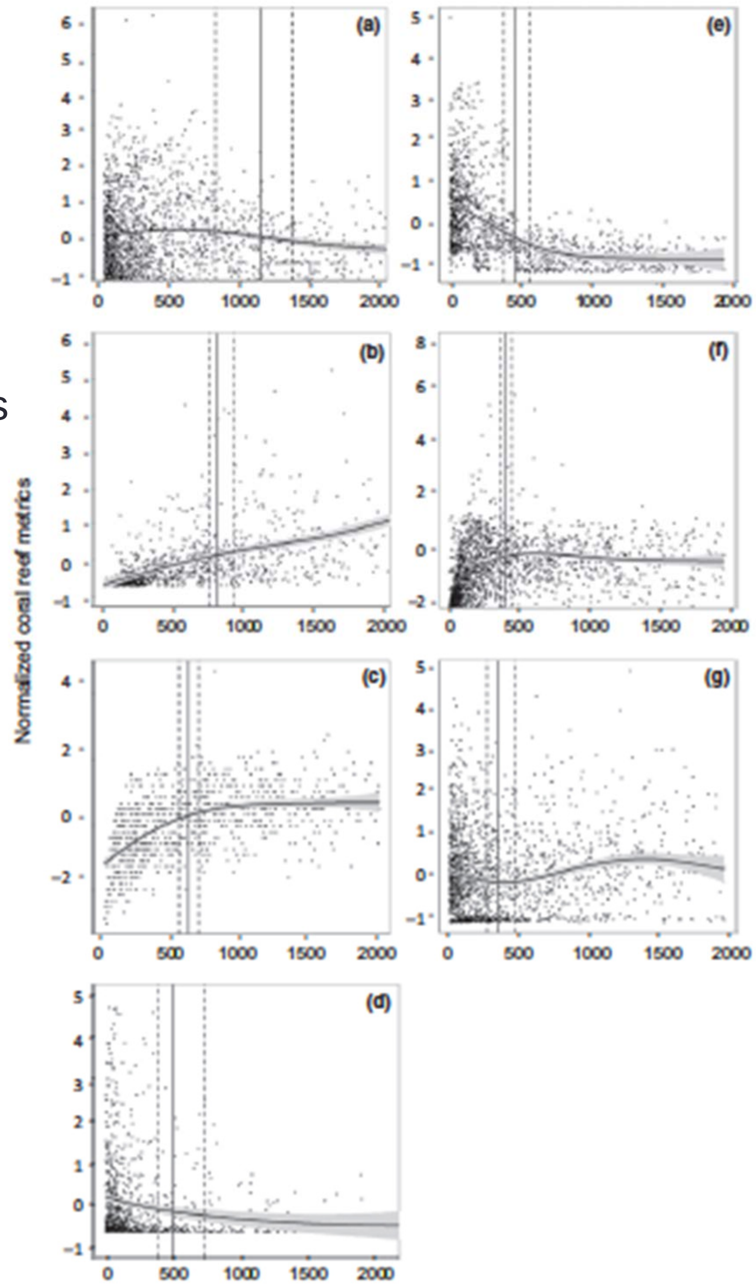
Karr et al. 2015 *J. Applied Ecology*

(a) % Macroalgal cover

(b) % Invertivorous fishes

(c) Fish species richness

(d) Urchin biomass



(e) Ratio of macroalgal to Coral cover

(f) % Herbivorous fishes

(g) % Coral cover

Total fish biomass

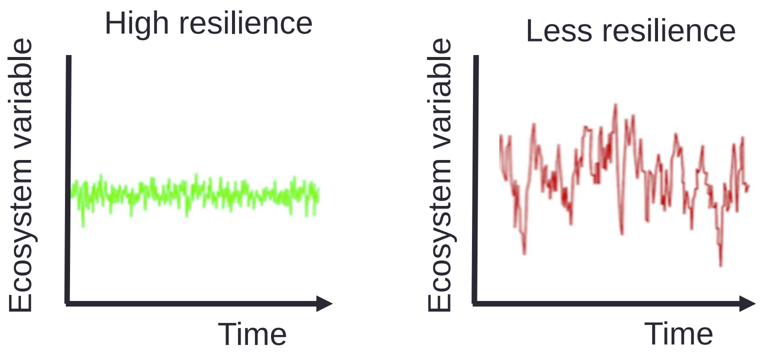
Karr et al. 2015

Generic early warning signals

- Metric-based indicators of ecosystem instability based on the complex systems theory of critical transitions and alternate stable states.

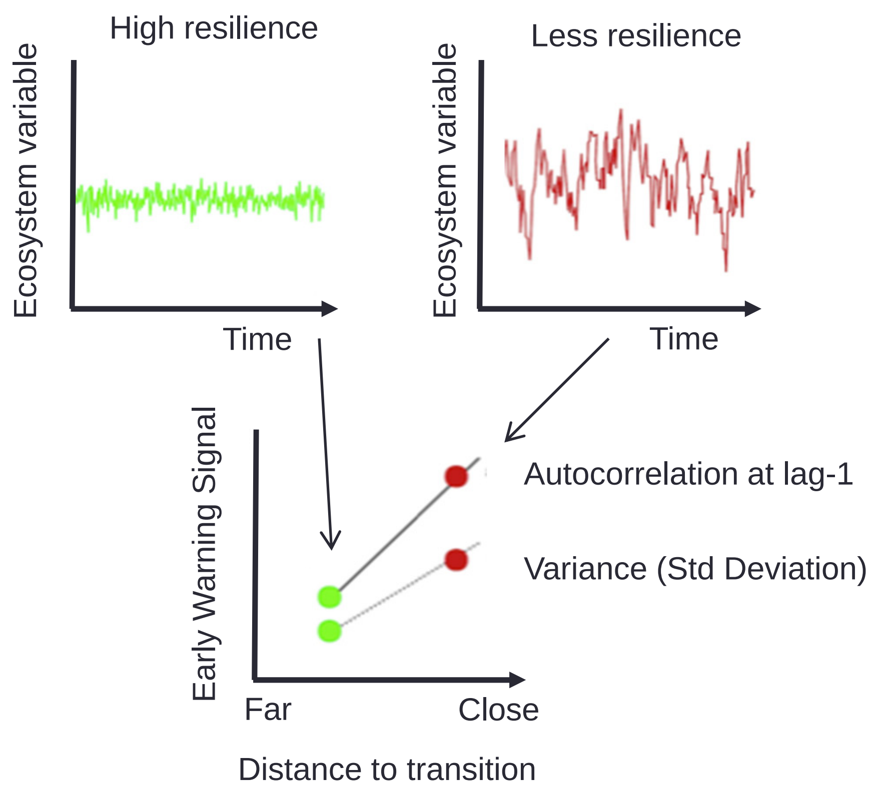
- ‘Critical slowing down” in population recovery from perturbations as resilience declines and a critical transition approaches

Rising variance and rising autocorrelation are potentially a signal of an approaching shift



From Wouters et al. 2015

Rising variance and rising autocorrelation are potentially a signal of an approaching shift



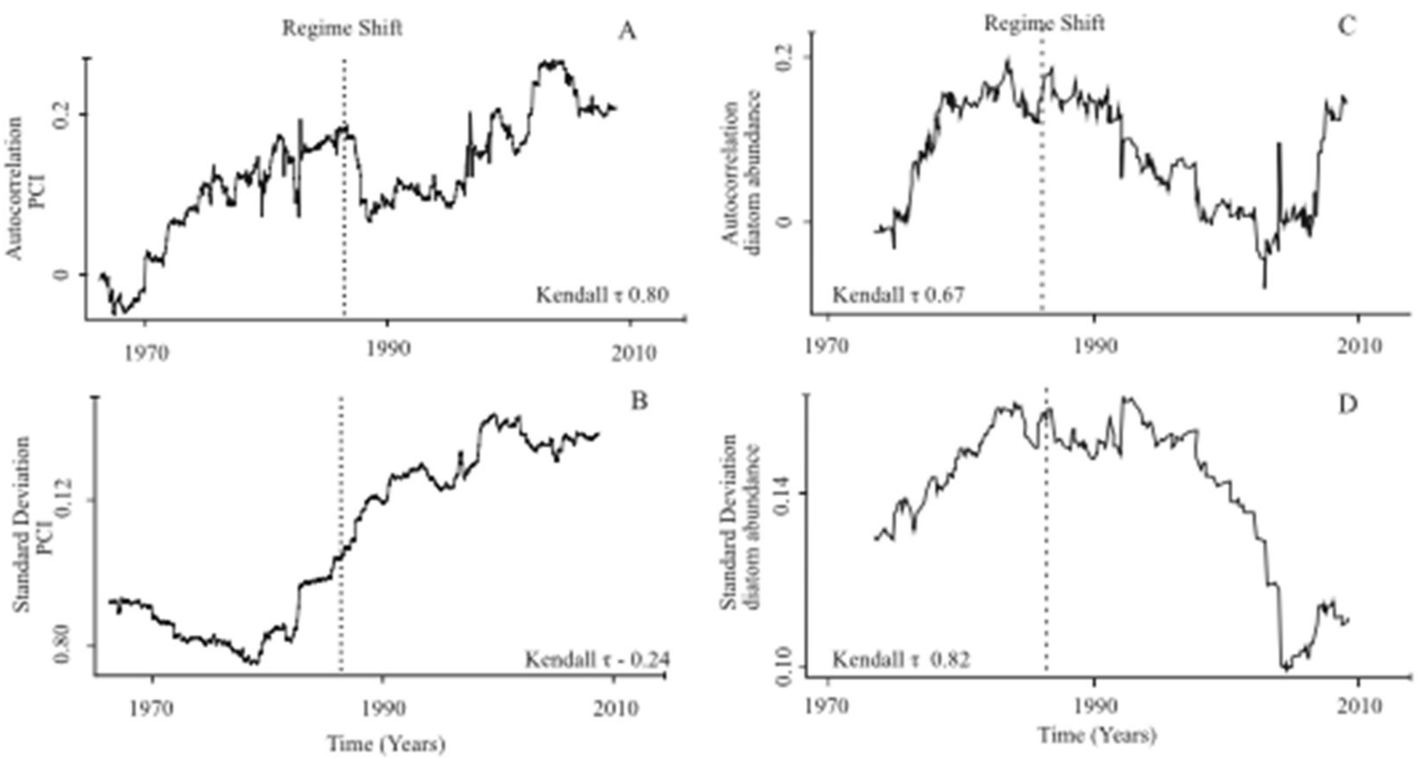
From Wouters et al. 2015

Generic early warning signals

- Metric-based indicators of ecosystem instability based on the complex systems theory of critical transitions and alternate stable states.
- ‘Critical slowing down” in population recovery from perturbations as resilience declines and a critical transition approaches
- Past work indicates they could be useful management tool, but their utility only recently assessed in marine ecosystems

Empirical examples

Rise in temporal variability (SD and autocorrelation) prior to regime shift in the North Sea



From Wouters et al. 2015

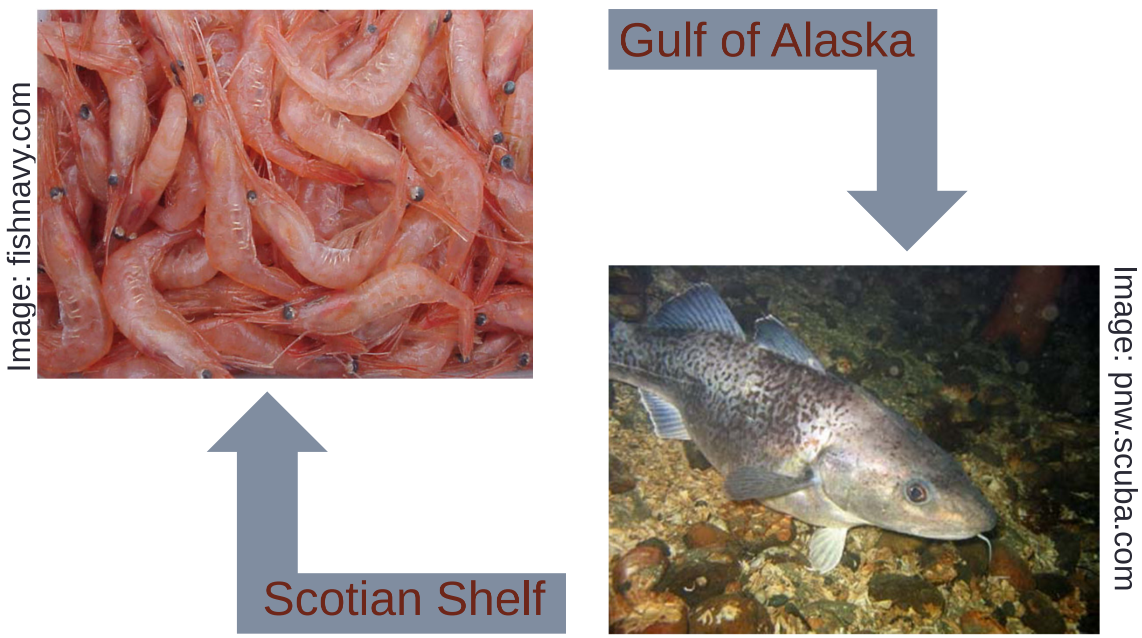
Empirical examples

Rising spatial variability in catches of crustaceans up to 4 years prior to collapse (Litzow et al. 2013)

Image: www.hcn.org

Empirical examples

Rising spatial variability in cod:prey abundance ratios accompanying the reorganization of two continental shelf ecosystems (Litzow et al. 2008)



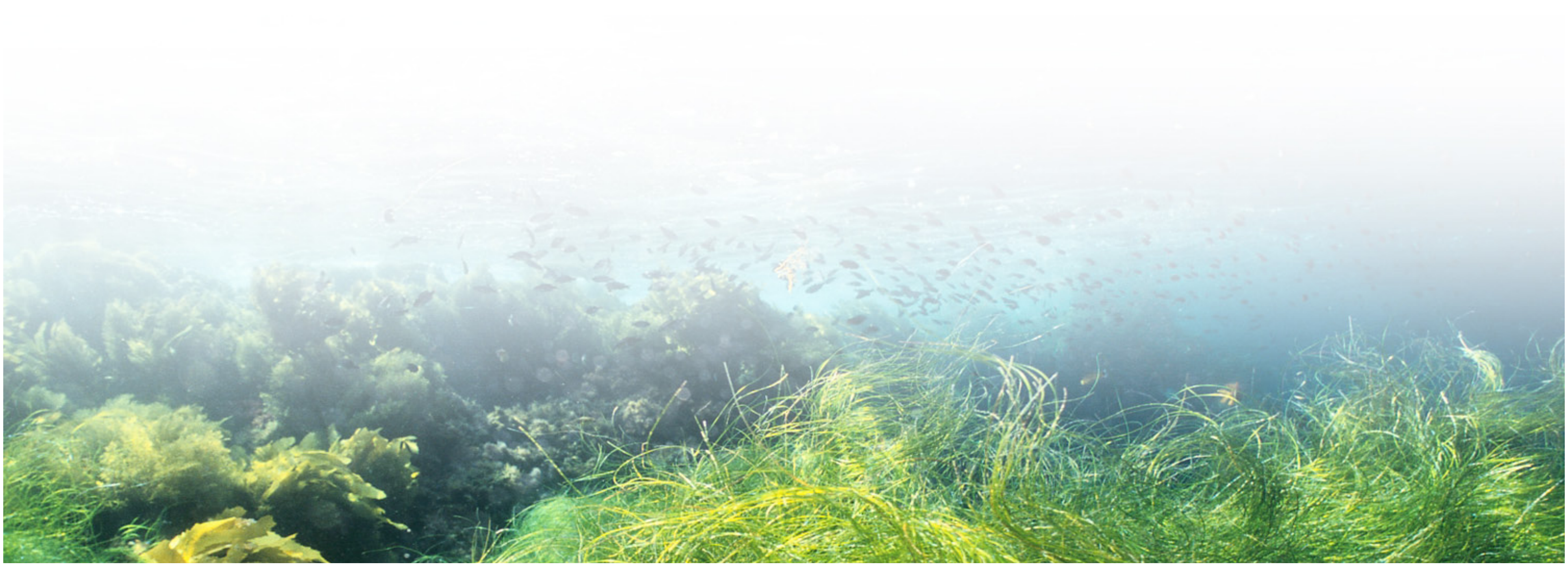
Empirical examples

Rise in variability in Arctic sea ice extent prior to acceleration in loss rate of sea ice (Carstensen and Weydmann 2012)

Image: www.climatecnentral.org

Why do we see mixed results?

- Meta-analysis to identify the factors distinguishing successful and unsuccessful applications of EWS in field studies (published studies and new analysis)

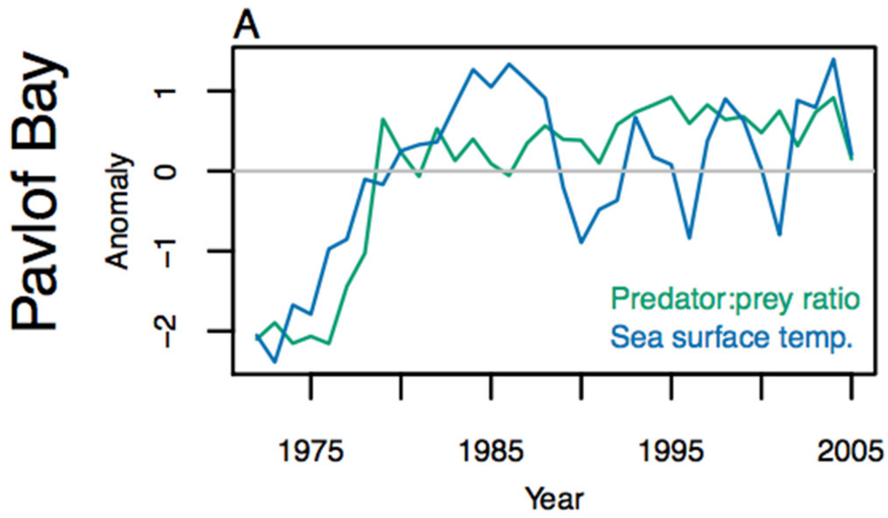


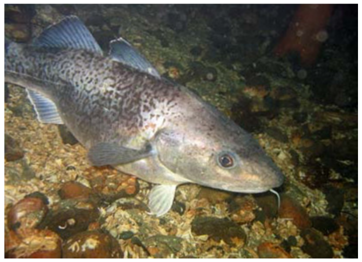
Why do we see mixed results?

- Meta-analysis to identify the factors distinguishing successful and unsuccessful applications of EWS in field studies (published studies and new analysis)

➢ Analysis demonstrating nonlinearity in ecosystem dynamics are more likely to support theoretical EWS predictions than studies with linear or undetermined dynamics

Example: *successful* application of EWS





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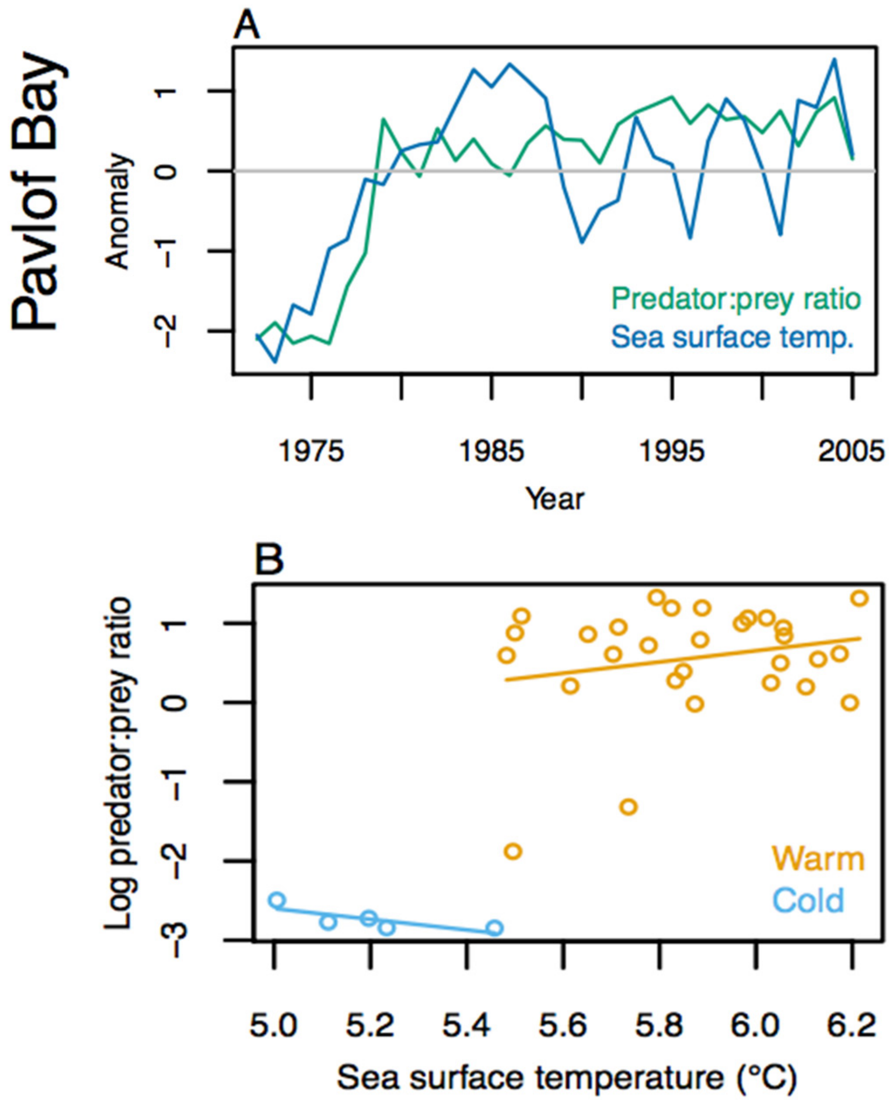
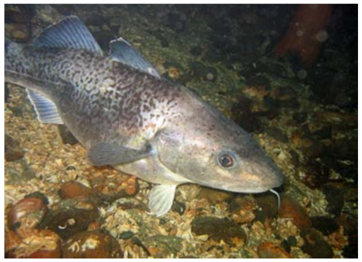
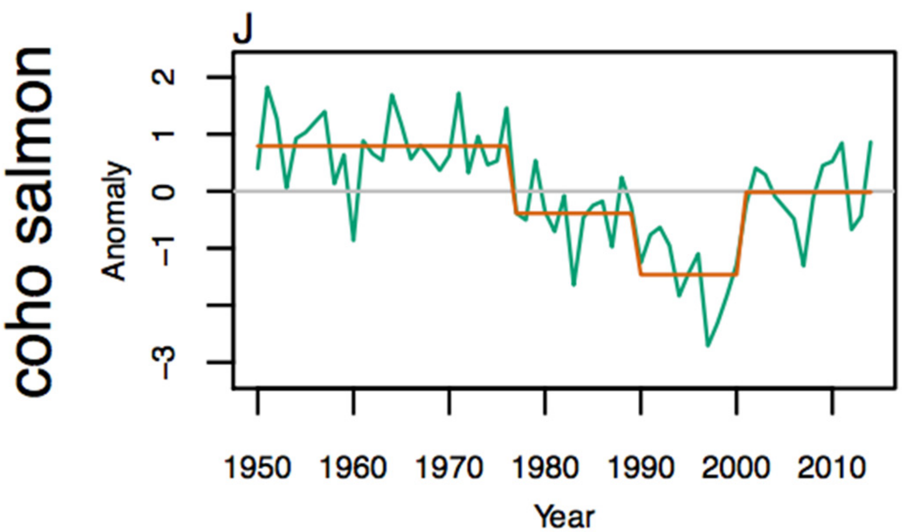
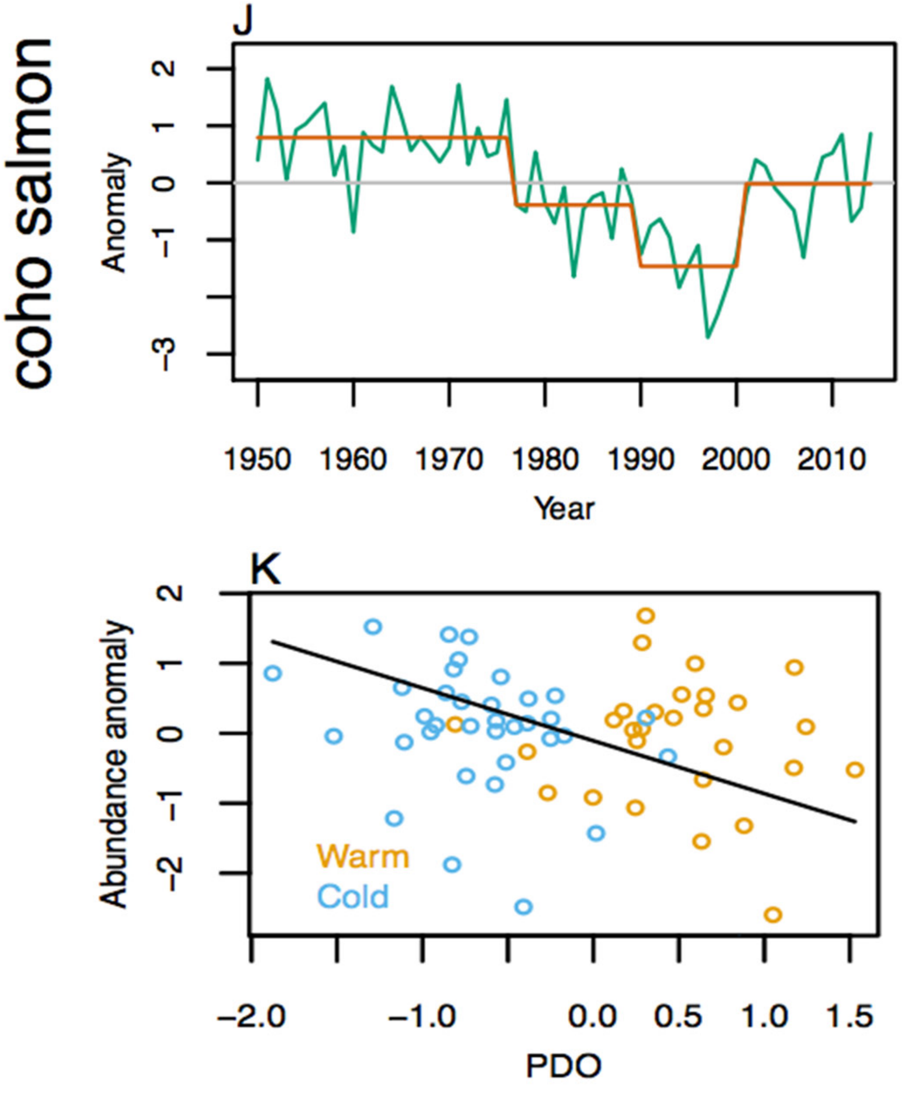




Example: *unsuccessful* application of EWS



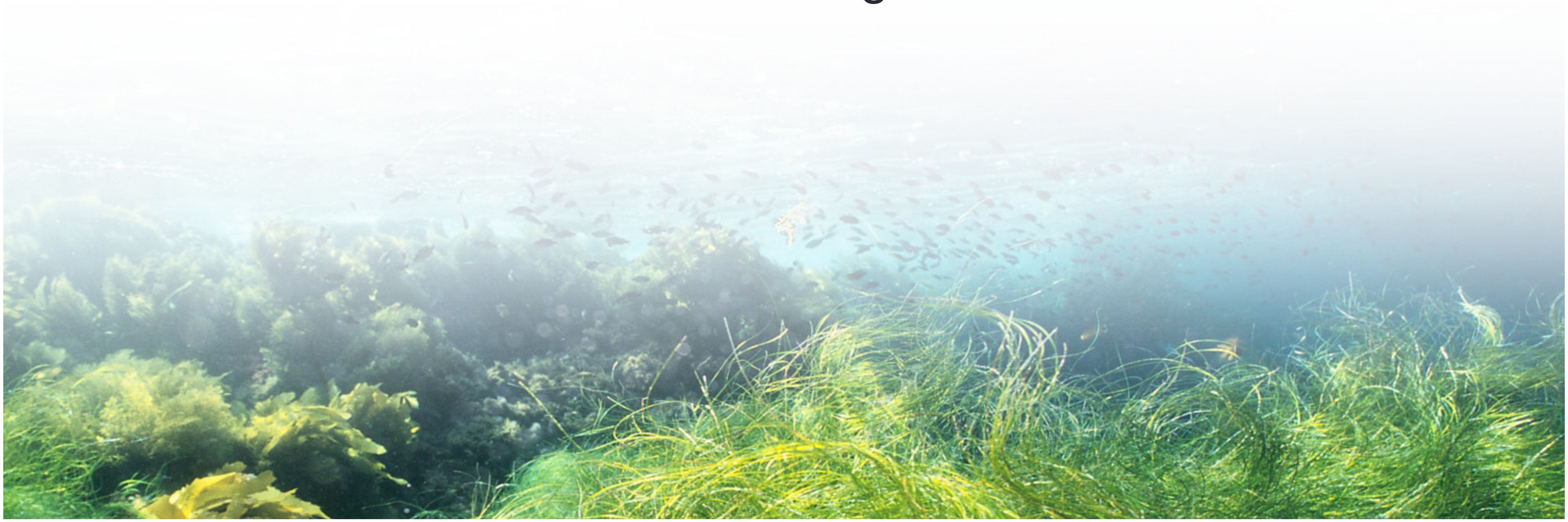
Example: *unsuccessful* application of EWS



Next steps

- Testing for nonlinear dynamics or signs of hysteresis is a key step for improving field studies of EWS and hastening the testing and application of this promising idea

- Provide more tests of EWS in the California Current, Gulf of Alaska and Eastern Bering Sea



Summary

- Nonlinearities are common in open ocean ecosystems
- Where these nonlinearities do exist, they tend to be strongly nonlinear and thus may have detectable thresholds
- Nonlinearities may be systematically underestimated
- EWS are promising, but need more tests in ocean systems
- Might dramatically improve our ability to manage nonlinear ecological change

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Bill Peterson
Adrian Stier (UW)
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Stephanie Zador

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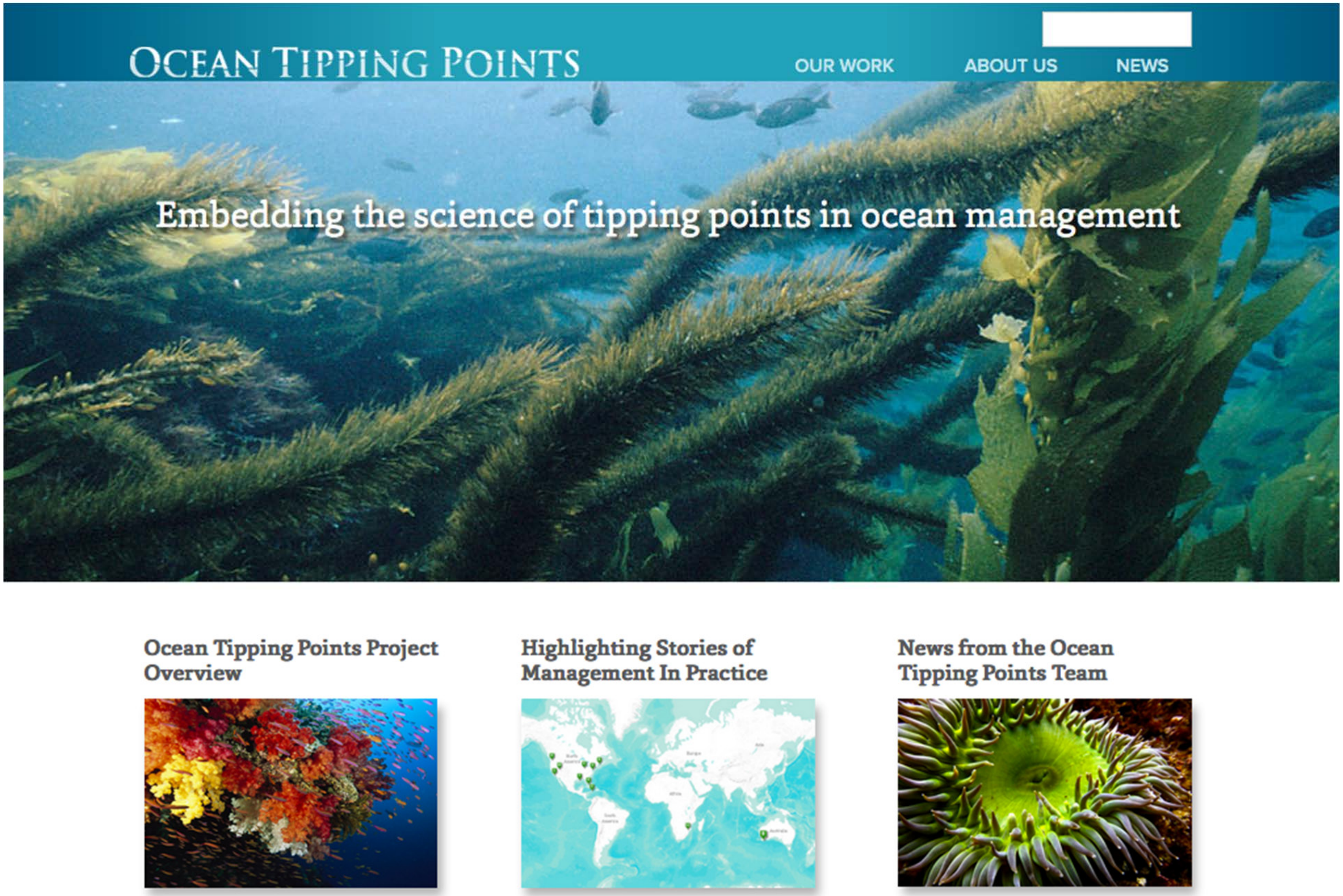
OSU/CIMRS
Jennifer Fisher

Farallon Institute
Mike Litzow

http://www.oceantippingpoints.org

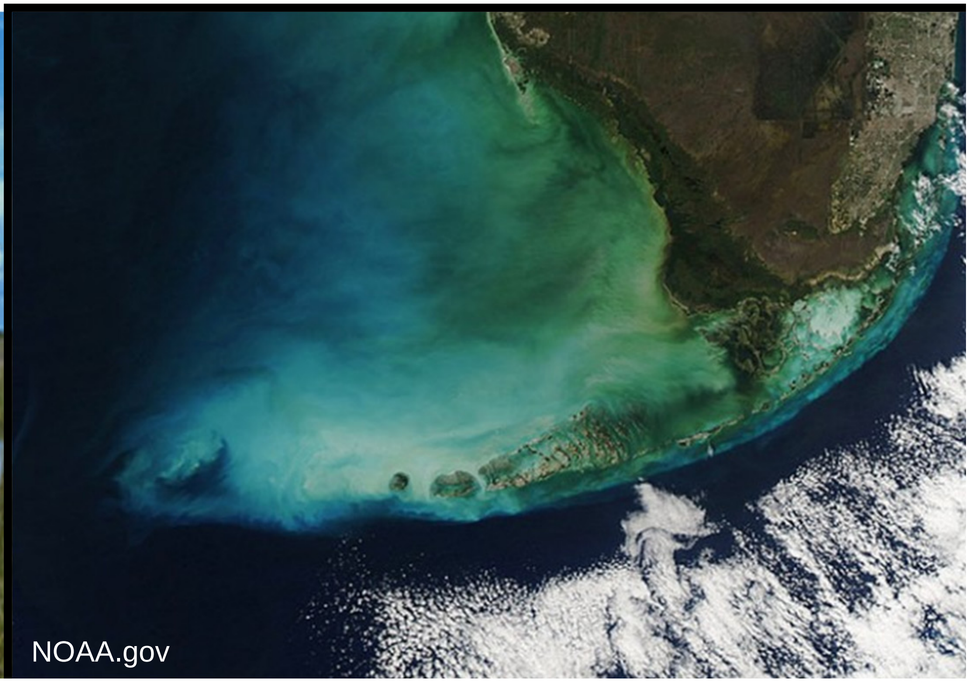


Thank you!

Google images

Mary.Hunsicker@noaa.gov

Kelly et al. (2014) reviewed management measures implemented in ecological systems that have thresholds. Successful attributes?



They found that…

- **Threshold management works.** More explicit use of thresholds in management is strongly associated with better environmental outcomes.

- **Responsive monitoring is key**. Good outcomes are also associated with routine monitoring requirements in both retrospective and prospective cases.

- **Scale matters.** Threshold-based systems with smaller geographic areas are more likely to have good management outcomes.

Kelly, Erickson, Mease, Battista, Kittinger, Fujita, 2014. Phil Trans Royal Soc. B.

Table 3. Summary of principles for managing ecosystems prone to tipping points.

Social-ecological observation	Management principle
1. Tipping points are common.	1. In the absence of evidence to the contrary, assume nonlinearity.
2. Intense human use may cause a tipping point by radically altering ecological structure and function.	2. Address stressor intensity and interactive, cross-scale effects of human uses to avoid tipping points.
3. Early-warning indicators of tipping points enable proactive responses.	3. Work toward identifying and monitoring leading indicators of tipping points.
4. Crossing a tipping point may redistribute ecosystem benefits.	4. Work to make transparent the effects of tipping points on benefits, burdens, and preferences.
5. Tipping points change the balance between costs of action and inaction.	5. Tipping points warrant increased precaution.
6. Thresholds can guide target-setting for management.	6. Tie management targets to ecosystem thresholds.
7. Tiered management can reduce monitoring costs while managing risk.	7. Increase monitoring and intervention as risk of a tipping point increases.

Biophysical or Management Attribute	Our Definition
Discrete/ bounded system	The resource system is discrete and bounded (e.g., an estuary vs. the population range of the Bluefin tuna)
Size	The size of the resource system, reported in square kilometers (log transformed for analysis).
Quantitative Threshold Defined	A quantitative threshold has been enumerated/identified that defines the point at which nonlinear change in the resource system occurs.
Managing Primary Stressor	The manager of the resource system controls the primary driver of threshold change ("x"), an indirect variable that influences the threshold relationship ("z"), or both.
Cost-Benefit Analysis	A cost-benefit analysis that evaluates the consequences of management action vs. inaction has been used. Any documented quantification of monetary costs and benefits of management action qualified as a cost-benefit analysis.
Leading Indicators Available	An environmental indicator exists which could be used to identify ahead of time when a management action should be taken in order to avoid or recover from a threshold change. Leading indicators are surrogates for some larger ecological state or process that is undergoing the nonlinear shift. Often indicators are easier or more reliably monitored than the larger ecological state or process. Primary system variables involved in the threshold relationship (i.e., the driver of the change or the variable changing) do not qualify as leading indicators.
Model Type	If a model exists that describes the system and identifies where the threshold occurs, is it quantitative (capturing relationships mathematically) or qualitative (conceptually relating system features)?
Degree of Threshold-based Management: "Threshold-based management"	1: Managers have identified a quantitative ecological threshold, which they use to set targets and manage threshold variables; 2: Managers have a qualitative idea of the ecological threshold, which they use to set narrative objectives without the use of numerical targets; 3: Managers are unaware of, or ignore, the ecological threshold, but their management actions do impact the threshold relationship; 4: Managers are unaware of, or ignore, the threshold, and their actions do not impact the threshold relationship.
Management Duration	The time, in years, between the first set of management actions and the most recent report on the state of the ecosystem (i.e., the point at which the authors determined the outcome score).
Number of Managing Entities	The number of entities that are involved in the management of the resource system.
Jurisdiction over Key Stressors	The managers of the resource system have jurisdiction over all of the sectors/drivers that influence the threshold relationship.
Adaptive Management	The operational management rules require iterative updating of plans and targets to incorporate new information and changing environmental variables.
Hierarchical Level of Governance	The governance level of the primary managing entity. 1: local (e.g., municipality); 2: state; 3: national; 4: international (e.g., international commissions).
Notable NGO Presence	A Non-Governmental Organization was/is involved in motivating, influencing, or creating accountability for management of the resource system.
Routine Monitoring Requirement	The management of the resource system includes routine monitoring of an environmental variable on a time scale relevant to the ecological threshold.
Larger Legal Framework Present	A written, binding agreement that focuses on the relevant threshold exists. This agreement is separate from any management-level plans or strategy documents, and may be a treaty, regulation, or statute.
Human Development Index (HDI)	The Human Development Status of the nation in which the resource system is located. If the system spans multiple nations, an average was taken.
Binding Requirements	The legal framework (written, binding agreement) includes consequences if managers violate the agreement.

Box 1 The terms describing nonlinear theory and early warning signals often have meanings that are highly specific and context-dependent. Here we define some of these concepts as we use them in the paper.

alternative stable states Different configurations of a system that are able to exist at the same set of external conditions. Corresponds to a stable equilibrium or basin of attraction in nonlinear response to external conditions.

critical slowing down Reduced speed of recovery from perturbation as a critical transition is approached, due to a decline in engineering resilience.

critical transition Abrupt shift in a system caused by nonlinear responses to external conditions.

early warning signal / early warning indicator Model- or metric-based statistic able to warn that the system is approaching a sudden change, most often associated a critical transition.

fold bifurcation / saddle node bifurcation A critical transition between alternative stable states, corresponding to the threshold in external conditions at which stable and unstable equilibria meet.

hysteresis Different critical transitions in response to increasing and decreasing external conditions; responses to external conditions that depend on system state and the direction of change in external conditions.

linear Systems with dynamics that can be expressed statistically by models in which the estimated parameters are combined by addition. Thus a linear regression ($y = a + bx$) or a quadratic regression ($y = a + b_1x + b_2x^2$) both describe linear systems. In a linear system, the effect of any small perturbation decays in time.

nonlinear In a nonlinear system a small perturbation may propel the system to another stable state, and dynamics are dependent on the initial conditions. Statistically, the response variable cannot be summarized as a linear combination of estimated parameters.

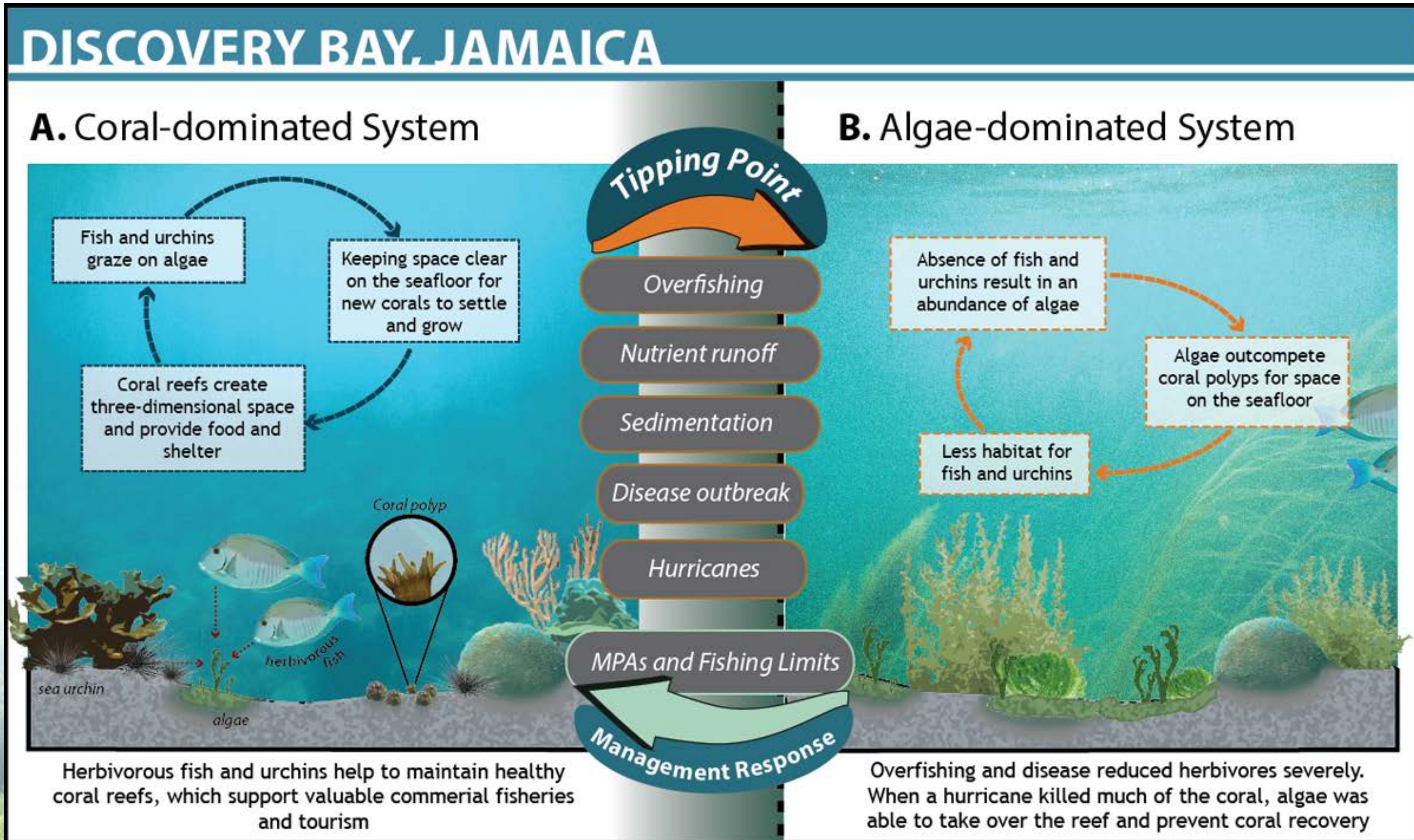
resilience Ecological resilience is the ability of a system to remain in its current state when exposed to perturbation. Engineering resilience is the speed with which a system returns to equilibrium after perturbation

Ecosystem Attribute	Indicator	Taxonomic group	Community	Definition and source of data	Time series	Sampling frequency
Species composition	Northern copepod anomaly, winter and summer	Invertebrates	Pelagic	Monthly anomalies in the relative biomass of copepods with cold-water affinities off Newport, OR (Peterson et al. 2015, NOAA);	1996 – 2014	Biweekly; summarized as winter and summer anomalies
Biodiversity	Species Richness, Species Density, Simpson's index	Groundfish	Benthic	Index of groundfish community composition (Keller et al. NWFSC)	2003 – 2014	Summers, Annual
Functional organization	Mean trophic index	Groundfish	Benthic	Trophic structure of groundfish community (Keller et al. NWFSC)	2003 – 2014	Summers, Annual
Functional organization	Scavenger biomass	Groundfish and invertebrates	Benthic	Relative biomass of scavengers, as defined by esp. Brand et al. (2007), from fishery independent surveys (Keller et al. NWFSC)	2003 – 2014	Summers, Annual
Functional organization	California sea lion pup production and growth	Marine mammals	Top predators	Average # of pups on San Miguel Island in late July and predicted daily growth rate of pups between June & October (Melin et al. 2012, Wells et al. 2013, NMML)	1997 – 2014	July and June - October, respectively; Annual

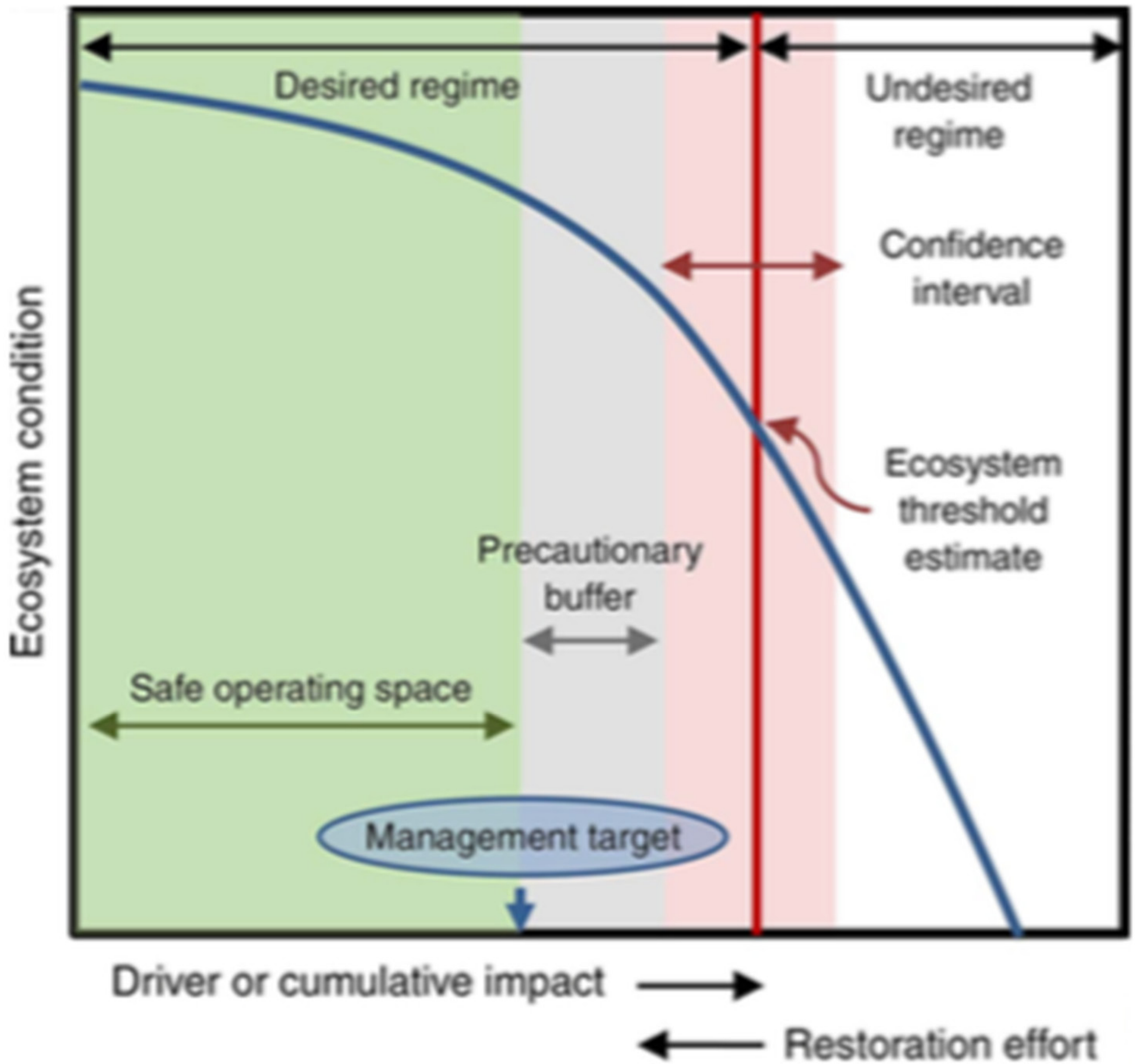
Component	Driver/ Pressure	Indicator	Definition and source of data	Time series	Sampling frequency
Oceanographic drivers	Basin-scale sea surface temperature	PDO summer and winter	Pacific Decadal Oscillation (PDO; Mantua et al. 1997) index for summer (July, Aug, Sept) and winter (Jan, Feb, Mar) months. Data accessed at http://research.jisao.washington.edu/pdo/.	1900 – 2014	Annual seasonal averages
	Basin-scale atmospheric forcing	NOI summer and winter	Northern Oscillation Index (NOI) is the sea level pressure difference between the climatological mean position of the North Pacific High and Darwin, Australia (Schwing et al. 2002). Data accessed at www.pfel.noaa.gov/products/PFEL-/modeled/indices/NOIx/noix.html.	1948 – 2014	Annual seasonal averages
	Changes in source waters	NPGO summer and winter	The North Pacific Gyre Oscillation (NPGO) is a low frequency signal in sea surface heights over the NE Pacific. Data accessed at www.o3d.org/npgo/.	1950 – 2014	Annual seasonal averages
Human Activities	Atmospheric pollution	Deposition of sulfate	Annual precipitation-weighted mean concentrations of sulfate measured at sites in CA, OR, and WA by the National Atmospheric Deposition Program.	1994 – 2014	Annual
	Commercial shipping activity	Volume of water disturbed	Calculated using draft, breadth and distance traveled within CCS of domestic and foreign vessels. Data from Army Corps of Engineers Navigation Data Center (ACENDC).	2001 – 2012	Annual
	Dredging	Dredge volumes	Dredge volumes for individual private contracts and Army Corps operated dredge projects in WA, CA, and OR. Data from ACENDC.	1997 – 2014	Annual
	Groundfish fisheries removals	Commercial landings	Metric tons of all species landed by commercial groundfish fisheries in CA, OR and WA. Data accessed via Pacific Fisheries Information Network (PacFIN).	1981 – 2014	Annual
	Habitat modification	Distance trawled	Kilometers trawled by the limited-trawl groundfish fishery in CA, OR and WA. Data from the Northwest Fisheries Science Center's Observer Science Program.	1999 – 2012	Annual
	Inorganic pollution	ISA-toxicity-weighted chemical releases	Releases of inorganic pollutants to the ground or water weighted by toxicity scores and impervious surface area (ISA) in the drainage watersheds of the CCE. Data from the Environmental Protection Agency's Toxics Release Inventory Program.	1988 – 2012	Annual
	Invasive species	Tons of cargo	Tons of cargo moved through ports in CA, OR and WA. Data from ACENDC.	1993 – 2013	Annual
	Nutrient input	Nitrogen and phosphorus input	Total farm and non-farm nitrogen and phosphorus input from fertilizer used in counties within CCE watersheds. Data from U.S. Geological Survey (USGS), Ruddy et al. (2006) & Gronberg and Spahr (2012).	1945 – 2010	Annual
	Organic pollution	Toxicity-weighted concentrations	Toxicity-weighted concentrations of 16 pesticides measured in water samples from stream-water sites in WA, OR and CA. Data accessed at http://pubs.usgs.gov/ds/655/.	1993 – 2010	Annual
	Total fisheries [illegible]	Total [illegible]	Metric tons of all species landed by commercial and [illegible]	1981 – [illegible]	Annual

Ecosystem state	Driver/Pressure	Analysis	Functional Form	Location of threshold	Best estimate of threshold location	Magnitude of response (%)
Copepod anomaly winter	PDO winter	RGF	--	-0.5 to -0.2	NA	--
Copepod anomaly winter	Habitat modification	truncated GAM GAM		143 to 234 138 to 252	208 227	70 30
Copepod anomaly summer	NPGO winter	GAM		0.2 to 0.8	0.2	180
Copepod anomaly summer	PDO summer	RGF	--	-1.2 to 0.5	NA	--
Copepod anomaly summer	PDO winter	RGF	--	0.7 to 0.8	NA	--
Scavenger ratio	Commercial shipping activity	RGF	--	14.7 to 15.2	NA	--
Scavenger ratio	PDO summer	RGF	--	-0.6 to 0.1	NA	--
Groundfish MTL	PDO summer	RGF	--	-0.3 to 0	NA	--
CA sea lion pup production	NOI summer	GAM		-0.4 to 1.2	0.2	10
CA sea lion pup production	PDO summer	truncated GAM GAM		-1.5 to -0.2 NTI	-0.8 NTI	10 NTI
CA sea lion pup production	PDO winter	truncated GAM truncated GAM		0.7 to 1.5 -1.4 to 0.2	0.9 -0.8	30 0

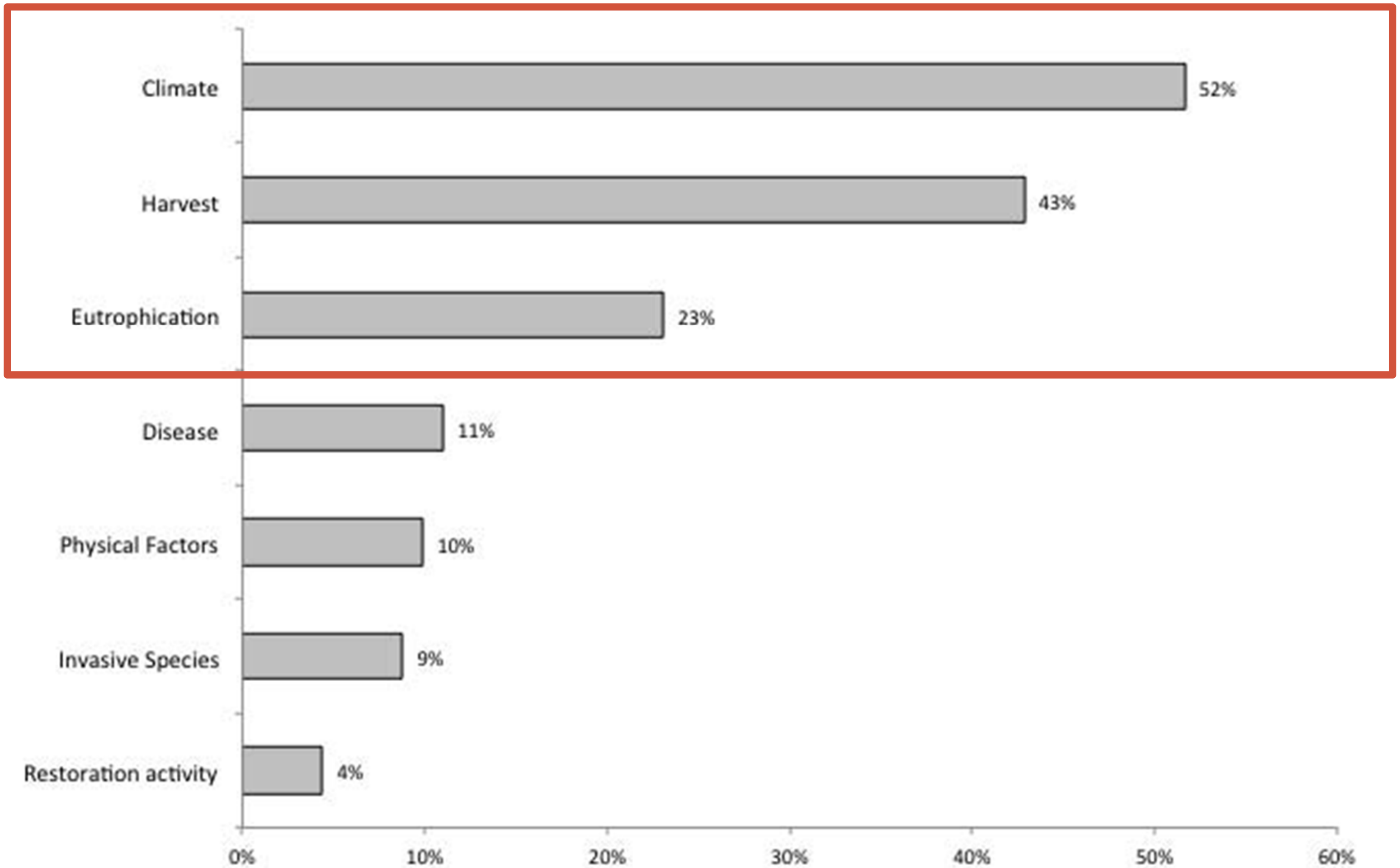
3. Changes in early warning indicators may precede tipping points



OCEAN TIPPING POINTS

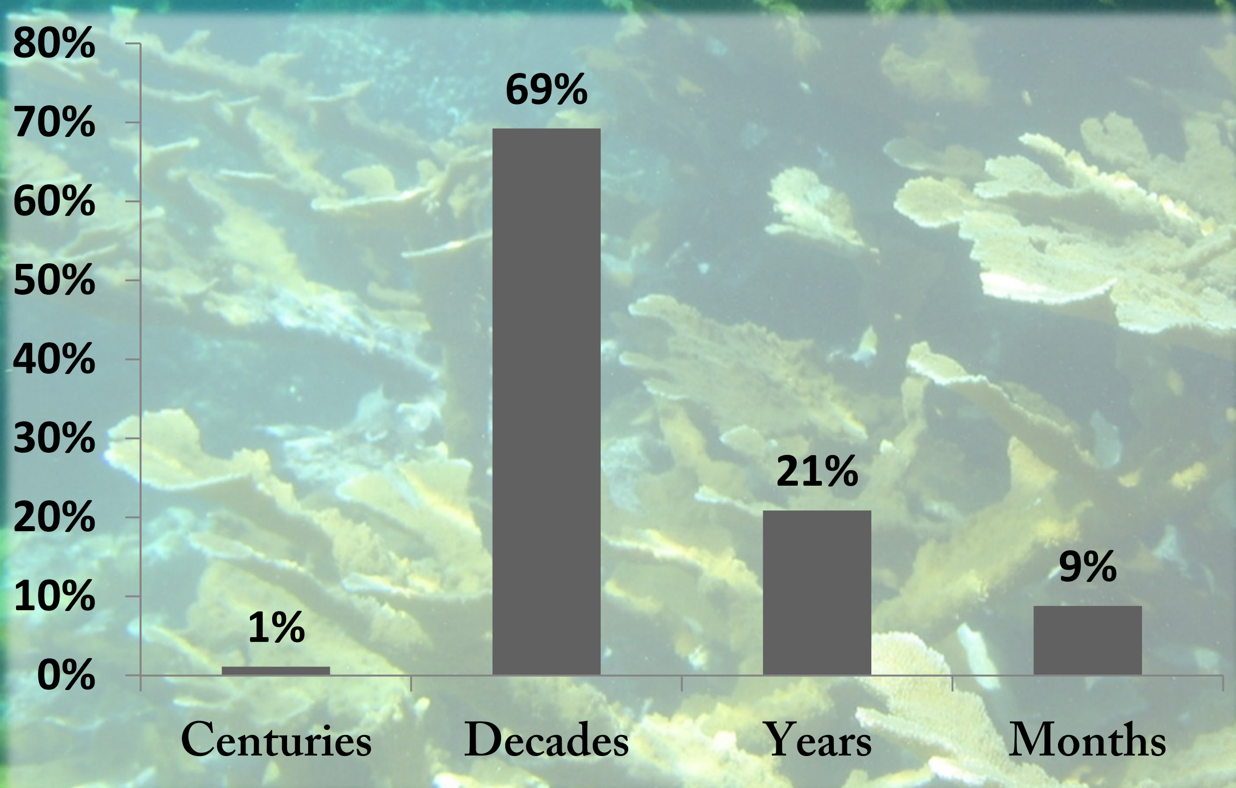

Desired regime
Undesired regime
Confidence interval
Ecosystem threshold estimate
Precautionary buffer
Safe operating space
Management target
Ecosystem condition
Driver or cumulative impact
Restoration effort

Drivers of Ecosystem Shifts



Kappel et al. *In prep*

Although recovery may be possible, ecosystems that have crossed a threshold tend to remain in an altered condition for decades



Kappel et al in prep

Why we are engaged

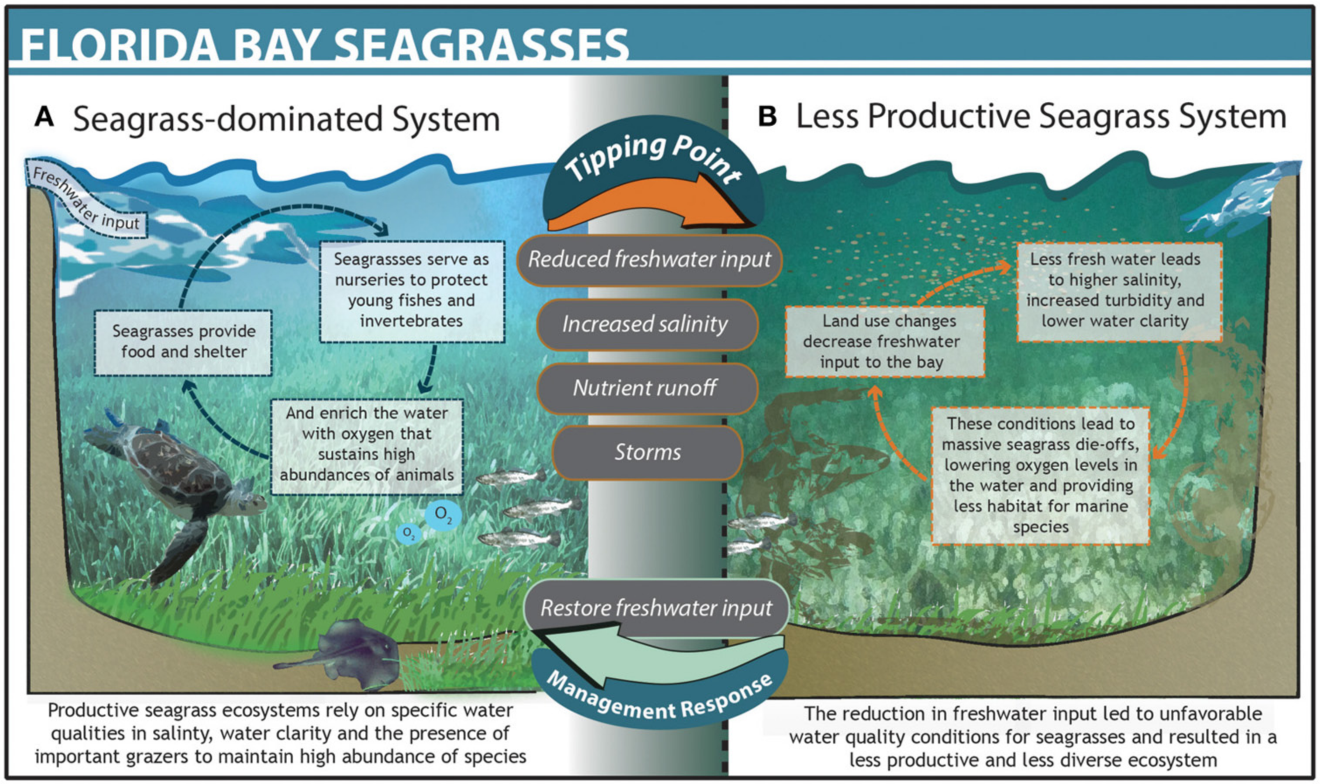
- Ecosystem tipping points may be rapid, unexpected and difficult to reverse.
- Crossing tipping points can have negative consequences for people's livelihoods and well-being.
- The ability to predict and understand ocean tipping points can enhance ecosystem management.
- Preventing a shift may be less costly than attempting to recover from one.

Non-linearity most common for response relationships involving species biomass and growth/condition

		Ecological responses											
		Species biomass			Growth and condition			Area occupied			Recruitment		
Drivers	**Metrics**	% NL	% L	N	% NL	% L	N	% NL	% L	N	% NL	% L	N
Climate	Large-scale climate patterns	**67**	**33**	**18**	-	-	-	**55**	**45**	**11**	**86**	**14**	**7**
	Salinity	**100**	**0**	**10**	**83**	**17**	**6**	21	79	19	-	-	-
	Temperature	**73**	**27**	**53**	**63**	**38**	**16**	42	58	31	43	57	28
	Winds and upwelling	**63**	**38**	**8**	**64**	**36**	**11**	-	-	-	-	-	-
Tropho-dynamic	Density dependence	**71**	**29**	**7**	**60**	**40**	**15**	**50**	**50**	**8**	-	-	-
	Predator and prey biomass	**63**	**38**	**40**	**64**	**36**	**11**	-	-	-	38	63	8
	Recruitment	29	71	7	-	-	-	-	-	-	-	-	-
	Nutrients	-	-	-	**50**	**50**	**8**	-	-	-	-	-	-
Pollution	Water clarity	22	78	9	-	-	-	-	-	-	-	-	-
	Oxygen	**100**	**0**	**41**	-	-	-	0	100	30	-	-	-
Fishing	Fishing effort, landings and catch	**50**	**50**	**42**	-	-	-	-	-	-	-	-	-

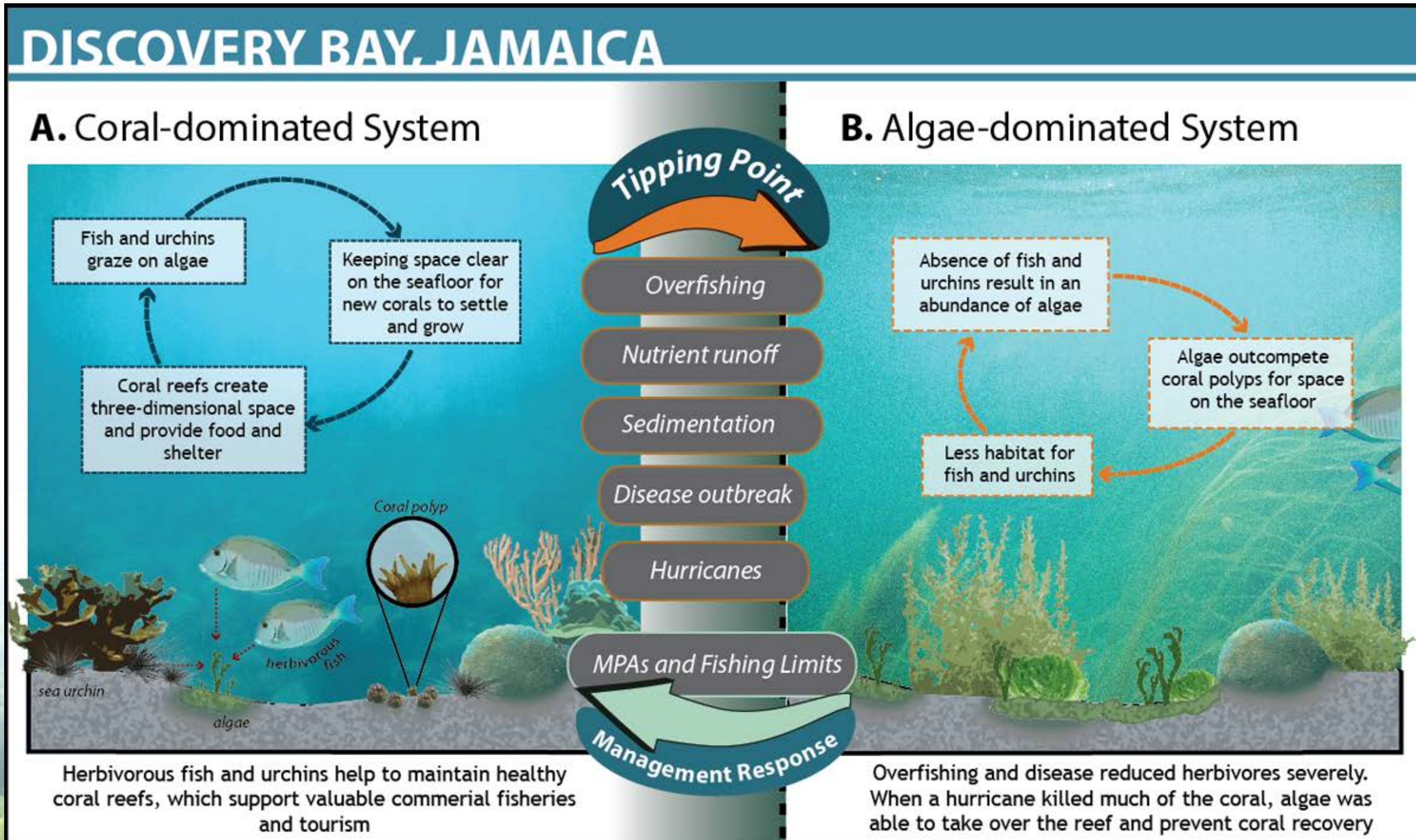
Threshold Management Works

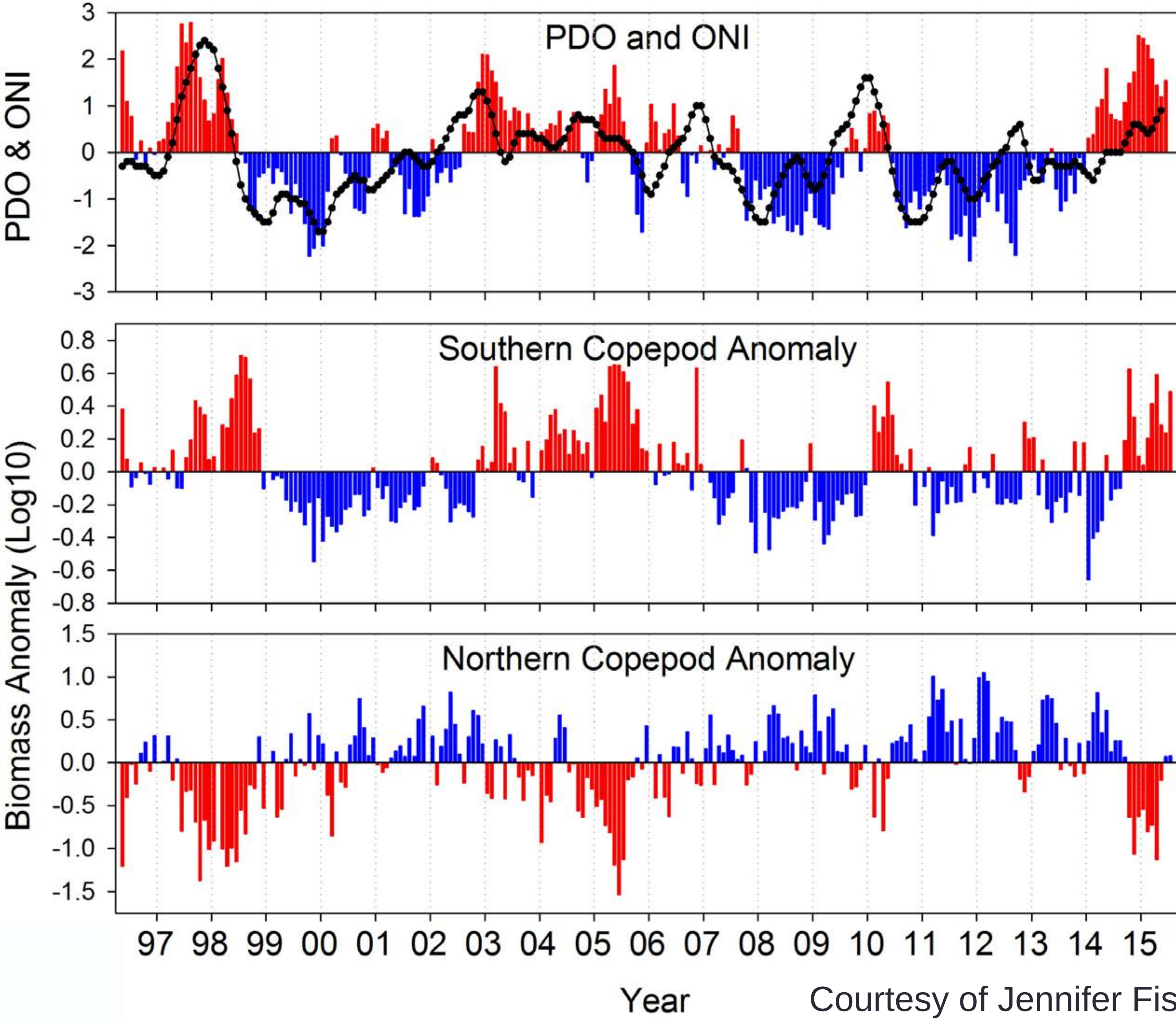
More explicit use of thresholds in management is strongly associated with better environmental outcomes.



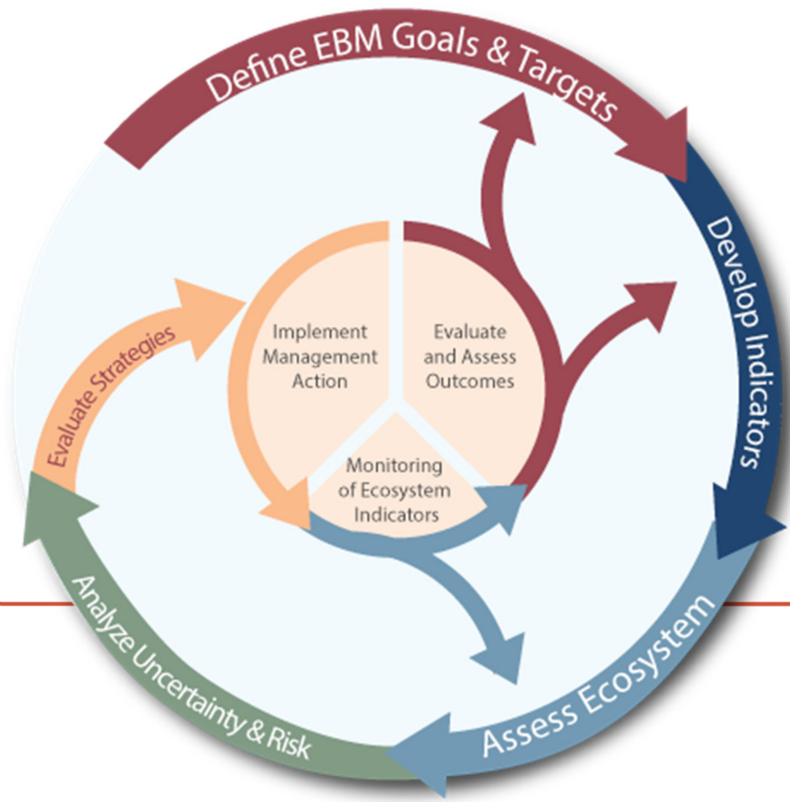
Kelly et al. 2014 Phil. Trans. Roy. Soc. B.

Changes in early warning indicators may precede tipping points





Courtesy of Jennifer Fisher

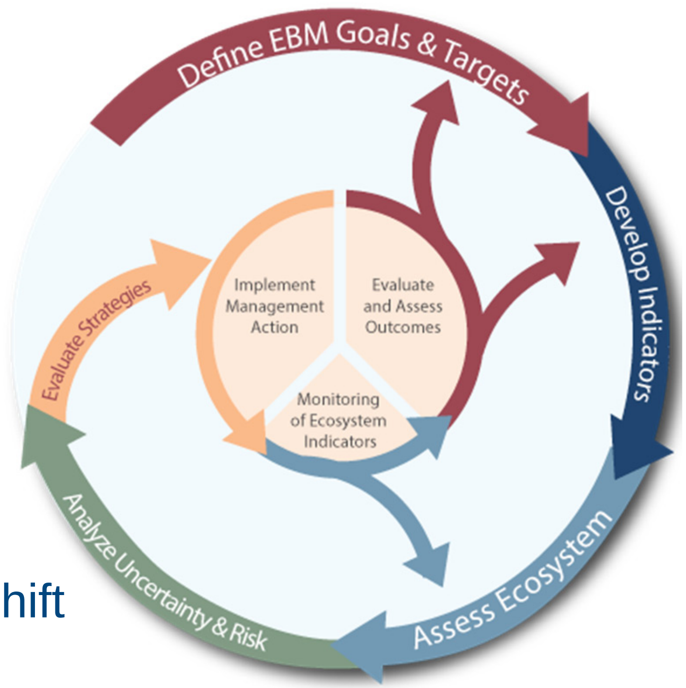


IEAs are intended to provide ‘*a synthesis and integration of information on relevant physical, chemical, ecological, and human processes in relation to specified management objectives* (Levin et al., 2008, 2009)’.

Linkage to Ecosystem-Based Management

Define desired ecosystem state

Scenarios of increasing (decreasing) resilience



Define thresholds of ecological indicators and identify early warning indicators

Probability of unwanted shift

Levin and Mollmann (2015)

Selkoe, Bleckner, Caldwell, Crowder, Erickson, Essington, Estes, Fujita, Halpern, **Hunsicker**, Kappel, Kelly, Kittinger, **Levin**, Lynham, Mach, Martone, Mease, Salomon, **Samhouri**, Scarborough**, Stier**, White, and Zedler. 2015. Principles for managing marine ecosystems prone to tipping points. Ecosystem Health and Sustainability 1(5):17.

Climate Tipping Points

- A common thread of the examples discussed was that fishery/ecosystem resource responses emerged from **multiple stressors** (e.g., increased temperature plus ocean acidification and human pressures) integrated by the resource of interest and the community in which they reside. This multi-stressor paradigm argues for:

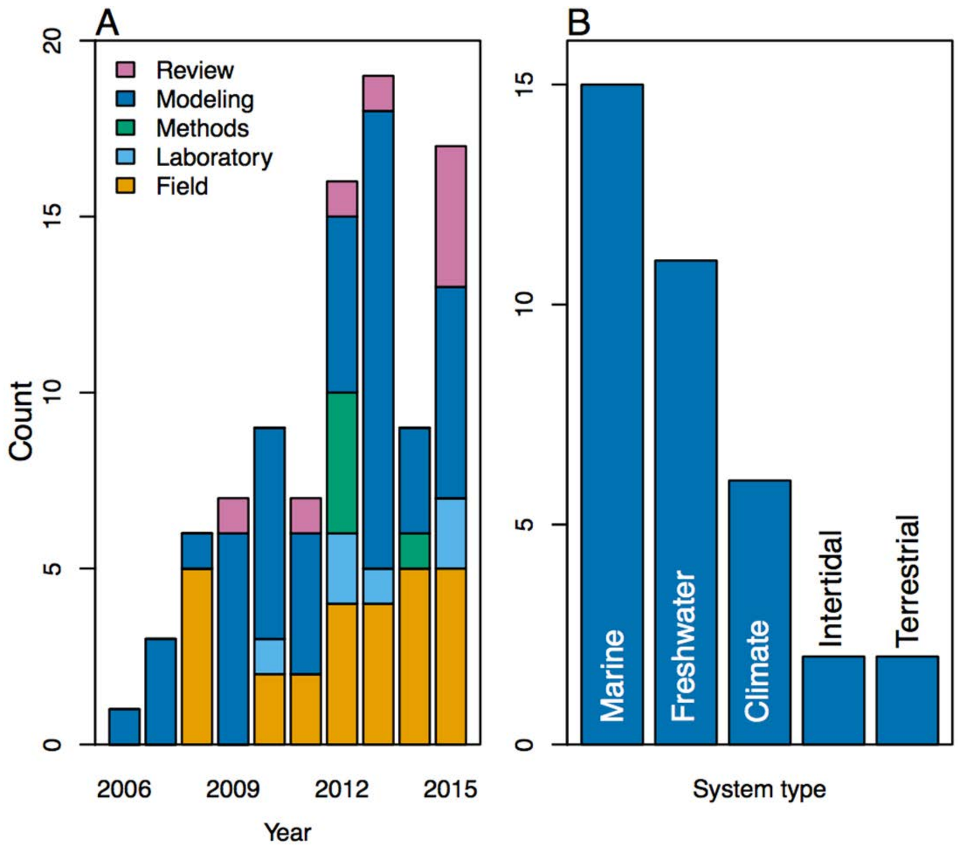
a) observational work to quantify multi-stressor responses, paired with

b) predictive understanding of how systems respond to changes in individual stressors within a multi-stressor environment.

c) quantitative models that to integrate this information to provide objective and reliable definitions of the resilience of clearly defined ecosystem services (e.g., catch, area of healthy reef), and develop predictive capacity.

- The resulting advances in scientific knowledge should be used to define “safe operating spaces” and adaptive management steps that ensure maintenance of the resource to the extent possible (see Figure below).

Outcome



- Analyses demonstrating nonlinearity in ecosystem dynamics are more likely to support theoretical EWS predications than studies with linear or undetermined dynamics

Litzow and Hunsicker *In Review*