The Ocean Tipping Points Guide

Science to Improve Management in a Changing Ocean

Ocean Tipping Points

Ocean Tipping Points Project. 2017. Ocean Tipping Points Guide: Science for Managing a Changing Ocean.

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The Ocean Tipping Points Project (www.oceantippingpoints.org) is a collaboration between University of California Santa Barbara and the National Center for Ecological Analysis and Synthesis, Stanford University's Center for Ocean Solutions, the National Ocean and Atmospheric Administration's Northwest Fisheries Science Center, Environmental Defense Fund, California Polytechnic State University, Stockholm Resilience Centre, the University of Hawai'i, Parks Canada, Fisheries and Oceans Canada, the Council of the Haida Nation, and the State of Hawaii, with primary funding from the Gordon and Betty Moore Foundation.

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To cite this report: Martone, Rebecca, Carrie Kappel, Courtney Scarborough, Ashley Erickson, and Kristen Weiss. 2017. Ocean Tipping Points Guide: Science for Managing a Changing Ocean. Stanford, California: The Woods Institute for the Environment, Stanford University, and the University of California Santa Barbara.

Purpose Of This Guide

The goal of this Guide is to improve your ability to detect and manage important tipping points in your ecosystem, helping you avoid unwanted surprises and prioritize effective management actions.

Crossing an ecosystem tipping point creates dramatic change. From collapsed fisheries and coastal dead zones, to melting sea ice and dying coral reefs, the consequences are often devastating to both the environment and the people who depend on it.

Tipping points are difficult to anticipate or detect. The initial change may be gradual but then rapidly accelerate as a tipping point is approached. Understanding how to predict and prevent the crossing of tipping points, or recover from ones already crossed, is critical to effectively managing natural resources in a changing world.

Researchers from the Ocean Tipping Points project have developed a set of valuable resources and analytical approaches to help practitioners and scientists better understand, predict, and manage these shifts. In this Guide, we provide four strategies for incorporating knowledge about ocean tipping points into your existing management decision-making. We have embedded this tipping points knowledge into a general adaptive management framework that is widely used in natural resource management.

"Management strategies that include monitoring ecosystem state and identifying measurable tipping points tend to be more effective in achieving management goals than strategies that do not consider potential tipping points."—Kelly et al. 2015

This Guide is not intended to be prescriptive, but rather to provide important concepts and approaches from tipping points science that can help support your existing resource management framework—whether you are embarking on a new ecosystem management process or you are looking to adapt and improve current monitoring or management for your system. We offer details, examples, and tools to support each of the four strategies and to help you think about how to implement this approach in your own system. You may work through the entire process, or pick and choose those concepts that are most useful to you.

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Characterize Tipping Points

Strategy 1. Identify Tipping Points in Your System

Strategy 1a.

Define tipping points of concern

What does this mean?

A tipping point is a point of rapid change from one set of conditions to another. In an ecosystem, a tipping point occurs when a small change in environmental or human pressures leads to a large change in components of a social-ecological system and the benefits they provide to people. When crossing these tipping points profoundly affects the entire ecosystem, we refer to them as regime shifts.

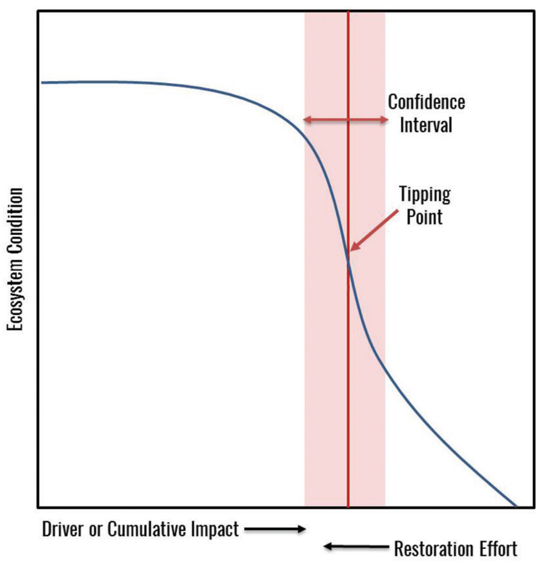


Figure 1, adapted from Selkoe et al. 2015. Relationship between driver level and ecosystem condition (blue curve). The tipping point (red line) represents the place of steepest change on the nonlinear curve, with a confidence interval (pink shading) on either side representing the zone of uncertainty around the exact location of the tipping point.

Tipping points occur in a wide variety of marine and coastal ecosystem types across the globe, as shown in the figure below. These ecosystem shifts can have large impacts on the social and economic systems that rely upon them.

"Identifying how and at what level activities and actions lead to ecosystem tipping points is highly relevant to choosing effective management targets and limits."
—Selkoe et al. 2015

Box 1. *The dynamic view*

Since the 1970s, ecologists have embraced the view that ecosystems are inherently unpredictable, dynamic and complex. Rather than marching through a predictable successional sequence (e.g., from grassland to primary forest to old growth) every time, very different biological communities can result from small differences in starting conditions. And those different communities, or "alternate states" of the ecosystem, can persist through time. Today, global climate change and other large-scale alterations to our environment are making ecosystems even more dynamic and unpredictable. As we enter uncharted territory, it may be impossible to anticipate future ecosystem states, but what we know about ecosystem dynamics suggests that nonlinear responses or tipping points should be expected. If change, and even abrupt change, is the rule, rather than the exception, how should management decision-making adapt?

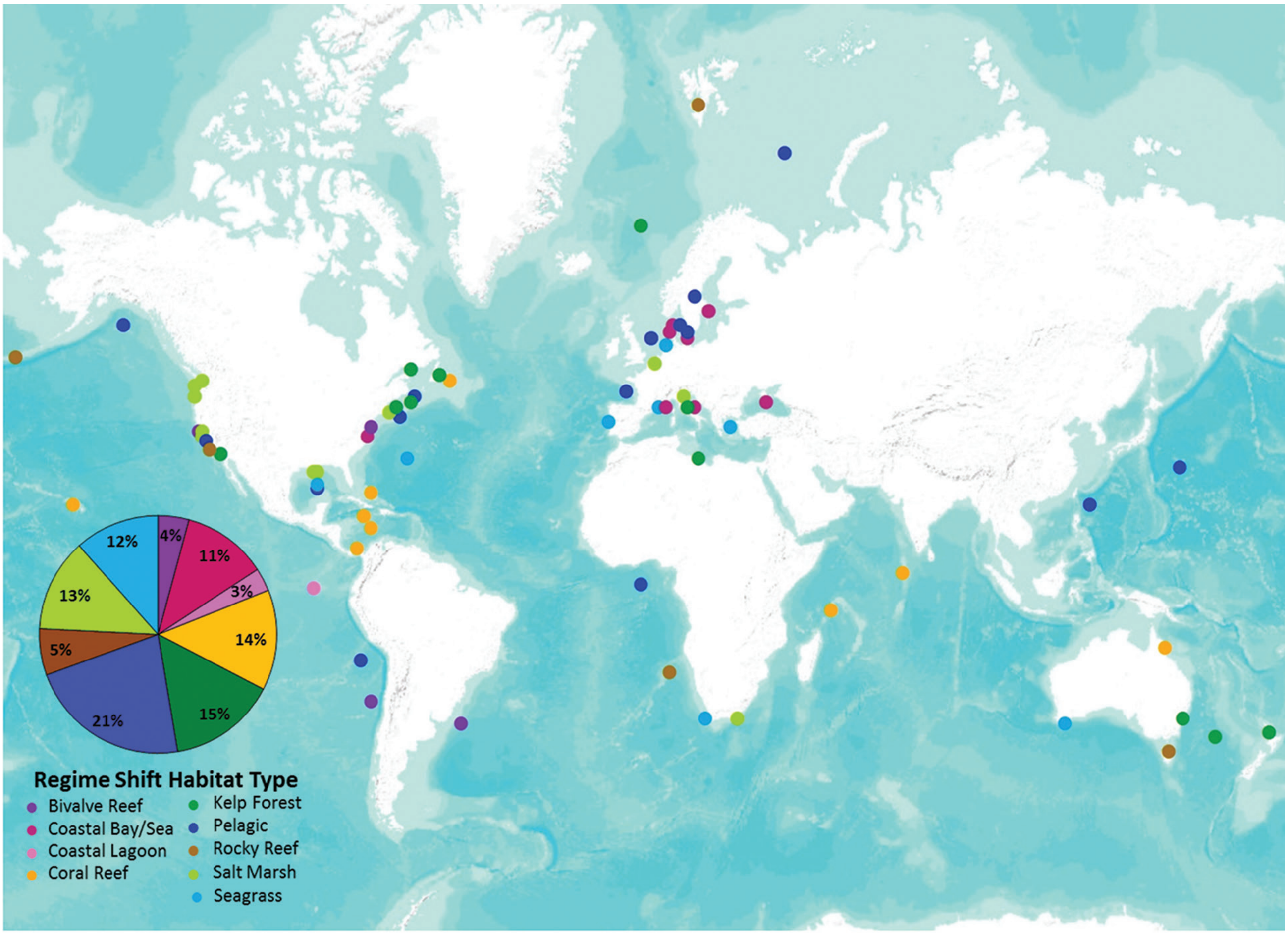
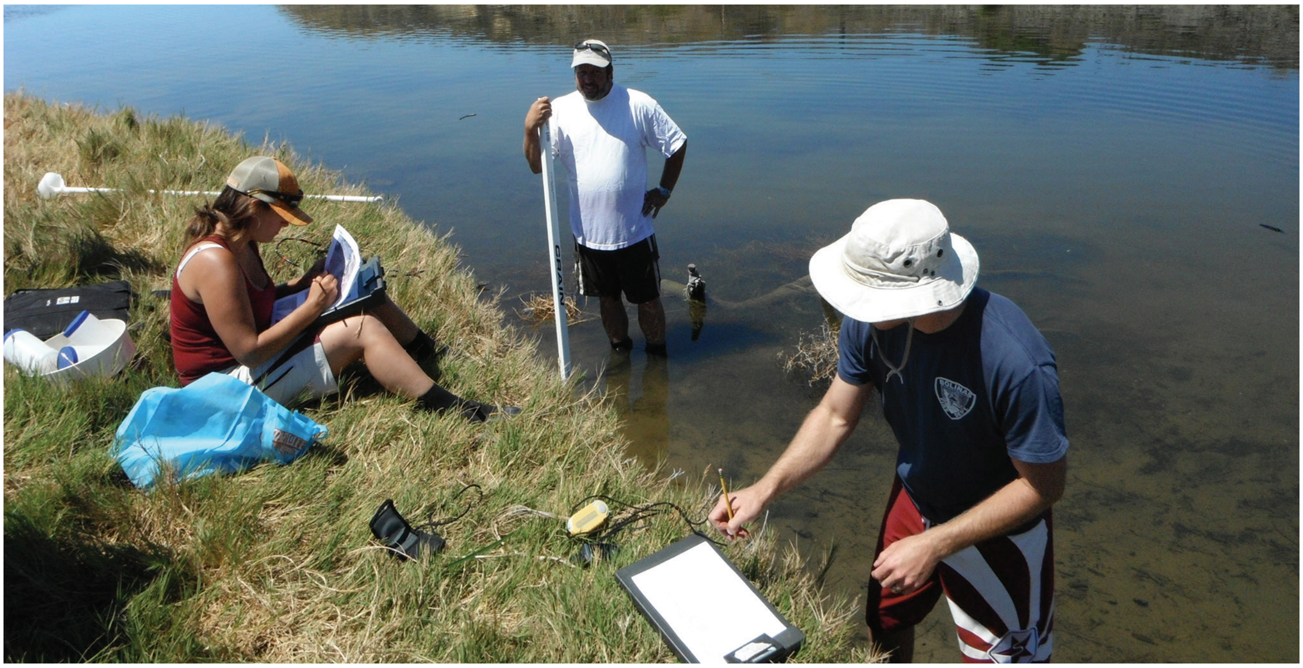


Figure 2, adapted from Kappel et al. in prep. Map of known marine and coastal ecosystem shifts around the world. Note that the higher frequency of regime shifts in temperate waters is probably a reflection of sampling effort as these areas have historically been better studied.

Social-ecological transitions may be difficult to reverse. When mounting stress disrupts the feedbacks that usually maintain a system in a given state, the system can cross a tipping point and rapidly reorganize into a new state with new feedback mechanisms that reinforce it. This can make it harder, or even impossible, to return to the previous state. For example, beginning in the late 1980s, fishermen in Maine took advantage of the boom in sea urchin populations that occurred with the collapse of cod. The aggressive overharvesting of green sea urchins from Maine's kelp forests resulted in massive declines of urchins along the coast. This overharvesting of sea urchins resulted in another tipping point for the system, shifting from an urchin-dominated patchy kelp forest, to one devoid of sea urchins and teeming with crabs and lobsters that now thrive in the newly established, dense kelp forests. Despite a variety of regulations, managers have not successfully halted or reversed the decline of green urchins. Although monitoring indicated sufficient settlement of sea urchin larvae, experiments have found that crabs have become the new apex predator, consuming sea urchins and their larvae before they can re-establish.

But not all tipping points are negative. In some cases, a tipping point may lead to rapid and dramatic improvements in ecosystem conditions, something that can be critical to understand when planning restoration activities.



Why is it important?

Scientists, managers, stakeholders, and policy-makers can benefit from considering possible tipping points, whether the context is restoration, fisheries, water quality, or ecosystem-based management.

Our recent review of 51 case studies with ecosystems prone to tipping points showed that, in a variety of settings, **management strategies that include monitoring ecosystem state and identifying measurable tipping points tend to be more effective in achieving management goals than strategies that do not consider potential tipping points** (Kelly et al. 2014).

Identifying and characterizing tipping points in your system can help you to avoid crossing unwanted tipping points and enhance your management effectiveness. Understanding tipping points in your management context can also help you recover and restore an ecosystem once a critical threshold has been crossed. If your system has already crossed a tipping point, getting to a more desirable state will depend upon knowing where the threshold for recovery lies and taking actions that increase your chance of restoring the system. By understanding the feedback mechanisms that maintain the system in the alternate state, managers can prioritize those actions: if you know which mechanisms are maintaining the system in a desirable state, you can take action to protect them; if you know which are keeping the system in an undesirable state, you can take action to disrupt them. For example, in salt marshes of the Eastern United States, cordgrass experienced widespread die-offs due to overfishing of crabs. Snails that would otherwise be kept in check by crabs were released from predation, leading to high grazing pressures on the cordgrass. This caused areas of exposed peat that could not support cordgrass growth. However, cordgrass was able to recover over time. The exposed banks

Box 2. *Tipping points and thresholds*

> A tipping point occurs when a small change in environmental or human pressures (or management actions) leads to a large response in the structure and function of the ecosystem. This nonlinear response is triggered when the system crosses a critical threshold. It's important to distinguish between such ecosystem thresholds and management thresholds (e.g., water quality standards), which may or may not be based on knowledge of an underlying nonlinear ecosystem response.

Figure 3, from Altieri et al. 2013 with permission. Stages of salt marsh recovery from die-off: (Top) overgrazed state with no cordgrass (Spartina alterniflora) within the active snail grazing zone; (Middle) initial colonization by cordgrass into the low zone where grazing and physical stress are lowest; (Bottom) cordgrass recovery spreads from the low zone upward, facilitated by group benefits.

eroded and peat transformed into mud. A new feedback mechanism allowed cordgrass to re-establish: initial colonization by cordgrass ameliorated physical stress, allowing further re-vegetation (Altieri et al. 2013). In this system and others, feedbacks between plants and substrate can play a critical role in rapid, reversible ecosystem shifts.

How do you do it?

Describing ecosystem shifts and characterizing past tipping points can be done both qualitatively and quantitatively. This can be done using data on temporal change (time-series data) or by using spatial data to determine the potential trajectory of systems. Which you use will depend on what data are available and relevant for the system in question. Below we review some of the more widely-used techniques and provide examples for further investigation.

Quantitative methods:

Advances in statistical techniques and computing power have made it easier than ever to identify nonlinear relationships in data and detect social or ecological thresholds (see Table 3 in section 1b for review of methods). The first set of methods are univariate correlational analyses, which can be used to fit non-linear relationships between drivers and ecosystem condition to identify how ecosystems change and the potential thresholds of change. Generalized additive models (GAMs) are the most common statistical method used to examine non-linear changes in ecological systems, using effective degrees of freedom, or smoothness of the function, as a measure of the strength of non-linearity. GAMs allow fitting non-linear functions to each predictor, making more accurate predictions for the response variable. The actual threshold or point of inflection can then be identified using second derivatives or change-point analysis (also known as STARS). The latter uses sequential t-tests on the mean or variance to detect significant changes in the slope of the relationship between a driver and an ecosystem response.

For example, Cury et al. (2011) used GAMs to establish numerical relationships between seabird breeding success and prey abundance and then applied change-point analysis to find the most likely point at which the slope of the relationship changed, i.e., the threshold level of prey abundance that resulted in a rapid change in breeding success (see Figure 2A in Cury et al. 2011 for example of GAM and change-point analysis results). Their analysis resulted in a rule of thumb they called "one-third for the birds," which provides a simple and quantitative target for managers to consider when evaluating forage fish abundance and determining allowable catch.

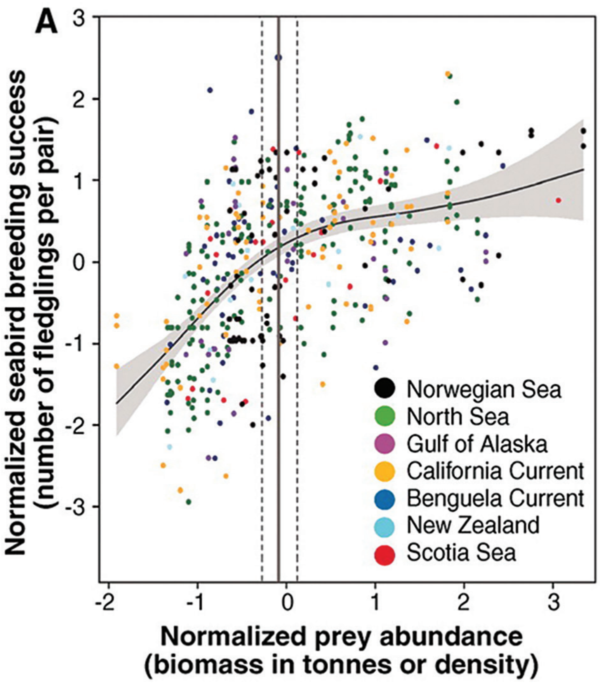


Figure 4, from Cury et al. 2011 with permission. Relationship between normalized annual breeding success of seabirds and normalized prey abundance. Each data point from all of the time series of seabird and prey species considered in the analysis was plotted with the predictions of a generalized additive model (GAM) (solid line). The gray area represents the 95% confidence interval of the fitted GAM. The threshold in the nonlinear relationship (black solid vertical line) and its 95% confidence interval (black dashed vertical lines) were detected from a change point analysis.

Multivariate methods such as cluster analysis, non-metric multidimensional scaling (nMDS), principal components analysis (PCA), and redundancy analysis (RDA) can also be used to identify ecological communities or regimes that are significantly different from one another. For example, in the Hawaiian archipelago, Jouffray and coauthors (2015) identified coral reef regimes using cluster analysis applied to spatial data on benthic communities (Figure 5, reprinted from Jouffray et al. 2015).

The quantitative approaches described above and links to examples, publications, code and resources are given at the end of Strategy 1b.

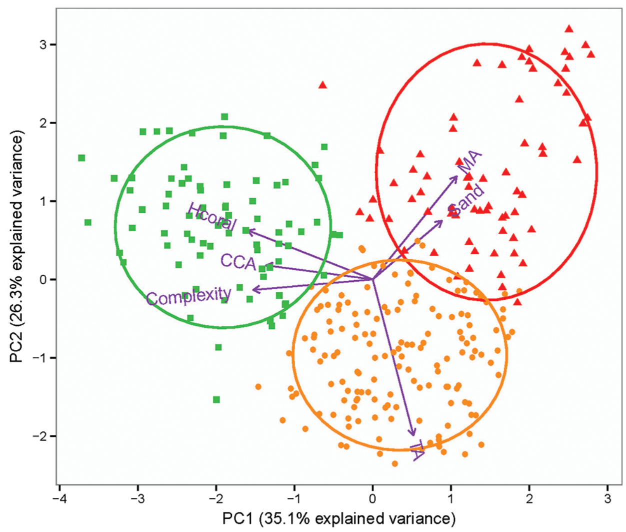


Figure 5, from Jouffray et al. 2015 with permission. Principal components analysis shows the existence of three distinct clusters of benthic reef communities in Hawaii: green = coral-dominated, red = macroalgae-dominated, orange = turf algae dominated. Each point represents benthic community data from an individual sampling location. Overlaid purple vectors represent the functional groups and habitat characteristics (e.g. complexity) that distinguish the different groups: Hcoral = hard corals, CCA = crustose coralline algae, complexity = habitat rugosity or roughness, TA = turf algae, MA = macroalgae, and sand.

Qualitative methods:

In many systems, quantitative time series are not available to help identify key drivers and describing tipping points. However, traditional and local knowledge can provide a historical perspective to help reconstruct ecosystem changes. For example, Salomon and coauthors (2007) examined the decline of a nearshore benthic invertebrate, the black leather chiton (*Katharina tunicata*, known locally as Bidarkis), on the rocky shores of the outer Kenai Peninsula, Alaska, USA. This grazing intertidal mollusk has strong top-down effects on seaweeds in the rocky intertidal, and is the basis for a culturally important subsistence fishery for Sugpiaq natives. Using multiple approaches, the authors describe the decline of *Katharina* and determine the causes. First, they used field surveys to examine the significant predictors of *Katharina* biomass across 11 sites varying in harvest pressure.

In addition, they analyzed archaeological faunal remains, historical records, traditional ecological knowledge, and contemporary subsistence landings to examine changes

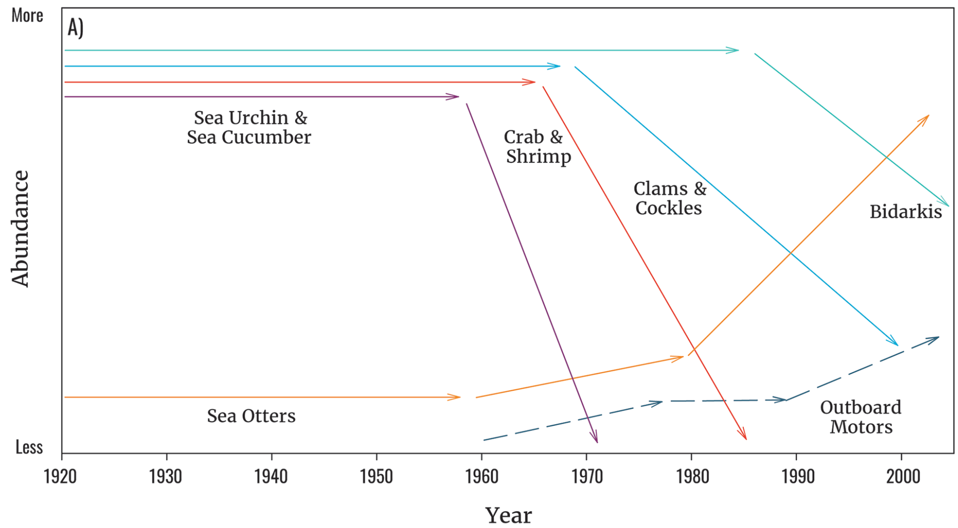


Figure 6, from Salomon et al. 2007 with permission. Declines in abundance of important harvested species on the outer Kenai Peninsula, AK associated with increases in harvesting efficiency with the propagation of outboard motors and sea otter abundance through time.

Table 1, *from Salomon et al. 2007 with permission. Timeline of major socio-ecological events in the history of the outer Kenai Peninsula, AK and quotes from traditional knowledge surveys.*

Time	Event	Traditional ecological knowledge—observation
1800s–1960s	sea otter extirpation	"When the Russians came they cleaned the sea otters out. When I was 18 yrs old [1953] there were no sea otters around Port Graham."
1930s–1950s	"high invertebrate densities and low kelp biomass"	"We used to be able to get all the Dungeness we wanted. We used to collect clams and cockles, nobody ever missed a tide. I didn't have concept of poor or rich in a western world sense. We were so rich because there was so much out there." "The sea back then was a dinner table set at low tides." "There was not much kelp in front of Nanwalek when I was young."
1960s	sea otter recovery	"They came back in the early 60s. The population exploded in the late 70's early 80's." "Boy, those things multiply!"
1960s	invertebrate decline begins	"We used to see sea urchins all over Nanwalek Reef in the early 1940s. By the late 60s sea urchins were mostly gone."
1964	Great Alaska earthquake	"After the earthquake, there was sunk land and no minus tides for about four years. After that it came back to normal." "The earthquake damaged the clam beds. This quake did not take the bidarkis, snails, and other invertebrates. If it did, they came back."
1970s	"increased harvest effort with increased storage abilities"	"In the past we picked just enough to eat and snack on. But when electricity and then freezers came to the village, people began to pick more because they could store them."
1980s	commercial crustacean crash	"[Dungeness] were wiped out because of commercial crab fisheries and dragging. They came right into this bay. Now they haven't been able to come back because of the sea otters."
1989	Exxon Valdez oil spill	"The oil spill impacted nature's cycles, the seasonal clock work of our culture, our life ways ... It had lingering effects, not only in our water but in our lives." "Clams and cockles and Dungeness crab were declining before the oil spill. The oil spill may have made it worse but they were already declining before the spill."
1989	increased harvest efficiency	"People locally were hired to help clean up the spill. Then there was more money that came to the village. More money let more people own more boats and bigger boats with better outboards. Many people could now go to places that they couldn't go to in the past."
1990s	"change in bidarki numbers and size"	"I started noticing bidarki declines 10–15 years ago." "It's harder to find the big ones now."
1990s–2000s	compensatory growth	"There are more little ones but they are not big enough to pick. I used to not see so many little ones."
1990s–2000s	serial decline	"The urchins were the first to go, then crab, then the clams. Bidarkis, they're the most recent change."

in harvest and *Katharina* biomass over time. Traditional knowledge surveys with Sugpiaq elders and village residents highlighted temporal changes in the relative abundance of invertebrate resources, changes in subsistence use, and sea otter presence from the 1920s to 2003. These data revealed that several benthic marine invertebrates (sea urchin, crab, clams, and cockles) declined serially beginning in the 1960s, co-occurring with recovery of the local sea otter population and increased shoreline harvest efficiency (Figure 6, Table 1, reprinted from Salomon et al. 2007). This work demonstrates the strength of integrating Traditional Ecological Knowledge to reconstruct ecological history and document ecosystem shifts.

Don't have any data?

If no time-series data are available for the ecosystem in question, or if the historical perspective does not reveal any prior tipping points, it may be useful to look at similar systems in other regions of the world and ask whether tipping points have occurred there and why. The past is not always the best guide to the future in a changing world. Maybe no record of regime shift exists because the drivers of change have been less intense in this region than others. Or perhaps the last big regime shift occurred before living memory. Drawing lessons by analogy to other regions may help you assess the potential risks in the face of data gaps and an uncertain future environment.

For example, while many Pacific reefs are still covered in lush corals and coralline algae, some Pacific reefs and the majority of reefs in the Caribbean have experienced dramatic declines in corals and a phase shift to seaweeds and sponges, driven by a combination of overfishing, land-based runoff, and disease. Managers in other parts of the world are increasingly concerned that amplifying stresses on reefs will lead to similar ecosystem shifts, a pattern that is already starting to emerge.

The Ocean Tipping Points team has assembled a database of tipping points in coastal and marine systems from around the world. By investigating this database along with other literature from similar systems you may gain insights into tipping points that could be crossed in your own system and ways scientists and managers have worked to avoid or recover from them (Kappel et al. in prep).

Table 2. *Historical regime shifts by habitat, including the region where the shift occurred and top drivers of these shifts.*

Habitat	Regions	Shift type	Top drivers
Open ocean systems	Atlantic Pacific Arctic Southern Oceans	Fisheries collapses Productivity shifts Hypoxia Dominant species declines	Climate Overharvest Nutrient addition
Coastal bays, seas, fjords	Baltic Sea Black Sea Mediterranean Sea Chesapeake Bay	Fisheries collapses Productivity shifts; Hypoxia Dominant species declines	Climate Overharvest Nutrient addition Invasive species Disease
Salt marshes	North America Europe South Africa	Marsh to tidal flat Native vegetation to invasive *Spartina sp.* monoculture	Climate Invasive species Species interactions Physical factors
Seagrass beds	North America Europe, Africa Australia	Seagrass to algal dominance Seagrass to barren sediment Seagrass to invertebrate dominance	Nutrient addition Climate Overharvest Species interactions Physical factors
Coral reefs	Caribbean Indian Pacific Oceans	Loss of coral dominance	Climate Nutrient addition Overharvest Disease
Kelp forests	North America Europe Australia	Kelp forest <-> urchin barren	Overharvest Disease Restoration Climate Physical factors

Strategy 1b.
Link ecosystem change to key drivers

What does this mean?

Once you have identified the possible tipping points in your system, you will want to determine what factors move the system toward a tipping point. We refer to both the environmental conditions and human activities that can change an ecosystem state as drivers. Effectively managing around these tipping points requires an understanding of the factors driving these changes.

Note: Some texts use terms such as "stressor" or "pressure" in place of "driver," but this Guide uses "driver," as this term most broadly captures both natural and anthropogenic factors.

Most studies of the relationships between drivers and ecosystem status focus on individual drivers, and perhaps as a result, many policies and regulations also focus on the management of single drivers (e.g., fishing, pollution). However, individual drivers may interact to yield surprising results, and it is often the interaction among two or more drivers that leads to a dramatic ecosystem level shift. While scientists are far from being able to predict the outcome of all possible combinations of environmental drivers on marine ecosystems, we do know that the more different drivers are combined, the more likely it is that their combined effect is more than the sum of their individual effects (Crain et al. 2008). And most areas of the ocean are subject to multiple drivers (Halpern et al. 2008). For these reasons, it's important to be alert to cumulative impacts and to test for the effects of multiple drivers simultaneously whenever possible.

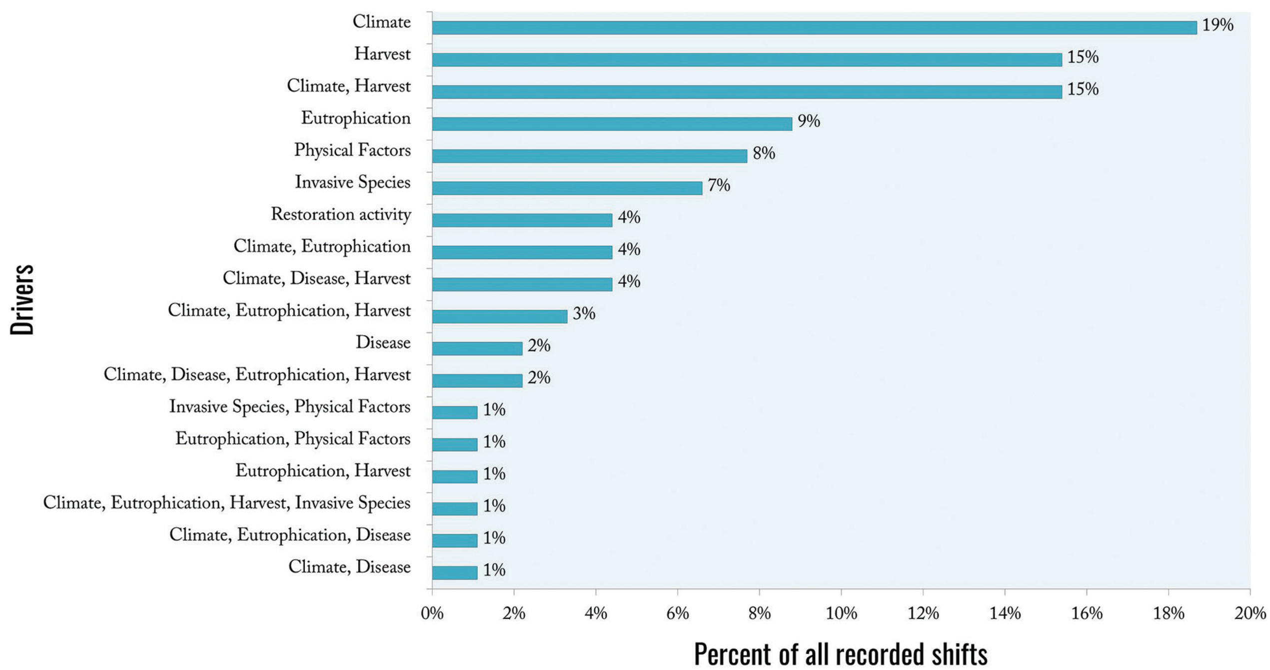
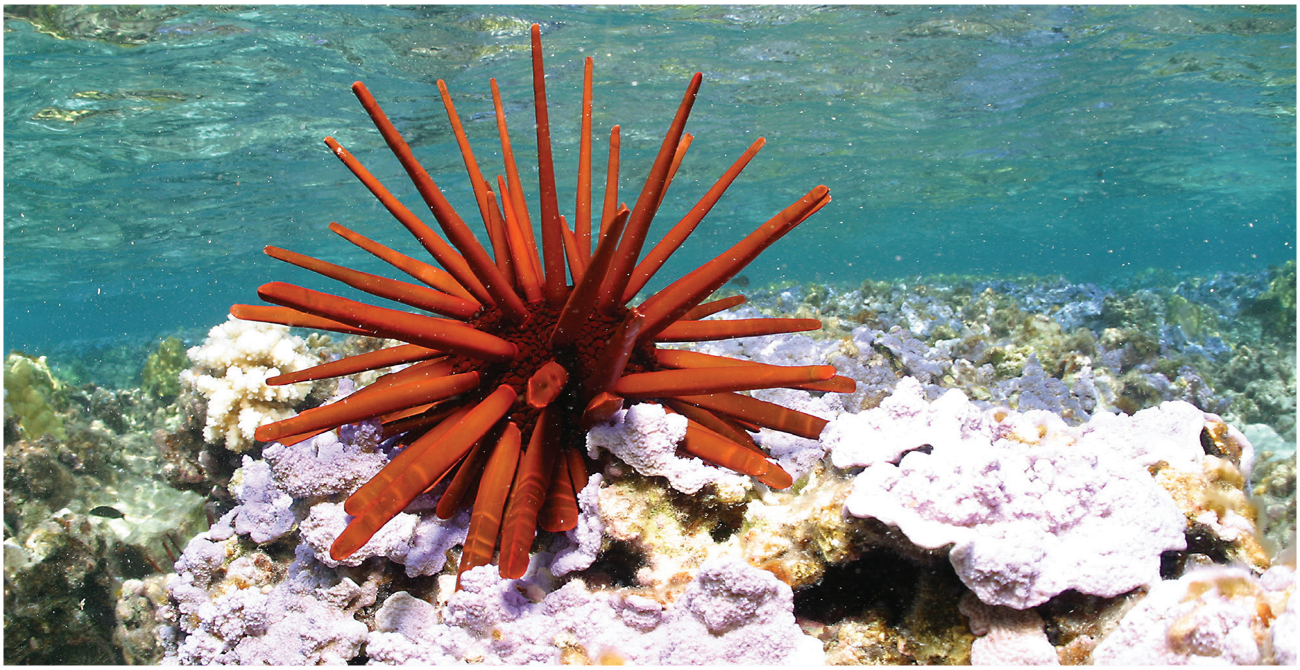


Figure 7. Major drivers and combinations of drivers reported to contribute to observed marine regime shifts around the world based on Kappel et al.'s review. Note that these results may be biased toward attributing regime shifts to a single driver, as studies of multiple drivers are limited.



Why is it important?

Identifying the key drivers that can lead (or have led) to a tipping point in your ecosystem is essential to planning a management response. By defining and prioritizing the key drivers acting on the system that are within your management control, you can more clearly define your management objectives and narrow your options for management response.

Quantifying relationships between drivers and ecosystem responses can help you identify where potential thresholds or tipping points may occur and refine your monitoring plans and targets. In some cases, this may reduce costs and effort; for example, if the relationship between drivers and a tipping point is known, monitoring should be intensified when the system appears close to a tipping point, but could be reduced when far from the tipping point (Stier et al. submitted). ***Thresholds*** can inform target setting for management by providing concrete information about system limits, helping to simplify debate about how much human activity is acceptable (Samhouri et al 2012) and move such debates toward a more objective basis. For example, in the Caribbean, Ocean Tipping Points colleagues (Karr et al. 2015) have shown that a suite of coral reef ecosystem changes is associated with fish densities below 30% of unfished levels: the ratio of macroalgae to coral is higher, the proportion of herbivorous fish in the fish community is lower, and coral cover is much lower, suggesting that a tipping point has been crossed. Similar results were obtained in a study of Indian Ocean coral reefs (McClanahan et al. 2011). Knowing the driver levels at which such dramatic changes are likely to occur can inform management target setting. Management targets should be informed by these thresholds, as well as influenced by people's social preferences and how much risk a society is willing to take in their management decision-making. These are discussed in more detail later in this Guide, see strategy 3b, "Use social preferences, risk tolerance and social and ecological thresholds to inform target-setting" for more information.

How do you do it?

As with identifying whether there is a tipping point of concern in your system (Strategy 1a), both qualitative and quantitative methods can be applied to identify potential drivers of change.

Quantitative Methods

Many of the same statistical techniques that can help you identify tipping points in your system can also be employed to further help you identify the major drivers of these ecosystem changes. Generalized additive models (GAMs) can be used to fit non-linear relationships between drivers and ecosystem condition to identify key drivers of change and potential management levers.

Multivariate statistical tests such as principal components analysis (PCA) and redundancy analysis (RDA) also can be used to examine relationships between drivers and ecological responses. As described in section 1a, these techniques are also useful for identifying regime shifts, and, in combination with change point approaches, determining thresholds in multivariate datasets.

For example, scientists have identified regime shifts in the Central Baltic by applying PCA to environmental time-series data to determine key periods of ecosystem change, followed by STARS to identify the threshold (Möllmann et al., 2009; Tomczak et al., 2013). The analysis identified key drivers of change in the food web, which included a shift in the North Atlantic Oscillation (NAO) that altered thermal, salinity, and nutrient regimes, along with overfishing. The combination of climate- and human-induced drivers on the Baltic Sea ecosystem resulted in new species interactions that led to feedbacks that prevented the recovery of cod, even after hydrological conditions were favorable for cod larvae.

Other multivariate methods like **boosted regression trees** are also being used to identify direct and indirect effects of drivers on ecosystem components (Elith et al., 2008; Jouffray et al., 2015). While these approaches can be used to identify drivers and quantify thresholds, one disadvantage is that they are correlative and so they are not able to tell you about directionality (e.g., fishing effort could both influence and be influenced by ecosystem condition).

Redundancy analysis is another multivariate approach that can examine non-linear relationships between drivers and ecological responses (Makarenkov and Legendre, 2002; Borcard et al., 2011). Perry and Masson (2013) used RDA to analyze regime shifts in the Salish Sea. They identified a set of six explanatory variables (Chinook salmon hatchery releases, recreational fishing effort, human population size, sea surface temperature, wind, and the North Pacific Gyre Oscillation index) as good predictors of regime shifts. One limitation, however, is that RDA cannot address temporal correlation in datasets.

There are additional multivariate approaches that are better suited to detect patterns in time-series data. For example, **dynamic factor analysis (DFA)** is a dimension-reduction technique that can be used to examine relationships between response and explanatory variables (Zuur et al., 2003). Scientists have applied DFA to compare trends across ecosystems (Link et al., 2009) and to identify the major drivers of ecosystem changes, such as relationships between warmer sea surface temperatures and higher salmon abundance in the Gulf of Alaska and eastern Bering Sea (Stachura et al., 2013).

Multivariate autoregressive state-space models (MARSS) can be used to examine how non-linear responses in ecosystems are related to biotic processes and changes in external drivers across space and time (Hampton and Schindler, 2006). The strength of MARSS models is that they can focus attention on key drivers of community change and quantify interaction strengths among drivers.

Choosing among these models will depend on the question of interest, the data type, and model assumptions. We describe the strengths, weaknesses, and additional examples of application in the table below. These methods are explored in more detail in Foley et al. (2015).

Table 3. *Summary of quantitative analyses for identifying tipping points of concern and the drivers of change (adapted with permission from Foley et al. 2015)*

Generalized additive model (GAM)	
Output	- Identifies shape and strength of non-linear relationships between ecological condition and ecosystem driver(s)
Strengths	- Identifies key drivers - Flexible in its ability to fit any shape relationship
Weaknesses	- Correlative - No directionality of relationships - Computationally complex - May overestimate degree of nonlinearity if overfitting is not controlled
More information & examples	Hastie and Tibshirani (1990), Guisan et al. (2002)
Software & code examples	gam package for R
Change point analysis (e.g., Sequential t-test on the mean, STARS)	
Output	- Identifies point of inflection in relationship between ecological condition and ecosystem driver(s), i.e. the threshold
Strengths	- Identifies location of the threshold or regime shift and corresponding driver/pressure level - Identifies leading and lagging indicators
Weaknesses	- Correlative - No directionality of relationships - Does not explicitly take autocorrelation into account
More information & examples	Rodionov (2006), Cury et al. (2011), Matteson and James (2014), Karr et al. (2015)
Software & code examples	VBA for Excel at www.BeringClimate.noaa.gov and strucchange, changepoint, cpm, bcp packages for R
Redundancy analysis (RDA)	
Output	- Identifies non-linear relationships between ecological condition and ecosystem driver(s) - Determines likelihood of regime shift
Strengths	- Accommodates multivariate datasets - Identifies regime shifts
Weaknesses	- Correlative - No directionality of relationships
More information & examples	Makarenkov and Legendre (2002), Borcard et al. (2011)
Software & code examples	rda function in vegan: community ecology R package

Principal components analysis (PCA)	
Output	- Identifies key periods of ecosystem change and associated driver(s)
Strengths	- Accommodates multivariate datasets - Facilitates linking time of ecosystem change to driver number and level - Does not require a priori hypothesis of regime shift year(s)
Weaknesses	- Correlative - No directionality of relationships - No statistical significance of relationships
More information & examples	Hare and Mantua (2000), Möllmann et al. (2009), Tomczak et al. (2013)
Software & code examples	princomp and prcomp in the R Stats package
Boosted regression trees	
Output	Identifies potentially significant direct and indirect effects of drivers on ecosystem components
Strengths	- Identifies indirect effects - Facilitates experimental and observational studies of ecosystem effects
Weaknesses	- Correlative - No directionality of relationships
More information & examples	De'Ath (2007), Elith et al. (2008)
Software & code examples	gbm R package

Qualitative methods

Literature review:

Building off of other available work can also be a good place to start identifying potential drivers when long-term or spatially robust data are unavailable. The Ocean Tipping Points project's ecosystem shifts database documented 91 regime shifts across all major ocean basins, and nine different marine ecosystem types from the coastal zone to the open ocean (Figure 8, Kappel et al. in prep). We also identified the major drivers of these shifts. The most commonly cited drivers include climate change, eutrophication, and changes in harvest rates. By looking at similar ecosystems you may be able to draw preliminary conclusions about potential drivers of concern for your own system.

Expert knowledge:

Conceptual models provide a framework for understanding ecosystems holistically. Conceptual models represent ecological and/or social components and how they link to one-another, often with a focus on food web relationships. These models may also depict biophysical conditions and potential external drivers (e.g., nutrient input or shifting ocean temperatures) that are most likely to influence or alter those relationships. The information used to build conceptual models can be gathered via literature review and/or through local and expert knowledge.

For example, in Haida Gwaii, British Columbia, Stier and coauthors (2016) elicited experts' conceptual models of the herring-centric food web from a set of experts (Figure 9, adapted from Stier et al. 2016). These models were then used in network analysis to explore potential implications of various environmental drivers and management decisions.

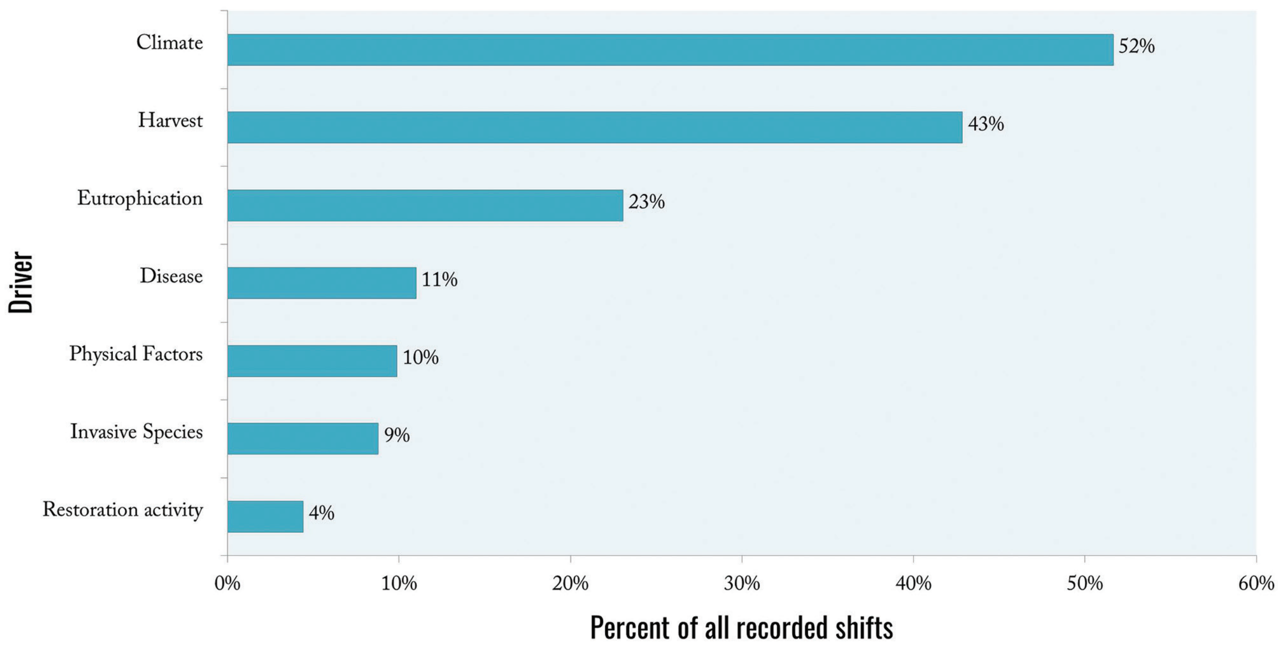


Figure 8, adapted from Kappel et al. unpublished data. Top drivers of 91 marine ecosystem regime shifts from around the world.

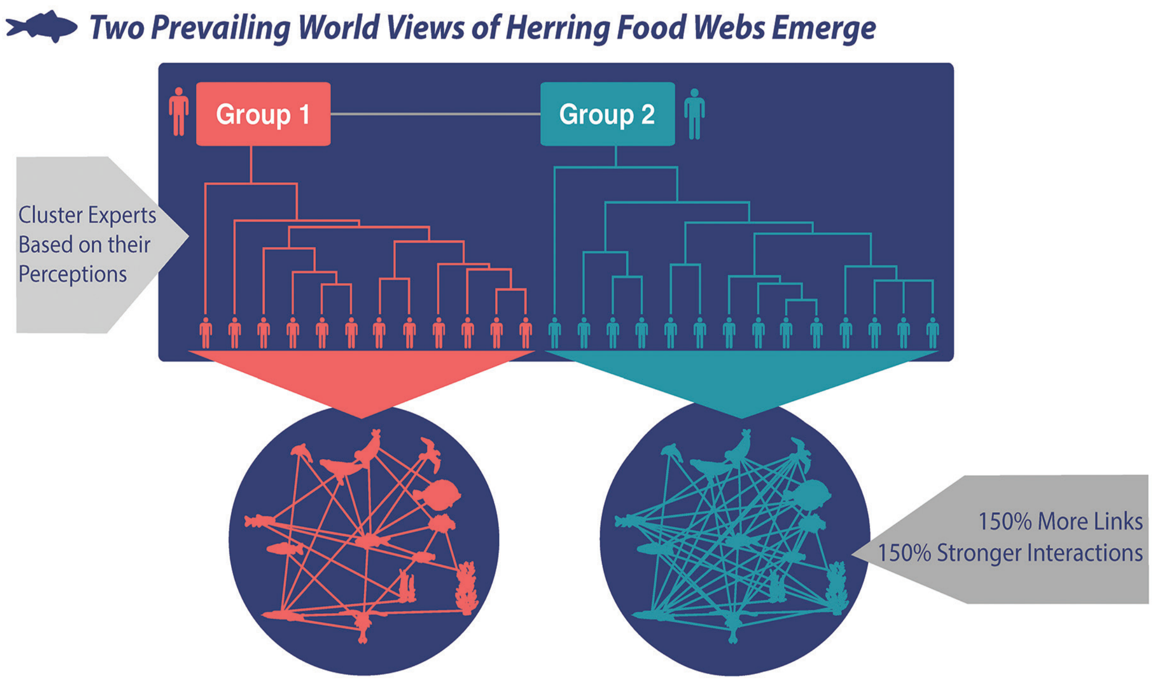


Figure 9, adapted from Stier et al. 2016 with permission. Experts clustered into two groups based on their view of the Haida Gwaii foodweb with herring at its center. Group 1 saw the food web as simpler, with fewer, less strong connections. Group 2 viewed the food web as more complex, with more and stronger linkages among species. Neither demographics, professional affiliation, nor years of experience explained these differences.

Similar to conceptual models, many management agencies are using influence diagrams such as Pathways of Effects approaches to identify potential drivers or combinations of drivers that might influence the system of interest. These influence diagrams are conceptual tools that illustrate the potential cause-and-effect relationships among socio-economic, cultural, and ecological dimensions of a system or problem. Such influence diagrams can be constructed with stakeholder input. This is an important step for characterizing what matters to different groups and how such things might be affected directly or indirectly by management decisions (Chan et al. 2012). Constructing these diagrams with local knowledge holders can help identify differences in perception within the community that can be further explored or addressed. For example, if the differences in perception are based on a lack of awareness of scientific information, improved education and outreach can foster shared understanding. Alternatively, such differences can point to areas of critical scientific uncertainty for further research. In addition, divergent stakeholder views or risk tolerances can be included explicitly in decision-making processes (e.g., by illustrating tradeoffs in what different people care most about). Working with stakeholders to construct an influence diagram or system map can be an effective way to draw on local knowledge, empower participants, and generate common understandings of the system so as to reduce conflict and enhance communication.

Quantitative, semi-quantitative and qualitative methods can then be applied to these linkage diagrams to further explore consequences of decisions. Examples include structural equation modeling (SEM), Bayesian belief network analysis, loop analysis, and fuzzy cognitive models. For example, Martone and colleagues (2017) developed a simplified diagram of the social-ecological connections in small-scale fisheries of Baja California, Mexico (Figure 10, from Martone et al. 2017). Using qualitative loop analysis, the authors identified potential social and ecological consequences of natural perturbations and management decisions on a coastal fishery, and identified which drivers and pathways may have greater influence on the outcomes, highlighting potentially important relationships to examine in future research and analysis.

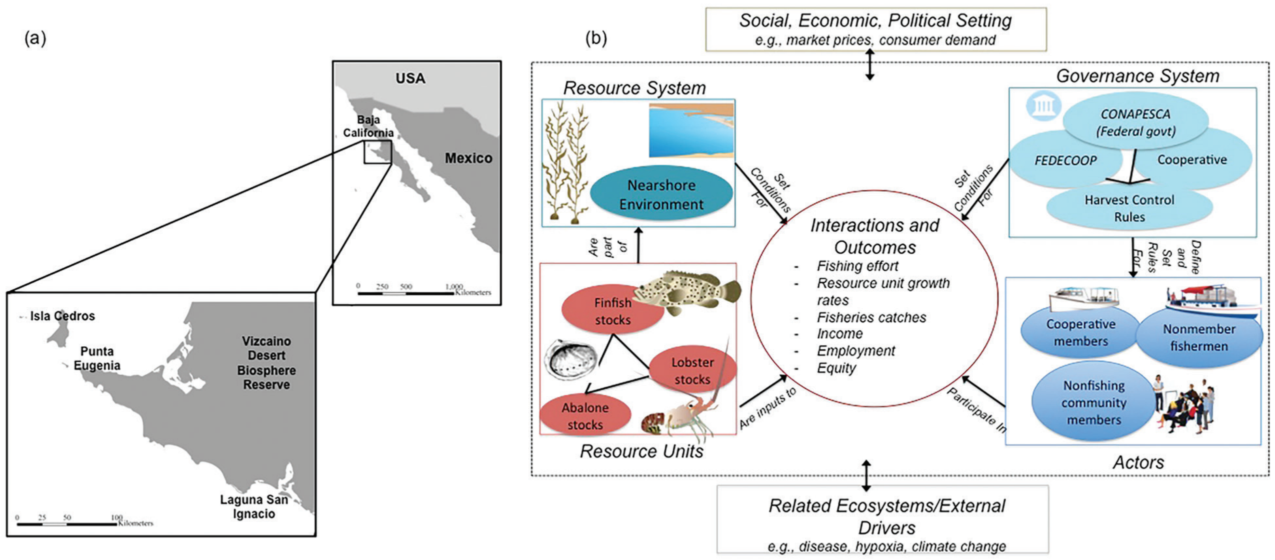


Figure 10, from Martone et al. 2017 with permission. The fishing cooperatives of the Vizcaino region in Baja California Sur, Mexico: (a) map of the study area showing location along the coastline from Punta Eugenia to Laguna San Ignacio; (b) conceptual representation of the social-ecological system (SES) based on the updated SES.

Define
Management
Objectives

Strategy 2. Define Management Objectives in Relation to Ecosystem State

"Defining thresholds and setting precautionary buffers can be viewed as setting the boundaries of a system's 'safe operating space,' in which risk of an unwanted regime shift is low and resilience is high"—Selkoe et al. 2015

Background

Integrating tipping points science into management objectives will help focus and prioritize management actions and inform the design of monitoring systems. A tipping point perspective can be integrated into management objectives from the outset by stipulating that the system needs to stay within a certain range of conditions associated with the desired ecosystem state(s).

There is no one prescription managers must follow to appropriately define their management objectives in a system prone to tipping points. Rather, setting management objectives using a "tipping points lens" entails being aware of the possible regimes, the drivers of those regimes (see Strategy 1), the social preferences that people have for those regimes in their system, and risk tolerance. Because ecological regime shifts are often accompanied by shifts in the ecosystem benefits provided to people, understanding different stakeholders' preferences for alternative ecosystem states and how tolerant people are of risk is central to setting environmental management objectives and responding to potential regime shifts.

Strategy 2a.

Characterize social preferences for ecosystem states

What does this mean?

When people rely heavily on their ecosystem for their well-being, a shift in ecosystem state can mean a shift in the benefits provided to people and, often, who receives them.

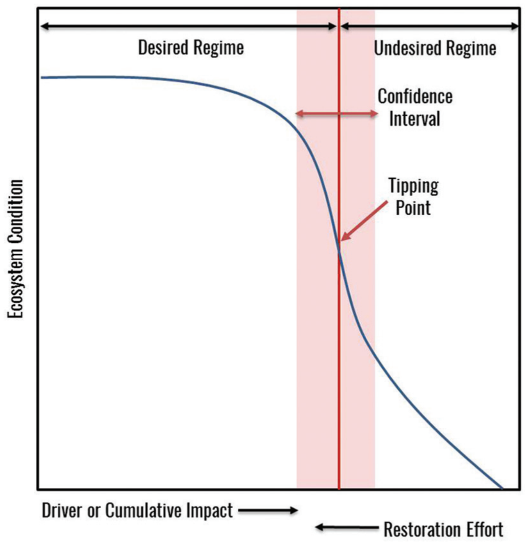


Figure 11, adapted from Selkoe et al. 2015 with permission. In this hypothetical scenario, the area to the left of the tipping point is the desired ecosystem state and right of the tipping point is an undesirable regime, into which the ecosystem may "tip" if driver levels exceed the threshold level.

Sometimes, there will be consensus among all groups about what the preferred ecosystem state is. In other cases, there will be tradeoffs among the preferences of different groups (e.g., conservationists may want to see otters reintroduced and kelp forests restored, while urchin fishermen may oppose reintroduction of otters, which are voracious urchin predators). Ecosystem shifts can lead to some groups benefiting, while others lose out. Revealing the range of views people have for the most preferred state of their ecosystem and who wins and who loses in the case of a regime shift can expose potential sources of conflict as well as opportunities to build consensus.

For example, historic over-hunting of sea otters for their fur caused localized extinctions of the species throughout its range. The loss of sea otters marks a tipping point for kelp forest habitat by removing the top predator, leading to immense growth in sea urchin populations. High urchin numbers lead to increased grazing pressure on kelp, causing a dramatic shift from a kelp dominated ecosystem to a barren rock and sediment dominated one. When such tipping points occur, the distribution of ecosystem benefits to humans can shift considerably. Kelp habitats support important commercial fish species and attract diving and snorkeling tourism, and sea otters are valued for wildlife viewing and can increase tourism revenues (Martone et al. in prep). However, in the absence of otters, fishermen that target sea urchins often gain substantial benefits as catches increase. Here the social system has shown that it can adapt to an ecosystem shift, and while conservationists and recreationists may prefer the kelp dominated system, urchin fishermen strongly prefer the urchin dominated one, making the overall socially desired state of the ecosystem less obvious. Furthermore, there are many benefits that might be derived from each ecosystem state, including carbon sequestration, subsistence harvest of invertebrates, commercial finfish harvest, and tourism (Gregr 2016), as well as a number of cultural and social benefits (Chan et al. 2016). This means that different management alternatives will come with very different costs and benefits depending on the sector, increasing the importance of including all stakeholders in clearly articulating the desired state of the ecosystem in any management process (See Figure 12 for more information).

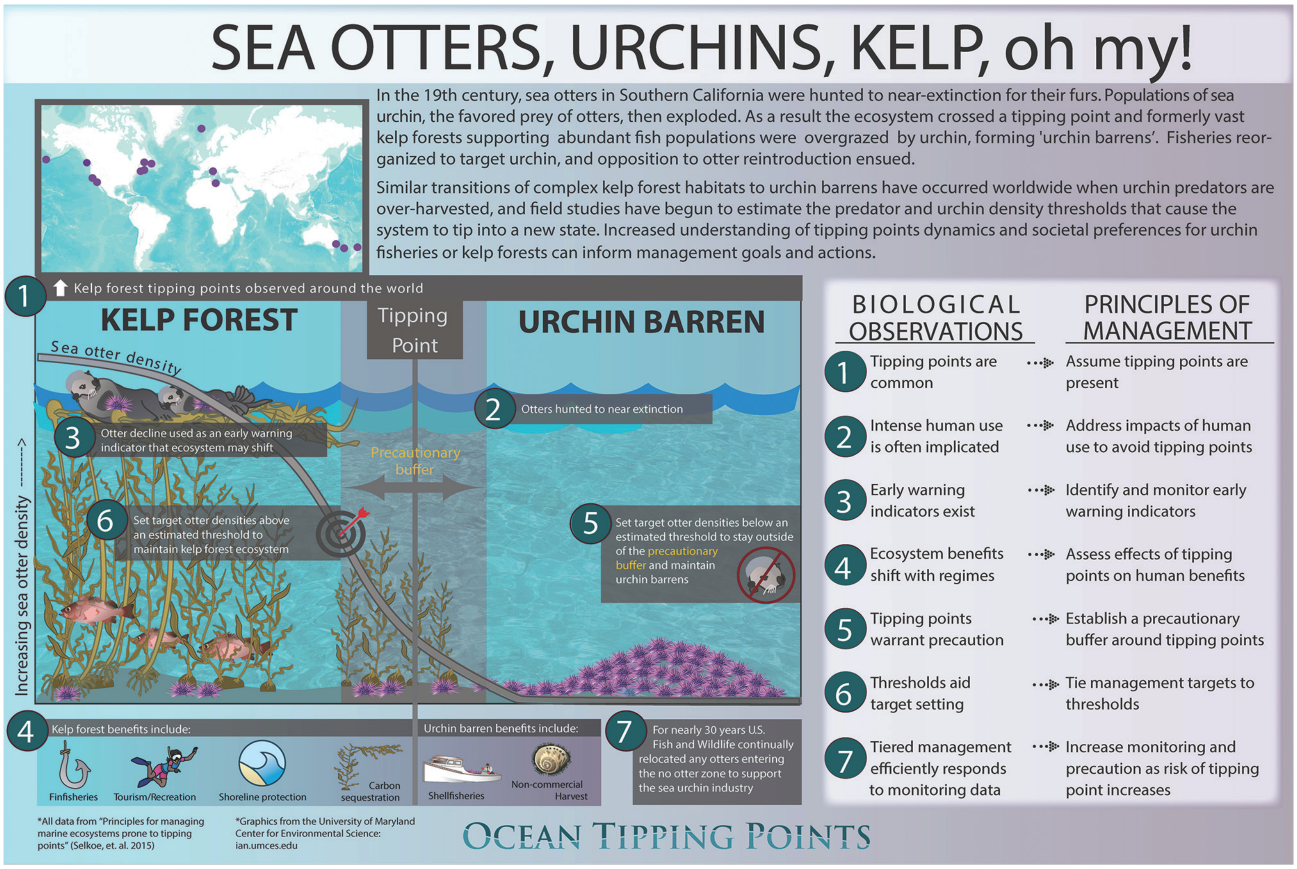


Figure 12. Credit: Ocean Tipping Points Project. Design by: Jacklyn Mandoske.

Why is it important?

"Tipping points to me could be a call to action… The community knows; they've seen changes, they know that things aren't like what they used to be."—Katie Nalasere, Education Specialist, Hawaii Division of Aquatic Resources, Kauai

We have found that the tipping point concept facilitates communication among disparate groups and helps stakeholders, scientists, and managers to discuss socio-ecological change in constructive ways. These dramatic and sometimes irreversible changes resonate with people. Taking time to discuss the implications of these shifts, and what they would look like for local communities who depend on these changing ecosystems, can draw out novel information about values and preferences among diverse stakeholders.

In the face of potentially dramatic, abrupt, and often persistent social-ecological change, understanding how stakeholder groups view those changes takes on a greater weight. The costs of such changes will likely not be borne evenly by all groups and may be large and swift, possibly exacerbating inequitable distribution of costs and benefits among stakeholders and sectors.

The governing laws, regulations, and guidance documents under which you operate as a resource manager represent an overarching view of society's preferences for how the environment and people's activities should be managed. Gathering more detailed and nuanced understanding of the diverse views of stakeholders may be a requirement of those policies or a desirable addition to the decision-making process.

Engaging user groups to explore tipping point scenarios and discuss the distribution of anticipated costs and benefits across stakeholders can help foster dialogue about equity. Whether you tap into stakeholder preferences through research or through direct participation by stakeholders, you are likely to uncover new knowledge from non-traditional sources. Talking about values and preferences can lead to unexpected management solutions that meet the needs of communities while simultaneously promoting ecosystem health and function. Discussions with stakeholders may lead to new management options, help narrow the set of possible actions, or yield insights into how to frame or communicate your plans.

When tipping points occur in a system the difference between those who benefit and those who suffer in the face of system change can be large. Management processes that enable all relevant stakeholder groups to have a seat at the table may help alleviate or even avoid inequitable outcomes through participatory management.

How do you do it?

Participatory process design and the study of coupled social-ecological systems are both relatively new methods that are continually being refined. Below we discuss some methods that researchers and managers have used in the past, which could be transferred to other settings. We encourage you to also reach out to social scientists and skilled facilitators working in your region for other ideas and ways to build on existing work.

Table 4. *Summary of potential methods for characterizing values and preferences for ecosystem states and the benefits and services they provide (adapted with permission from Chan et al. 2012).*

Method	Source	Purpose	Pros	Cons	Additional Information/ Sources
Narrative Methods	Chan et al. 2012	Tease out local eco-system-related values and their connections to activities, ecosystem services, and benefits; elicit qualitative expressions of values, especially place/heritage, spiritual and transformative values	Particularly appropriate when epistemological norms and methods vary greatly across participants and when value articulation is difficult; circumvents assumptions about local values and ES	Conversion of narratives to metrics difficult though resolvable in conjunction with Structured Decision- Making (SDM) or Qualitative Comparative Analysis (QCA— Ragin 2008)	Satterfield 2001, Satterfield and Slovic 2004, Satterfield et al. 2011, Basurto and Speer 2012
Structured Decision-making (SDM)	Chan et al. 2012	Identify values as statements of what matters and objectives, structuring evaluation of alternatives by expressing means and ends indicators for objectives	Flexible, multi-metric approach including building of metrics in locally appropriate language, and of performance measures	Labor intensive; might only be appropriate for valuation and tradeoffs, not entire decision if application context is ES	Gregory et al. 2001, Keeney and Gregory 2005, Espinosa-Romero et al. 2011, Gregory et al. 2011
Mental/ Cultural Models	Chan et al. 2012	Tease out lay theories of social-ecological systems (SES), local cause-effect logics more broadly, possibly including eco-system-level 'production functions'	Ideal for parsing assumptions of constituents in situ when worldviews and epistemological norms differ. Adaptable interview protocols already available	Less useful when cause-effect SES relationships not primary concerns. Values usually more implicit than explicit in cause-effect outputs	Kempton et al. 1995, Kempton and Falk 2000, Morgan et al. 2002, Jones et al. 2011
Paired Compari-sons	Chan et al. 2012	Elicit relative preference weightings or rankings across multiple benefits or scenarios	Very good for achieving ordinal rankings of value priorities with statistical power when conducted across larger constituencies. Value weights are inferred, rather than directly assigned. Very doable across education levels. Can be used in conjunction with visual material and contextual detail	Very design intensive; dollar valuations added when necessary via damage schedule; only possible for small numbers of benefits / objects (usually <10); as numbers of benefits increases, so does needed survey length	Chuenpagdee et al. 2001, Chuenpagdee et al. 2006
Norm-based preference surveys	Chan et al. 2012	Elicit statements of broad values and environmental principles (not valuation; generally for value 'held' not assigned)	Widely used and tested protocols across international audiences. Available databases of results at regional and national levels	Values usually spatially nonspecific	Stern and Dietz 1994, Dunlap et al. 2000; Levin et al 2015

Discursive Approaches/ Citizen Juries	Chan et al. 2012	Make collective choices through expert testimony and discourse (citizen juries use analog of legal juries for significant decisions). Often rely on consensus decisions.	Format is familiar, allows for expert presentations of information, and careful deliberation on decisions.	Labor intensive, Expensive to run (often run for one or two weeks as does a normal jury). Costs of expert time and travel.	Crosby 1995, O'Hara 1996, Coote and Lenaghan 1997, Spash 2007.
Q method	Murray et al. 2016, MacDonald et al. 2014	Combines interviews, document analysis, individual and small group structured data gathering, and Q factor analysis to systematically explore how individuals perceive subjective (qualitative) information.	Allows participants to raise their own topics rather than categories being imposed by the researcher. Does not require large population samples to obtain statistically valued results.	Time intensive, so not well suited to cross-sectional or large sample sizes. Not designed for generalization across populations	McKeown and Thomas 1988, Swedeen 2006, MacDonald et al. 2014, Bacher et al. 2014, Sainsbury and Sumaila 2003.
Contingent Valuation	Venkastachalam 2004	Flexible non-market valuation method that is widely used in cost–benefit analysis and environmental impact assessment to elicit the value of an environmental good directly through questions about willingness to pay to have more of a benefit.	Built on economic theory, yields estimates in common (monetary) metric, powerful method to communicate value.	Some values are difficult to measure in this format, e.g. spiritual value and valuation can be incomplete, biased and uncertain. Often the scenarios described in the studies are unfamiliar, and sometimes unrealistic.	Venkastachalam 2004, Mitchell and Carson, 1989, Cummings et al., 1986.
Choice-Modeling	Bennett and Blamey 1999	Uses a group of methods to determine preferred options by asking individuals to choose between alternative scenarios that differ in their environmental and social dimensions.	Allows participants to choose between attribute combinations, rather than attaching direct monetary values to environmental goods that they are not used to valuing. Possible to determine, separately yet simultaneously, the importance of economic, social, and environmental factors.	Less direct method of eliciting values. When people have a good sense of the value of a particular environmental good, it is best to ask them directly about this value, instead of asking in a circumscribed way.	Mavsar et al. 2013, Riera and Signorello 2012, Naidoo and Adamowicz 2005.

For example, Pacific herring are key species that contribute to cultural, social and economic dimensions of human well-being in Haida Gwaii, British Columbia. To understand the diverse socio-cultural values and practices regarding herring, Poe and colleagues (in prep) worked with the Haida Nation to implement semi-structured interviews with Haida community members. Employing this narrative method helps characterize the potential social impacts of ecological and management changes, both past and future, and helps guide goal-setting for fisheries and ecosystem managers in Haida Gwaii. Specifically, by linking Haida values for and relationships with herring with the spatio-temporal changes in herring populations, they identified potential social-ecological tipping points in the system.

In addition, they used mixed community-based social science research methods to build a definition of sustainability that embeds these elicited socio-cultural values regarding herring on Haida Gwaii. Starting with categories of sustainability and the herring fishery, they developed a set of statements from semi-structured interviews with local people to identify how they define sustainability with respect to their relationships with herring and the marine environment. They then held a set of workshops that implemented "Q-methodology", where residents of Haida Gwaii were asked to sort this series of statements according to their relevance (Loring et al. in prep). This provided an understanding of the factors that influence perceptions of sustainability in herring fishery and ecosystem management. These statements were further integrated into norm-based preference surveys that allowed the authors to identify anticipated effects of ecological changes on socio-cultural values to aid ecosystem-based decision-making for Gwaii Haanas (Levin et al. in prep).

Strategy 2b.

Analyze risk of crossing a tipping point and characterize people's risk tolerance to changes that could result

What does this mean?

Identifying the ***safe operating space*** for management decisions involves identifying the likelihood or risk of crossing a tipping point. Risk of undesirable impacts to the ecosystem is a function of both probability of a tipping point occurring and the potential magnitude of its effect.

Just as people have different preferences for what they want their ecosystems to look like, their tolerance for crossing social and ecological thresholds may vary. Risk tolerance—defined here as willingness to accept the possibility of crossing a tipping point versus accepting precautionary management measures—is related to stakeholders' values and preferences for different ecosystem states. Thus, decision-making includes both the 'objective' facts of how systems change and subjective views of the desirability of what is to be gained or lost by a particular decision (Burgman 2005). The role of science is to understand how each ecological change impacts not only the ecosystem, but also the associated economic and cultural systems, how different user groups may benefit or be harmed by these changes, and how risk-averse these different groups are to change, in order to best inform policy development and target setting.

'Risk' can be defined in different ways, depending on how governments, stakeholders, and scientists value the outcomes at stake (Fischhoff 1995) For example, some people care primarily about threats to human life; others care about the economy or the environment as well, and each of these concerns need to be accounted for with different risk estimates. Risk tolerance is often inversely related to the resource's perceived ecological or social value. That is, decisions to undertake or implement more stringent, restrictive, or expensive risk management measures will gain greater acceptance for highly valued resources than for less valued resources (SETAC 1997).

For example, in Figure 12, Stakeholder A may have values related to the resource, such that they have low tolerance for crossing a tipping point. Thus, they may be supportive of targets that are squarely located in the safe operating space area of the graph. Stakeholder B, however, may have strong values more linked to the driver of change, and thus would be less accepting of precautionary targets and choose targets that fall within the precautionary buffer or even in the zone of uncertainty (confidence interval). Ultimately, identifying people's values and determining their risk tolerance will help identify management options that represent "acceptable and reasonable risk," i.e., those that would be viewed as neither under-protective of the resource nor overly burdensome to stakeholders.

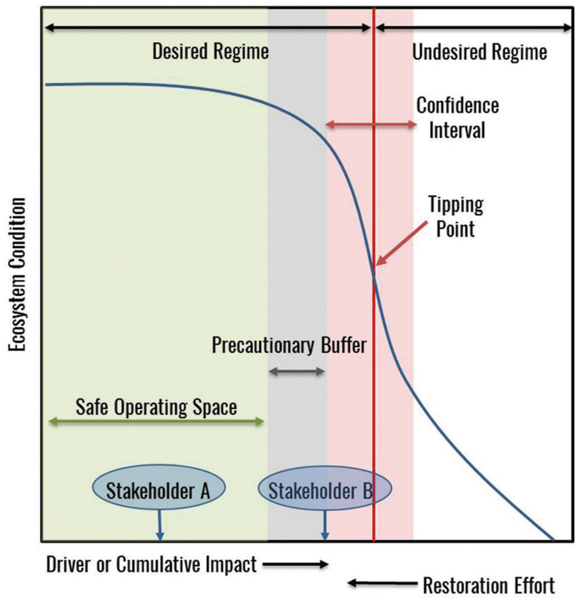


Figure 13, adapted from Selkoe et al. 2015 with permission. Different stakeholders (A and B) exhibit different preferences for acceptable driver or cumulative impact levels given different values and/or underlying risk tolerances.

In the figure below you can find two different real-life applications of the conceptual model developed above—both for kelp forest-urchin barren systems where sea otter populations were rebounding naturally or through active restoration, but where stakeholder preferences differed dramatically. In Scenario A, stakeholder engagement processes determined the management goal to be maintaining an otter-free zone in southern California, USA. In response to strong preferences by urchin fishermen to maintain urchin barrens, and a low tolerance for risk, between 1989 and ca. 2001, the U.S. Fish and Wildlife Service (FWS) captured and moved every otter in southern California that strayed beyond a designated sea otter zone around San Nicolas Island, back to San Nicolas or central California. This objective created a very wide precautionary buffer and a management target set close to zero otters. In Scenario B the management goal was to maintain kelp forests through otter protection. In parts of Alaska, a sea otter recovery management plan sought to maintain a minimum density of otters to support kelp forests and the tourism trade. Otters need habitat that offers protection from orcas, so in response to mounting orca predation, FWS designated critical habitat to protect areas where orca predation success is lowest. This strategy allowed for higher risk tolerance with a narrower precautionary buffer, a larger safe operating space, and a management target aimed at a minimum number of otters (Description and Figure 13 from Selkoe et al. 2015).

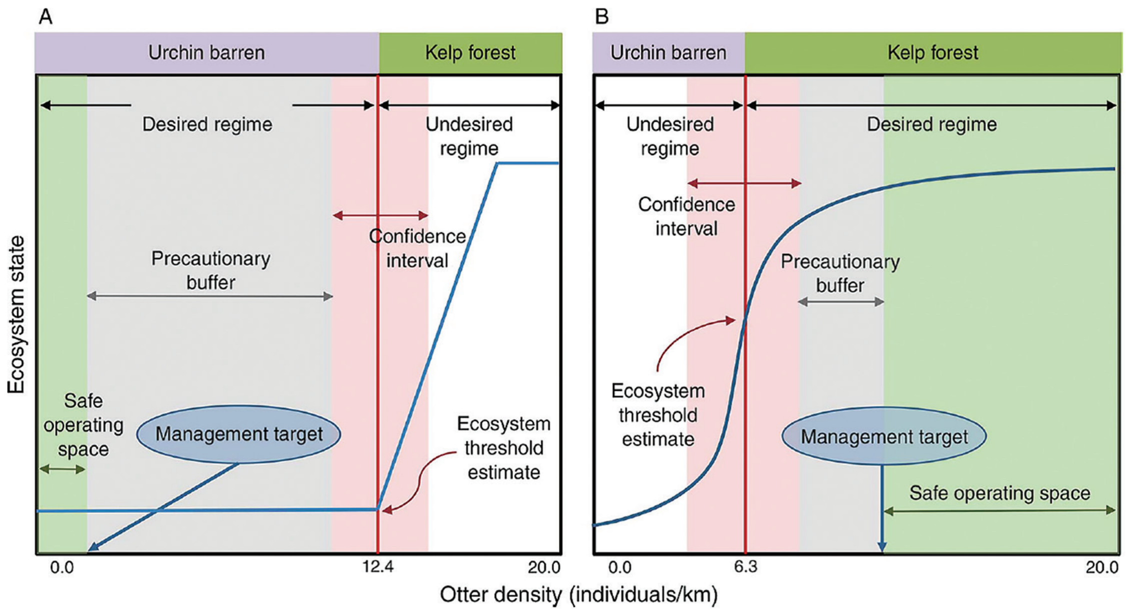


Figure 14, adapted from Selkoe et al. 2015 with permission. Panel A represents the otter exclusion zone maintained in Southern California (from 1989-2001) to protect urchin fisheries from otter predation. The threshold number of otters that can trigger a shift from urchin barren (fishermen's desired regime) to kelp forest is 12.4 otters/km of coastline. Note the low risk tolerance for otter invasion and loss of urchin barrens. Panel B represents active management for otter restoration and kelp forest recovery, the desired regime in Alaska. Here the threshold for kelp forest recovery is 6.3 otters/km and the management target, in terms of minimum otter density, is close to this number.

Why is it important?

Precautionary regulation is often unpopular, financially costly, or impractical, partly due to economic discounting and underestimation of future risks (Scheffer 2009). However, tipping points change the balance between the costs of action and inaction. The cost of inaction skyrockets in a system that exhibits tipping points as pressure on a system intensifies, compromising resilience and leaving little buffer for the system to absorb unforeseen shocks (Figure 15, adapted from Kelly et al. 2014a). Moreover, many ecosystems tend to include feedback loops that reinforce certain states; if these feedbacks are present and act to maintain the ecosystem in an undesirable state after a tipping point is crossed, restoration costs and the risk of failure also increase.

Rigorous cost-benefit analysis can help to inform precautionary target setting and reveal how costs and benefits are distributed among stakeholders to assess equity. Reducing uncertainty through increased information and high risk tolerance may allow managers to approach a system's tipping point more closely when setting targets. Early action to preserve resilience of a desired state is more practical, affordable, and perhaps effective than late action to prevent a tipping point, or to recover the system, which may require extreme measures (Kelly et al. 2014a).

For example, in some cases, the decision by fisheries managers to set harvest levels below maximum sustainable yield (MSY) has been motivated by boosting precaution in order to avoid severe economic consequences of crossing a tipping point (i.e., stock collapses; Punt et al. 2012). Australia has fully adopted risk-based measures throughout their fisheries management (Smith et al. 2009). Similarly, scientists are calling for managers to significantly reduce take of forage fish below MSY to avoid risk of negative ecological effects for predators that depend on these species (e.g., sea birds, mammals, and commercially valuable larger fish like halibut, salmon, and rockfish; Cury et al. 2011, Hunsicker et al. 2010, Smith et al. 2011, Pikitch 2012).

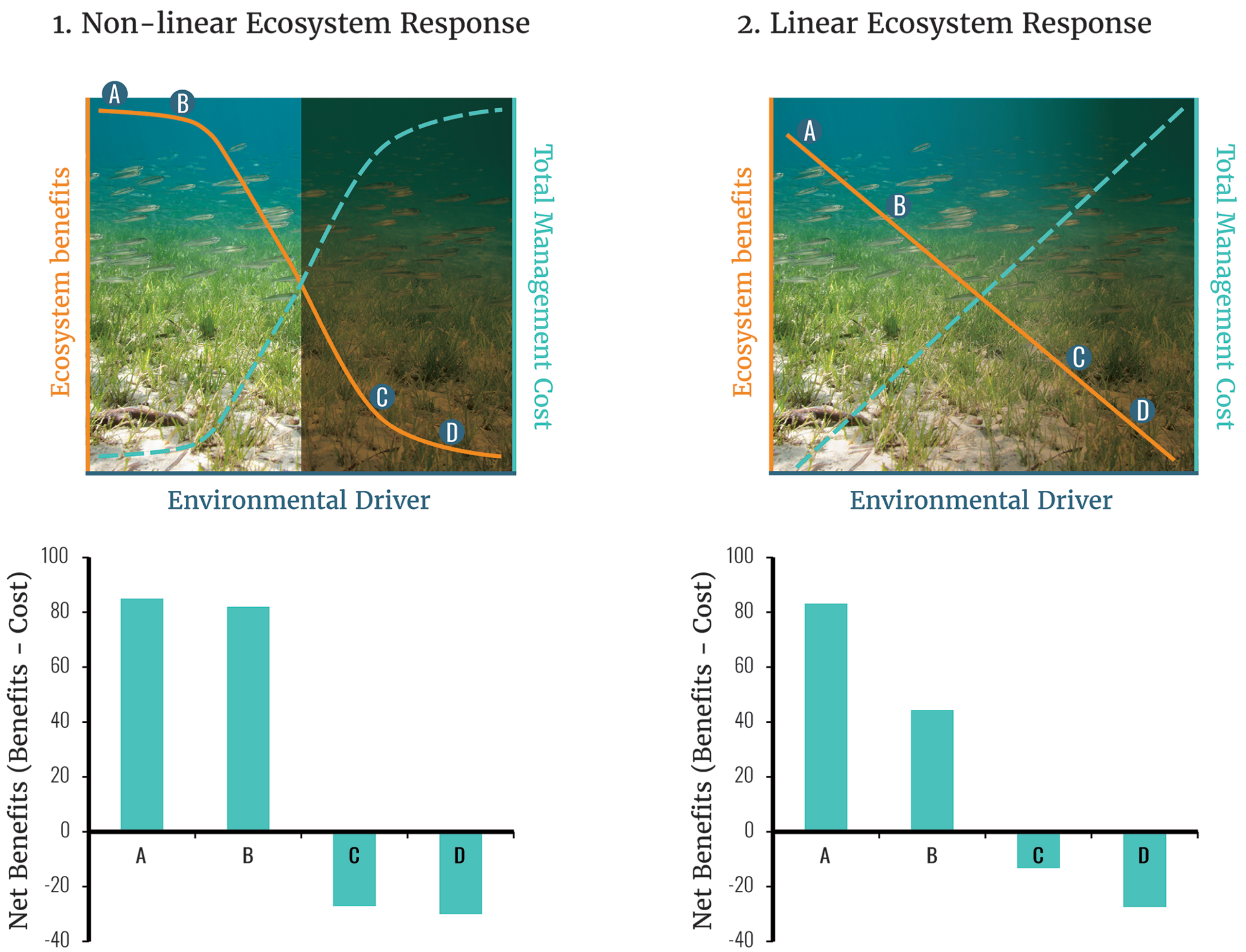


Figure 15, modified from Kelly et al. 2014. Two hypothetical relationships between ecosystem state (e.g., an unimpaired estuary with clear water vs. an impaired state with algae-dominated, turbid water) and the intensity of a human driver (e.g., nutrient input). In the nonlinear response scenario on the left, a small change in stressor intensity can drive a dramatic change in ecosystem state (e.g., from point "B" to "C" along the solid curve). The dashed curve represents the nonlinear increase in management costs that may result from a threshold change in the ecosystem. This cost curve assumes that management costs increase in step with environmental degradation. Cost for points along the line are shown below. On the right is the linear response case for comparison.

How do you do it?

Identifying thresholds in the ecosystem can help quantify and communicate the costs and risks of inaction. Capturing people's preferences and risk tolerance for these changes and the potential for trade-offs among different management actions can then follow. This can be done using a variety of social-science methods, including mental model interviews, choice experiments, and norm-based preference surveys (described below and summarized in Table 4).

Identifying the drivers of people's perception of risk is important for helping to address risk tolerance and evaluate management decisions. Risk perception is linked to its magnitude and consequences, but other factors can mitigate willingness to accept risk, for example, the level of personal control. In situations where people feel they are in control they will tolerate higher risks (Burgman 2005). People will also tolerate greater risks when given a choice versus when risks are imposed. Anchoring, or the tendency to be influenced by initial estimates, can also be a factor that can affect people's risk tolerance. Social science methods can reveal some of these and other biases and help structure the decision process (Stern & Fineberg 1996; Burgman 2005).

Below are some examples of methods you can use to characterize risk tolerance and identify factors that may influence a stakeholder's preferences for certain targets or management action.

Evaluating trade-offs among management decisions

Understanding how ecosystem dynamics respond to different management decisions can allow for examination of the costs and benefits of different management actions.

Ocean Tipping Points researchers examined the consequences of alternative forms of exploitation of Pacific herring off the coast of Haida Gwaii, British Columbia, Canada to achieve sustainable fisheries and conservation goals. First, team members interviewed individuals representing government bodies, conservation groups, and relevant industries to understand what factors influenced risk tolerance. The team then developed formal models to evaluate trade-offs between egg- and adult-harvest rates in relation to environmental variability, risk to fisheries in terms of the probability of fishery closures, and the risk to ecosystems based on the foraging needs of predators reliant upon these exploited stocks (Shelton et al. 2014). They then developed a risk plot comparing the probability of fisheries closure for the two different types of harvest and the ability of the ecosystem to support seabird foraging (Figure 16). This model was then developed into a decision support tool that allows stakeholders to examine how different harvest rates and environmental variability affect the probability of different outcomes for herring stocks and catches, providing further insights into their preferences and risk tolerance.

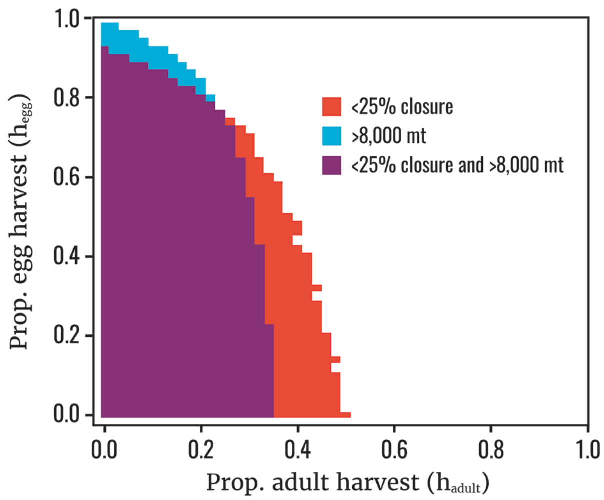


Figure 16, from Shelton et al. 2014. Risk plot comparing the probability of fisheries closure and $B_{ecosystem}$ for all combinations of egg and adult harvest. $B_{ecosystem}$ is an ecosystem threshold intended to leave enough herring biomass (8,000 mt) in the water to satisfy the needs of herring predators (purple and magenta areas). Many combinations of egg- and adult-harvest rates can allow the herring fishery to remain open at least 75% of the time (peach and magenta areas), while maintaining average herring biomass above $B_{ecosystem}$ (magenta area).

Risk assessment

Risk assessment processes evaluate the likelihood or probability that ecosystem components (e.g., populations, habitats, communities) may suffer adverse impacts as a result of human activities or management actions. Risk assessment and management are widely used and can be applied in a variety of situations, from those with minimal data and resources to those with detailed inventories and complex systems modeling (see Holsman et al. 2017 for a review). Whether qualitative, semi-quantitative, or quantitative, all risk assessment processes include:

- Identifying the sources of risk (drivers);
- Analyzing their consequences;
- Setting risk classes (e.g., high, medium, low risk) based on the exposure to drivers and potential consequences to ecosystem components, (note that this may include consideration of threshold responses);
- Evaluating outcomes from different management options; and
- Identifying risk management strategies.

Qualitative assessments are often based on expert judgment. For example, Hobday and colleagues (2011) describe an approach in which stakeholders evaluate the scale, intensity, and consequence of potential drivers facing ecosystem components. Such an approach could be applicable to thresholds if stakeholders and experts characterize the consequence of drivers as non-linear. For semi-quantitative and quantitative risk assessment methods, threshold-based science presents a unique opportunity to identify the degree of impact from a driver on the ecosystem and ultimately the services and functions provided by these ecosystems. The relationships between both ecological components and drivers and between components and the functions they provide are often non-linear, which can provide natural inflection points from which boundaries between impact or risk classes can be determined (Figure 17).

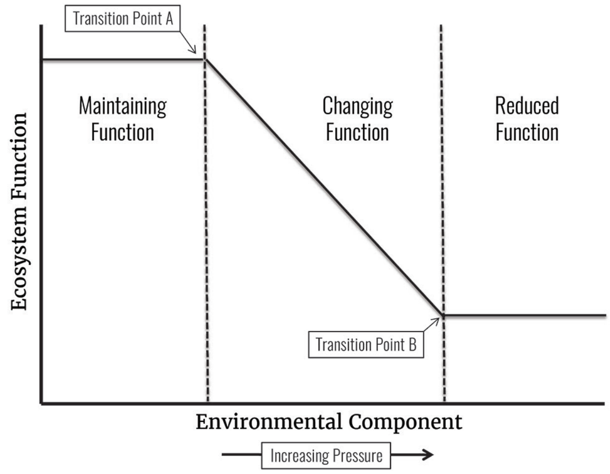


Figure 17, adapted from DFO (2015). The relationship between ecological components and the functions they provide in the ecosystem with categories that underlie risk of impacts to ecosystem components and their ecosystem functions. As the level of impact to ecosystem function increases, the ecosystem component moves from "Maintaining Function" towards "Changing Function" and "Reduced Function" categories. "Maintaining Function" means the ecosystem component resists or compensates in the face of perturbation in order to maintain ecosystem function, although there may be changes in status of the ecosystem component. "Changing Function" means ecosystem function systematically changes as the ecosystem component changes with perturbation. A period of altered status followed by recovery of the ecosystem component is expected to occur. "Reduced Function" means the ecosystem component has reached a status where function can no longer be provided or where recovery is no longer secure. The shifts from one category to another indicate transition points that may be used as limits or targets, depending on the trajectory of change.

Risk assessments should be able to identify the effect of multiple, interacting drivers and abrupt and non-linear changes in ecosystem components (Levin & Mollman 2014). If sufficient data and understanding of ecosystem dynamics are available, quantitative relationships between drivers and ecosystem components can be used to estimate risk (e.g., Stelzenmuller et al. 2010; Burgess et al. 2013; Fulton et al. 2014; Holsman et al. 2017). If insufficient data are available to parameterize models, qualitative or semi-quantitative methods such as the Comprehensive Assessment of Risk to Ecosystems (CARE) method can be used to combine available data with local knowledge to assess risk from individual drivers and the cumulative risk from several drivers (Battista et al. 2017). This method can also incorporate qualitative understanding of how different drivers interact to generate improved estimates of risk.

Once relationships between drivers and ecosystem components and potential ecological risks are determined, whether qualitatively or quantitatively, risk tolerance of different stakeholders should be identified. In risk assessment processes, this can be done using collaborative decision processes to set the boundaries between risk classes (e.g., very high, high, moderate, low, very low) or, if risk classes are predetermined (for example, based on ecological thresholds or limits), by using social science methods that identify stakeholders' willingness to be in a particular risk class. We describe some of these methods below.

Social science methods to identify people's perceptions of risks and benefits of decisions

A variety of economic and social science methods are available to help you understand people's judgments of risks and the desirability of different states. The first step is to identify the elements that influence people's perceptions of costs and benefits. This can be done using Mental Model Interviews to reveal each individual's understanding of how a process works and the factors that are important to people's perception of risks and benefits (Morgan et al. 2002). Other methods include workshops (e.g., Donatuto et al. 2014), systematic surveys (e.g., Safford et al. 2014), or economic value elicitation methods (e.g., Carson et al. 2001, Christie et al. 2006). These types of approaches are critical to identifying all the relevant elements within a process, including options, values, outcomes and uncertainties. Obtaining this information helps to avoid some of the biases that could arise when developing formal models without input from stakeholders. Once the key beliefs and elements are identified, the next step is to identify people's willingness to accept the ecosystem states and the management decisions that lead to those costs and benefits. Follow up experiments can then assess the role of specific factors in affecting people's values and willingness to accept decisions, (e.g., context, demography, identity).

For example, Wong-Parodi et al. (2016) used a mix of methods to understand people's willingness to accept different management options to respond to anticipated sea level rise. The team employed structured interviews using Surging Seas decision aid, which allowed participants to visualize and conceptualize the probability and impact of severe flooding events. Digging deeper, they followed these interviews with an experiment to determine if political identity influenced people's judgments and willingness to accept management options in the context of decisions about buying a home in an area subject to sea-level rise. The authors found that once immersed in a particular decision, participants with different political views responded similarly, except when a strong appeal to their political identity was embedded in the task. By understanding these differences and revealing them, one can incorporate appropriate structures into the decision process to address cognitive biases, increasing transparency.

Strategy 3. Set Targets and Design Monitoring

Background

Whether you seek to avoid an undesirable regime shift or you are trying to restore a system that has already shifted, knowing how close your ecosystem is to a tipping point is crucial. This includes knowing what trajectory your managed system is on, where it is currently and where you want it to be relative to the tipping point.

Here we review how indicators can help you recognize when your ecosystem may be approaching a tipping point, how this emerging science can inform the design of monitoring programs, and how ecological and social information about tipping points can assist you in setting management targets. Below are three definitions that will help you as you navigate through this strategy.

A ***target*** is a specific, measurable outcome you are trying to reach.
A ***benchmark*** is an intermediate, measurable outcome that can signal progress toward your target.
A ***limit*** is a specific, measurable outcome to be avoided.

Strategy 3a.

Identify early warning indicators that signal approach of a tipping point

What does this mean?

When assembled effectively, a suite of social and ecological indicators can help managers detect changes in ecosystem status and trends, providing them with the information necessary to evaluate their current and past policy decisions as well as plan for the future.

> *"Although it is difficult to predict the exact amount of stress that will trigger a tipping point, warning signs that precede the tipping point can be instrumental in avoiding collapse." —Selkoe et al. 2015*

Indicators help managers establish monitoring benchmarks that can be used to judge when a management target has been reached (Samhouri et al. 2011, 2012). These targets can be set by identifying particular ecosystem thresholds through quantitative analysis or through people's stated or revealed preferences for particular ecosystem conditions (Samhouri et al. 2013). Active monitoring of indicators in relation to these targets can inform adaptive management.

Early warning indicators are a specific type of indicator that provides information in advance of an ecosystem shift. These indicators are most effective if they provide information that allows managers to be able to anticipate shifts with sufficient time to respond.

Planting rose bushes in grape vineyards is an example of establishing an early warning indicator system. Roses and grapevines are both susceptible to the same fungus, but roses are more sensitive, so will respond first to the presence of the fungus. Once the roses start to show signs of the fungus they function as an early warning indicator to grape farmers that they need to act quickly to prevent the spread of the fungus to their grapevines.

Why is it important?

The “timely information” that early warning indicators provide could ultimately dictate whether or not a manager has enough lead time to effectively take action to avoid a looming ecosystem shift (Biggs et al. 2009). **Incorporating early warning indicators into your ecosystem monitoring portfolio can therefore help you to avoid undesirable shifts, plan for unavoidable changes, and track progress toward management targets.** This kind of information collection and feedback is essential to any adaptive management framework, and especially so when there is a risk of dramatic ecosystem level change or when mitigation is not an option.

How do you do it?

Complex systems theory predicts that, under certain conditions, generic “early warning” signs should presage critical transitions from one state of a system to another (Dakos et al. 2008, Scheffer et al. 2009). Early warning indicators, which constitute different statistical properties of time series or spatial data (Table 5, Foley et al. 2015 with permission), have potential application in a wide variety of situations where the change in state is characterized by ***hysteresis***. Litzow and Hunsicker (2016) highlight the importance of testing for nonlinear dynamics or hysteresis before attempting to apply early warning indicators in monitoring a system. From analysis of northeast Pacific ocean time series and literature review across many different study systems, they found that systems with evidence for nonlinear dynamics or hysteresis generally supported theoretical early warning indicator predictions, while those with linear or unknown dynamics did not. While their potential is alluring, some scientists caution against use of these indicators without thorough understanding of the underlying system dynamics (e.g., Boettiger and Hastings 2012). Boettiger and Hastings suggest it is unlikely that general indicators exist across systems because the context in which a system approaches a threshold is likely to be unique. Instead, they push for data-driven exploration and experimentation within systems to identify system-specific characteristics of impending thresholds.

Box 3a. *Major categories of early warning indicators (EWI) (with permission from Foley et al. 2015)*

Critical slowing down and flickering. As a system approaches a threshold, the time it takes to recover from a disturbance increases due to loss of resilience (Scheffer et al. 2009)and the structure and/or function of the ecosystem starts to alternate between two states over a short time period (Dakos et al. 2012).

Autocorrelation. Change across ecosystems tends to become correlated in space and time prior to a tipping point (Biggs et al. 2009; Kéfi et al. 2014). This shift occurs when large-scale drivers such as climate shifts, override feedback mechanisms that previously maintained stability and begin to dominate the ecosystem response.

Variance. The response of ecosystem components to drivers becomes more variable as a threshold is approached. Increased variance can be detected with little underlying knowledge of "normal" ecosystem dynamics (Carpenter and Brock 2006; Litzow et al. 2013), and can be detected in spatial and temporal analyses (Donangelo et al. 2010).

To learn more about these Early Warning Indicators, visit the **Early Warning Signals Toolbox** website: http://www.early-warning-signals.org/

"***Critical slowing down***," in which the time it takes a system to recover from a disturbance increases due to loss of resilience, is thought to be one of the most robust early warning indicators of an impending ecological threshold (Scheffer et al. 2009). However, while early warning indicators hold promise, researchers are just beginning to test them in experimental and natural biological systems (reviewed in Litzow & Hunsicker 2016). For example, rising ***spatial variance*** in fisheries catch time-series was found to be a precursor to historical fishing collapses in the Gulf of Alaska and the Bering Sea (Litzow et al. 2013). Similarly, variance in macroalgal cover, fish diversity, and other coral reef ecosystem status metrics appear to precede tipping points on coral reefs (McClanahan et al. 2011, Karr et al. 2015)

How useful early warning indicators are partly depends on the dataset to which they are applied. In general, you are seeking an indicator that has a good signal to noise ratio and which is sensitive to the purported driver(s) of ecosystem change. Species with short generation times such as zooplankton, for example, might provide earlier warning of a climate-driven ecosystem transition than larger, slower-growing species, however, their population dynamics may also be so noisy that trends in statistical properties like variance are difficult to detect.

Beyond generic statistical indicators, knowledge of the dynamics of your ecosystem can also reveal appropriate early warning indicators. For example, we know that diversity and functional redundancy at multiple levels (e.g., within species, across species, and across trophic groups) can affect a system's resilience to change. As components of the ecosystem are compromised or lost, the system may lose resilience and become more prone to crossing a tipping point with the next shock or stressor (Briske et al. 2006, Brandl and Bellwood 2014). In well studied systems, it is possible to relate specific changes in diversity and ecological functions to system resilience and to identify proxies or indicators of those changes for monitoring.

For example, scientists and managers are currently developing ecosystem indicators for Caribbean coral reefs based on threshold responses of the ecosystem to overfishing (Karr et al. 2015). Applying a method piloted in the Indian Ocean (McClanahan et al. 2011), the team analyzed monitoring data from 2,001 Caribbean coral reef sites that span a gradient of fishing intensity and reef condition. Karr and colleagues found that lower fish biomass was correlated with several other commonly monitored metrics of ecosystem condition, including decreased fish diversity and coral cover, and increased macroalgal cover. In this system, reductions in fish biomass appear to be good indicators of forthcoming ecosystem shifts (Figure 18, adapted from Karr et al. 2015, with permission). Coral cover, on the other hand, which has historically been used as an indicator of reef health, is associated with quite low levels of fish biomass, suggesting it's a lagging rather than leading indicator of coral reef tipping points.

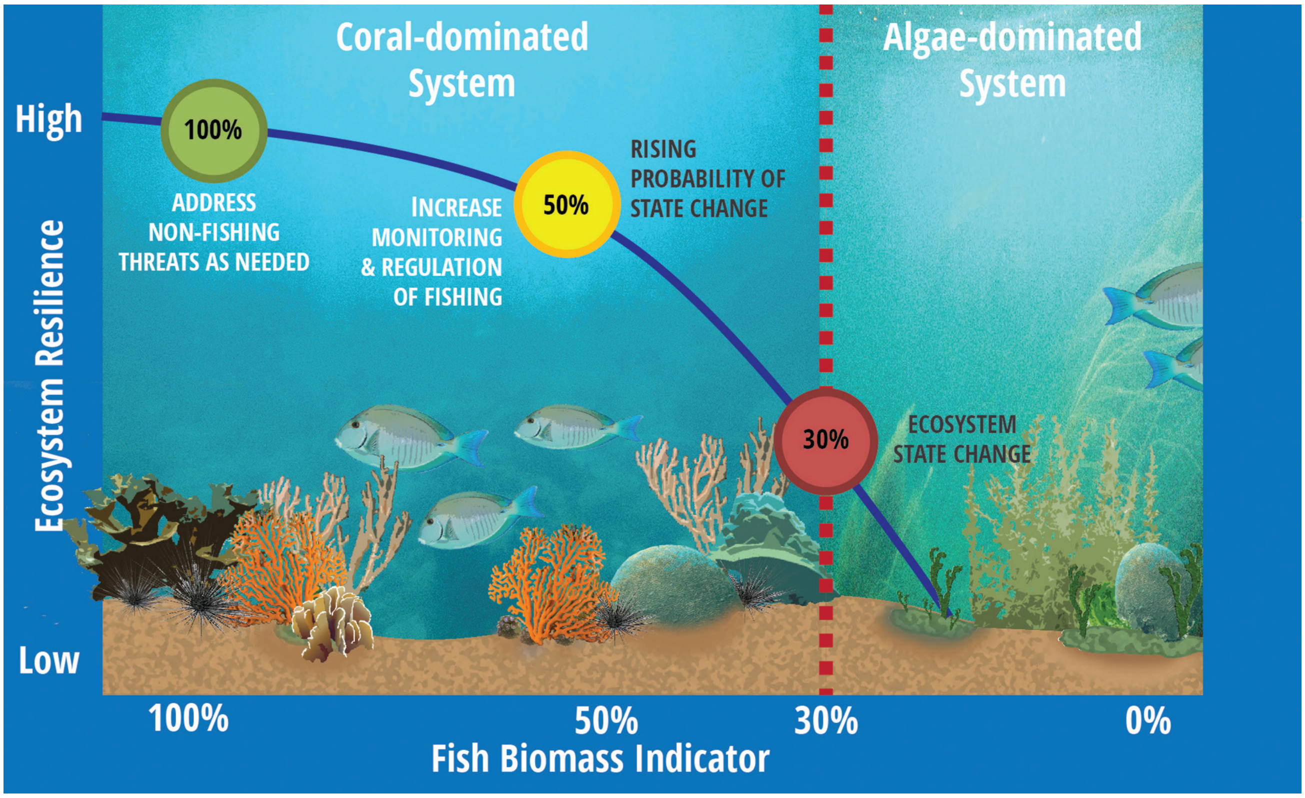


Figure 18, based on Karr et al. 2015. Coral reef studies suggest that a number of coral reef system traits related to resilience (e.g., the proportion of herbivorous fishes, the number of fish species, and urchin density) show steep declines when fish biomass falls below 50% of unfished biomass. Unfished density can be estimated from established local no-take reserves. A tiered approach to risk might set response plans based on these targets (colored circles).

Table 5. *Summary of methods for developing and analyzing early warning indicators of nonlinear ecosystem change (adapted with permission from Foley et al. 2015)*

Multivariate autoregressive state-space model (MARSS)	
Output	- Identifies how non-linear changes are related to biotic processes and changes in outside drivers - Quantifies interaction strength between driver(s) and response variable(s)
Strengths	- Accommodates multivariate datasets - Identifies drivers and ecosystem responses that could serve as early warning indicators - Quantifies interaction strengths among drivers
Weaknesses	- Correlational - Requires significant data inputs
More information & examples	Zuur et al. 2003, Hampton and Schindler 2006, Holmes et al. 2012, Hampton et al. 2013
Software & code examples	MAR1 and MARSS R packages; Matlab code (Ives et al., 2003)
Structural equation modeling (SEM)	
Output	- Predicts how an ecosystem is likely to respond to changes in direct and indirect drivers
Strengths	- Predicts directionality and strength of relationship between driver and ecosystem response - Accommodates wide range of data types - Allows for incorporation of feedback loops and two-way interactions
Weaknesses	- Requires significant data inputs - Requires a priori understanding of ecosystem - Does not incorporate non-linearities in relationships
More information & examples	Grace 2008, Grace et al. 2010, Thrush et al. 2012, Fox et al. 2015
Software & code examples	sem R package
Regime shift indicators (e.g., variance; autocorrelation; critical slowing down and flickering)	
Output	- Provides early warning of threshold dynamics and regime shifts in spatial and temporal data sets
Strengths	- Accommodates wide range of data, including spatial and temporal data - Allows early identification of threshold dynamics and regime shifts
Weaknesses	- Requires significant data inputs - Usually retrospective - May not be transferable across systems
More information & examples	Dakos et al 2010, 2012, Veraart et al., 2012, Litzow et al 2013
Software & code examples	nlme R package early warnings R package, more info at: Early Warning Signals Toolbox

For additional resources, code, and methods that can be used to identify early warning indicators, visit **The Early Warning Signals Toolbox** website: http://www.early-warning-signals.org/

Strategy 3b.

Use social preferences, risk tolerance and social and ecological thresholds to inform target-setting

What does this mean?

Target-setting requires integrating people's values and tolerance for risk with the best available science to make a judgment about where you want the system to be. Defining thresholds and setting precautionary buffers can be viewed as setting the boundaries of a system's "***safe operating space***", in which the risk of crossing an unwanted tipping point is considered acceptable and resilience is high.

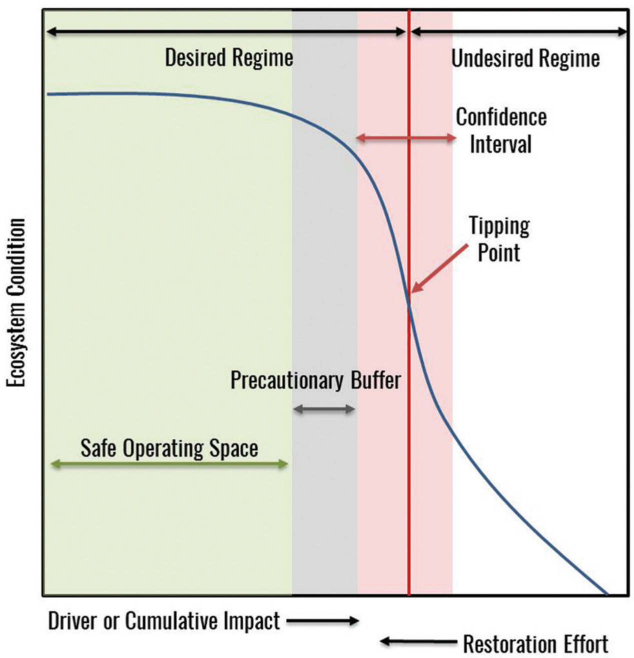


Figure 19, adapted from Selkoe et al. 2015 with permission. The safe operating space (green) for management represents the range of driver levels with a tolerable level of risk of tipping into an undesired regime or ecosystem state and adequate to high resilience. If the risks associated with crossing the tipping point or costs of mitigation are very high or if the location of the tipping point is highly uncertain, the precautionary buffer (blue) should be increased.

Scientifically quantified thresholds can provide important reference points in that process, as, for example, maximum sustainable yield determinations do in fisheries quota setting. Maximum sustainable yield (MSY) is determined through stock assessment methods that consider the nonlinear relationships between a species' biomass, carrying capacity, and growth rate. It represents a limit for the amount of fishing a population could sustain under prevailing ecological and environmental conditions, fishery technological characteristics (e.g., gear selectivity), and the distribution of catch among fleets—"as reduced by any relevant economic, social, or ecological factor". The final target, optimum yield (OY), refers to the amount of fish that provides the greatest overall benefit to the Nation, accounting for food production, recreational opportunities, and protection of marine ecosystems but never exceeding sustainable levels, defined by MSY. The definitions of both maximum sustainable yield and optimum yield contemplate consideration of both species-specific and ecosystem thresholds and societal perceptions of risk. Current management guidance (NOAA's National Standards Guidelines) calls for MSY and OY to provide the basis for both status determination criteria—criteria that define when a stock is overfished or subject to overfishing—and required catch limits for each fishery. In other words they are directly linked to the legally harvestable portion of fishery resources and the regulatory thresholds beyond which rebuilding plans are required and accountability measures (i.e., consequences) are triggered. In this way, the regulatory system calls for incorporation of social, economic, and ecosystem considerations.

Why is it important?

Setting targets helps you, as a manager:
- Track your progress;
- Anticipate upcoming shifts;
- Trigger appropriate, proactive management actions; and
- Evaluate the success of those actions.

It also allows the public and policymakers to do the same, leading to greater public understanding and enhanced accountability. In a system that is prone to tipping points and potentially high uncertainty, targets can help you track whether your management is maintaining the system within the determined safe operating space or moving it along a desirable trajectory.

How do you do it?

Once you have identified the known thresholds (Strategy 1), people's social preferences and risk tolerance (Strategy 2), and indicators of these changes (Strategy 3a), the next phase is to identify your targets in relation to the indicators you are monitoring. Below we describe a few examples that illustrate the approaches people have used.

2020 targets for the Puget Sound

In 2011, the Puget Sound Partnership ("Partnership") employed a science-based decision-making process for understanding environmental, social, and economic trade-offs associated with the human activity and management decisions that affect the health of Puget Sound. Using the Integrated Ecosystem Assessment (IEA) framework, the Partnership identified and adopted ecosystem recovery targets that would help them work toward certain desired conditions for the ecosystem by 2020. First, the Partnership identified a number of indicators of the system. Scientific advisors then developed potential targets for those indicators based on thresholds, and/or baseline reference conditions. Stakeholders then provided perspectives about socially acceptable definitions of recovery by 2020, based on their risk tolerances. Together, these thresholds and social values informed the 2020 ecosystem recovery targets adopted by the Partnership's Leadership Council (see the Puget Sound Vital Signs Website). For example, for eelgrass targets, scientists at NOAA developed a food web model to examine how different social-ecological indicators of the ecosystem respond to changes in coverage of native eelgrass, and the subsequent economic, cultural, and ecological benefits of eelgrass recovery (Levin et al. 2015). A variety of eelgrass reduction and restoration scenarios were evaluated (Figure 20). Based on this analysis and input from stakeholders, the Partnership adopted a target of 120% of the area measured in the 2000–2008 baseline period.

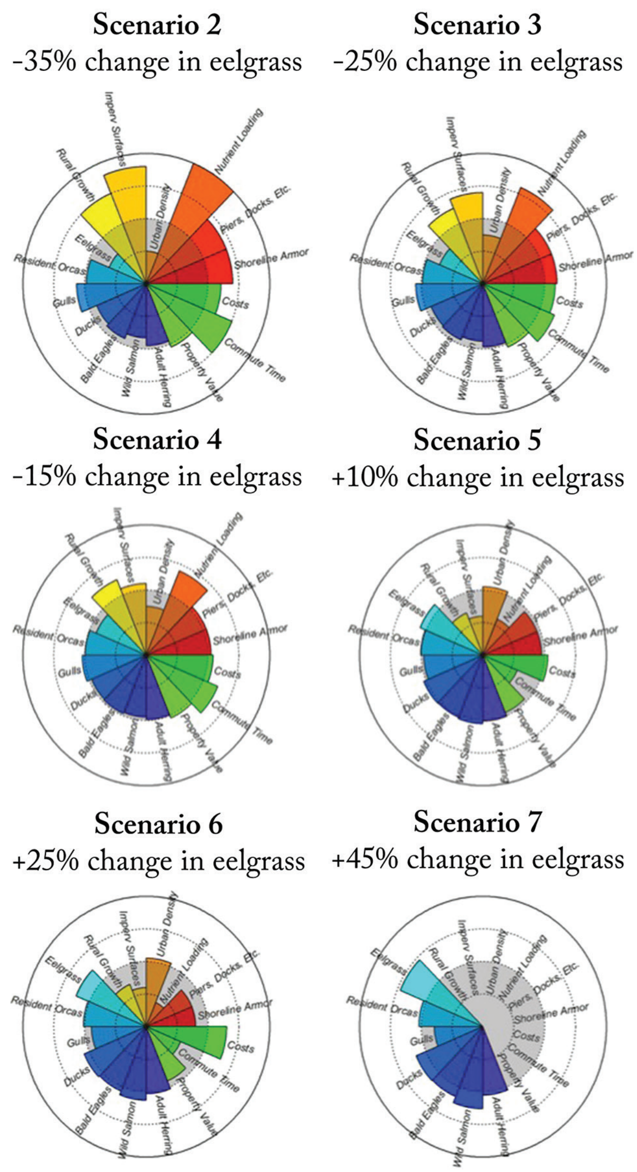


Figure 20, adapted from Levin et al. 2015 with permission. Below is an example of radar plots which were used by Levin and co-authors to show relative trade-offs among 16 different attributes for 6 scenarios related to changes in eelgrass habitat, land use, and shoreline development. Values are plotted relative to the status quo (scenario 1), which is depicted as the gray circle in each plot. Biological ecosystem components are shown in blue; costs are in green; yellow, orange, and red depict anthropogenic pressures and some geographic attributes of the region.

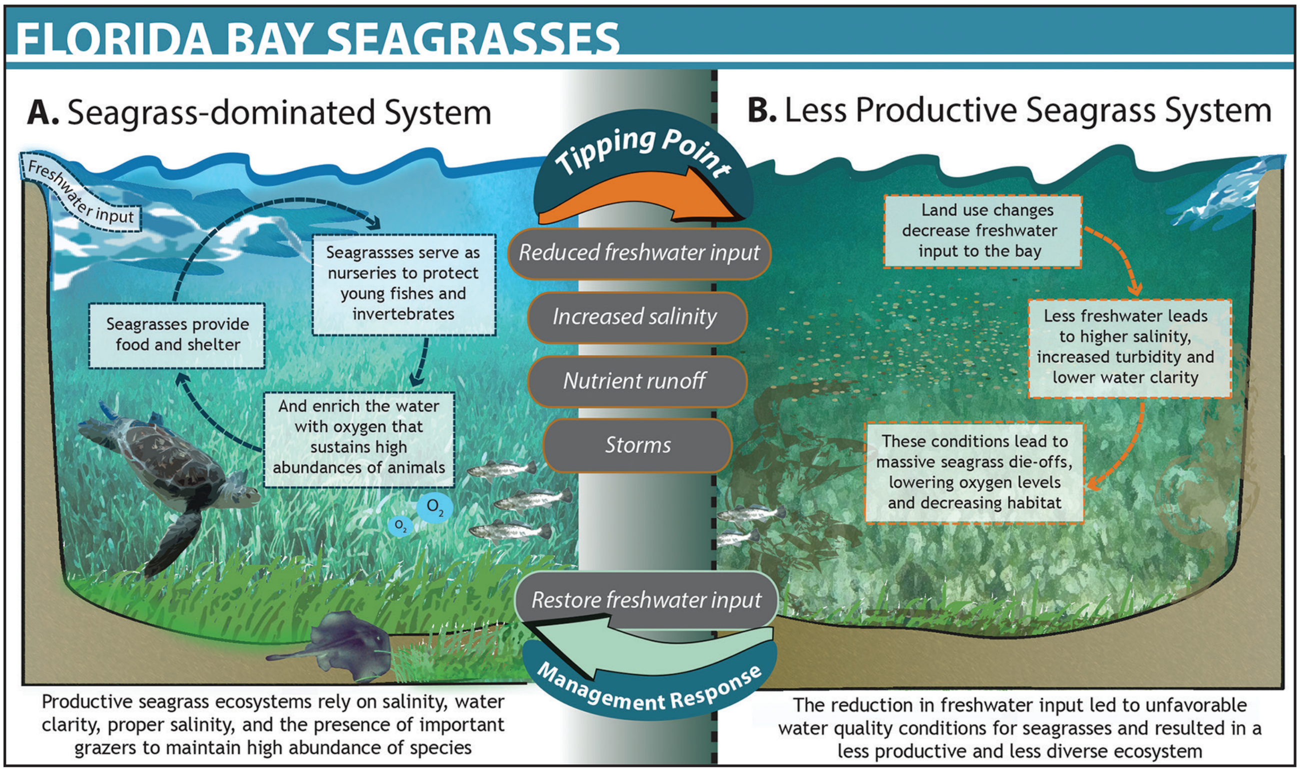


Figure 21. Credit: Ocean Tipping Points Project. Design by: Jacklyn Mandoske.

Seagrass loss in Florida

Florida Bay is home to vast stretches of productive seagrass beds that serve as nursery grounds for juvenile fishes and food and habitat for many other marine species. In the 1980s, changes in upstream land uses critically lowered the amount of fresh water supplied to the bay (Rudnick et al. 2005). Less fresh water led to increased concentrations of salt and decreased circulation, agricultural discharges resulted in higher nutrient inputs, and the lack of storms and declines in sea turtle and other wildlife populations may have altered ecosystem dynamics. The interaction of these factors led to a mass die-off of seagrass, affecting 30% of the entire seagrass community, lowering oxygen in the water, and resulting in a non-linear shift between clear water and turbid water in some areas of the Bay. In response, managers at the South Florida Water Management District (SFWMD) launched the first restoration and monitoring efforts in 1992. However, competing scientific hypotheses for the mechanisms of seagrass die-off made it challenging to identify the key drivers and mitigate ecosystem change (Gunderson 2001). After years of experimenting with various potential drivers, the SFWMD created the Minimum Flows and Levels program to maintain freshwater delivery and restore the seagrass ecosystems of the bay. They set a minimum threshold of freshwater input of 105,000 acre-feet of water over a 365-day period, based on the relationship between these drivers, water clarity and seagrass die-offs. For Florida Bay, an exceedance of minimum flow is deemed to occur when the average salinity over 30 or more consecutive days exceeds 30 parts per thousand at the Taylor River salinity monitoring station. If this minimum threshold of freshwater input is breached, upstream municipal and agricultural water uses are prohibited until water delivery is restored. These minimum flow levels are subject to review and revision, allowing for adaptive management of the system as managers monitor seagrass recovery (Madden et al. 2009). As a result of the program, seagrass was restored and has been maintained in Florida Bay over the past decade. However, recent spikes in temperature are putting pressure on the system, indicating the need to revisit the key drivers in the face of a changing climate (See Figure 21 above).

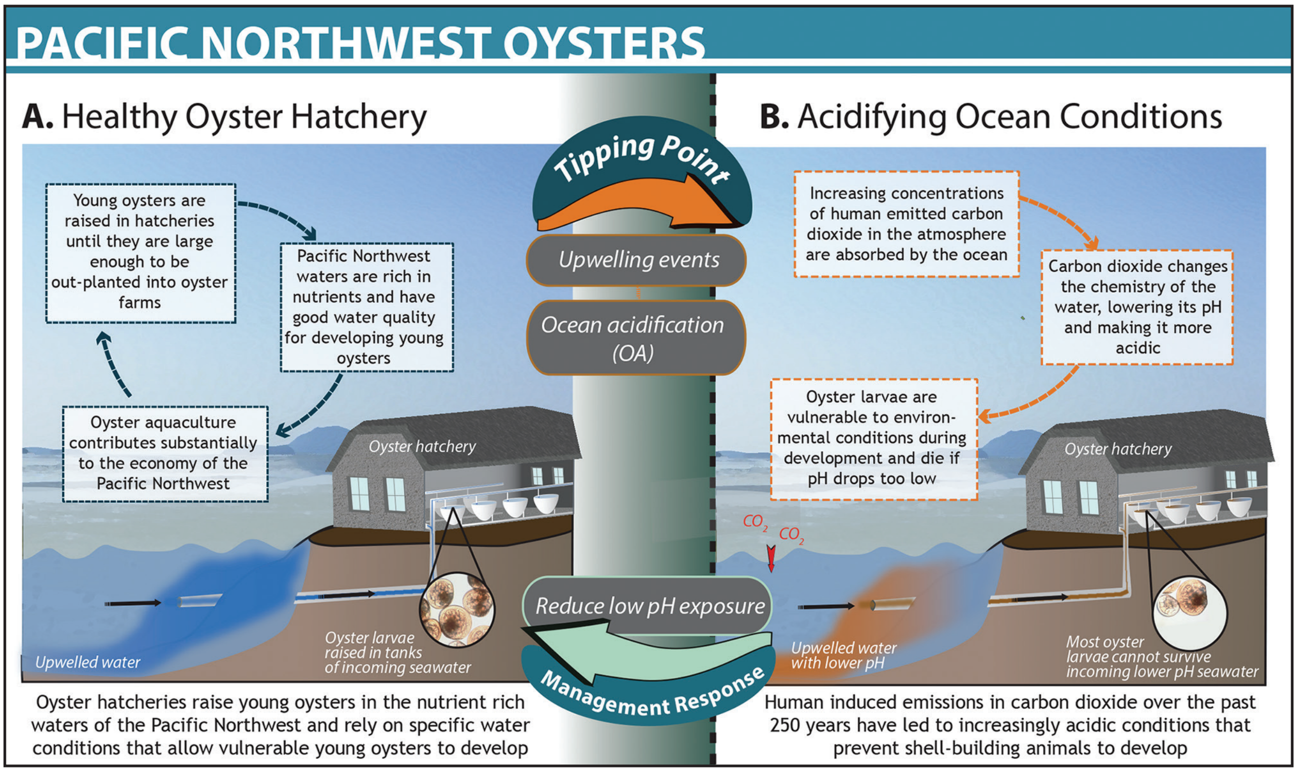


Figure 22. Credit: Ocean Tipping Points Project. Design by: Jacklyn Mandoske.

Oyster die-offs in Pacific Northwest

In the Pacific Northwest oyster farmers began seeing massive die-offs of up to 80% of their oyster larvae, or "seed" beginning in 2005 (Grossman 2011). Recognizing the threat of acidification to the regional economy, local culture, and coastal environment, commercial oyster fisheries began investing in research to better understand the underlying cause of the massive die-offs of oyster larvae. Researchers identified ocean acidification as the major cause of the massive mortality events between 2005 and 2009 (Barton et al. 2012). Following this finding, the federal government invested $500,000 in monitoring equipment for coastal seawater in order to acquire real-time data on ocean conditions (NOAA 2011). This real-time monitoring allowed oyster growers to identify when coastal seawater aragonite saturation state (a key parameter of seawater carbonate chemistry) exceeds a critical threshold value of ~1, at which larval growth and shell development are compromised (Waldbusser et al. 2015). Initial solutions have relied on managing around the problem, such as limiting seawater intake to times when conditions are acceptable to young oysters or buffering incoming seawater by adding basic chemicals, such as sodium carbonate (baking soda) (Dewey 2013). However, in the face of global climate change, these solutions are only temporary. Some companies have chosen instead to relocate hatchery operations to more tropical locations less vulnerable to ocean acidification. The collaboration between oyster fishermen and scientists in the Pacific Northwest has resulted in many [growers recovering nearly 77% of their losses](#) (See Figure 22 above).

Strategy 4. Evaluate Management Scenarios and Select a Course of Action

Background

Once you have a clearly defined set of objectives, benchmarks, and targets you are trying to reach, and limits to avoid, it is time to decide on a course of action. Here we build on Strategies 1, 2, and 3 to use the information that has been gleaned throughout the process to take management action.

What set of strategies will help you to reach your goals? In the face of uncertainty and complexity, scenario analysis can help you weigh the costs and benefits (aka tradeoffs) of different alternative management actions. Depending on your particular policy context, it may be useful (or requisite) to evaluate the anticipated ecological, social, economic, and cultural impacts of any proposed action or plan across multiple species, habitats, and stakeholder groups. For systems prone to tipping points, the challenge is to do so while also specifically evaluating whether the alternatives under consideration can reduce the chances of crossing undesirable tipping points or enhance the chances of recovery. Such scenario evaluation may range from qualitative to quantitative analysis, depending on your team's technical capacity and access to data and what is appropriate to the management decision under consideration (See Figure 23 below).

"Ultimately, understanding shifts between ecosystem states, particularly given interacting and changing stressors, requires getting comfortable with estimation and prediction, and investing in good data. Ongoing research on effective system indicators, costs of management action or inaction, and societal preferences and trade-offs among management options will continue to generate new insights into how best to manage ecosystems prone to tipping points."—Selkoe et al. 2015

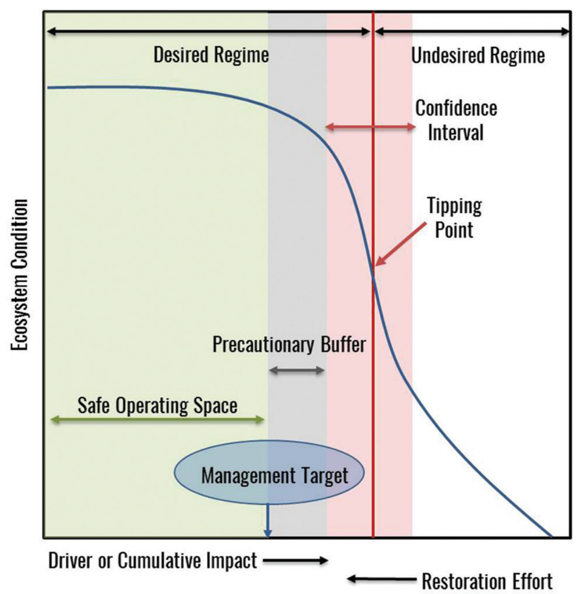


Figure 23, adapted from Selkoe et al. 2015 with permission. Management target is set outside the precautionary buffer to avoid undesirable tipping points while maximizing ecosystem benefits accruing from the driver being managed.

Strategy 4a.

Develop potential future management scenarios and choose appropriate decision support tools to evaluate them

What does this mean?

Scenario analyses allow for the development of a range of potential future scenarios and trajectories due to social and ecological changes. These scenarios can then be investigated with both qualitative and quantitative methods. They can be developed to encourage dialogue among user groups about the benefits and challenges associated with different future scenarios and thus require information on how ecosystems and social components interact (Collins et al. 2011).

Scenario analysis can help identify the costs and benefits of different alternative management actions and can be an especially powerful decision tool in ecosystems prone to tipping points (Levin and Mollmann 2014). In such systems, scenario analysis allows you to explore alternative perspectives about thresholds, feedbacks, and system resilience, and gain insight into the potential consequences that may occur with abrupt or non-linear changes. Ecosystems that experience tipping points often surprise scientists and managers, and thus 'what-if' scenarios offer a useful approach for analyzing consequences of abrupt social-ecological changes.

Where social-ecological thresholds exist, **cost-benefit analysis** can also assist in the decision-making process and may push managers to prioritize precautionary actions that result in economically or socially beneficial ecosystem outcomes. Where the cost-benefit relationship is linear, there is no obvious policy choice—each unit of cost will yield a consistent amount of benefit, and the agency must decide among alternatives solely based on social preferences and values. Conversely, where a nonlinear relationship exists between the costs and benefits of action alternatives, cost-benefit analyses can help to identify alternatives that provide the greatest benefit at the least cost.

In the case of nonlinear ecosystem responses, the costs and benefits of management actions may also change nonlinearly as that threshold is approached (Kelly et al. 2014). Here, cost-benefit analyses can provide agencies with a dual incentive to implement threshold-based management: both carrot and stick. The carrot is a management action that accounts for a more cost-effective economic threshold; the stick is often an existing regulatory requirement to conduct a cost-benefit analysis under certain statutes.

The usual caveats apply: costs associated with restricting economic activity that may generate risks to ecosystems and ecosystem services are often highly salient and relatively easy to quantify, while benefits are often not salient and difficult to quantify, exacerbating discount rates and failure to adequately consider non-market costs and benefits.

Tradeoff analysis can be another powerful tool that incorporates scenario and cost-benefit information into the process and can help managers understand potential resource use conflicts and stakeholder priorities (Lester et al. 2013). Trade-off analysis allows stakeholders to engage in management decision-making by evaluating the benefits and costs of different potential management strategies across multiple sectors or ecosystem services (White et al. 2012, Lester et al. in review). Quantifying the tradeoffs can help determine management priorities and options. It begins with identifying stakeholders and their interests, which inform different potential future scenarios, and then this information can be fed into a multi-criteria analysis which can rank the alternative future management scenarios from least to most socially preferred (e.g., Brown et al. 2001).

Given adequate information, such analyses can allow an agency to maximize benefit, minimize cost, and closely match economic decisions to environmental impacts on the ground. Moreover, such analyses may serve as a simple translation device for natural scientists to communicate the complexity of ecological thresholds to decision makers in a digestible manner.

Why is it important?

Deploying tools like scenario testing, tradeoff analysis, and cost-benefit analysis can save time and money by ruling out ineffective or inefficient strategies based on evidence. Where they exist, these tools can also reveal win-win solutions. And where tradeoffs exist, comprehensive analysis has been shown to focus attention on true (versus perceived) tradeoffs, which can help to defuse conflict. It may also help managers and stakeholders cope with uncertainty: exploring a range of future scenarios can help you to evaluate how robust your strategies are in the face of uncertainty. Such analysis may also provide insight into which strategies will be most resilient or adaptable in the face of future change.

How do you do it?

The **first step** in developing management scenarios is to identify the potential management alternatives that are most likely to keep your system within the '***safe operating space***.' This step builds off of the science and decision-making processes we reviewed in Strategies 1, 2 and 3. Key questions to ask to help you apply and expand the knowledge gleaned throughout these previous steps include:
- Which drivers are within your influence and what management decisions can you make to affect them?
- What set of options do you have at hand to avoid crossing undesirable tipping points or to increase the chance of crossing desirable ones?
- What stakeholders and sectors may be affected by the management decisions under consideration and what ecosystem functions, goods and services do they value and depend upon?

Depending on how comprehensive your scenario analysis process is, you may be able to consider all possible options (e.g., all possible spatial configurations in an ocean planning exercise) or a smaller set of alternatives.

The **second step** is to decide on your planning and decision-making time horizons. Questions to ask include:
- Are you considering a short-term decision, such as a fishing quota that will last through a season, or a longer-term decision, such as an area designation that may be in place for years?
- How far out into the future do you want to consider when weighing the tradeoffs associated with different actions you could take?

For example, when planning for new offshore development, you may want to consider how the infrastructure will affect the environment and existing users over its foreseeable lifetime. If climate change is a potential driver of ecosystem state change in your region you may want to forecast its effects over the coming decades and assess how best to adapt your management through time.

Third, consider whether there are different potential future conditions to evaluate in the plan. Again, this will incorporate the information that has been gathered throughout the planning phase and will rely heavily on Strategy 2 ("Define Management Objectives in Relation to Ecosystem State"). We want plans and actions that can be robust to a range of socioeconomic and environmental conditions. The longer the management decision-making time horizon, the wider that range of future states might be. In a system that is prone to tipping points, this is particularly important, because those conditions can change dramatically in a short period of time. It is valuable then to evaluate management strategies under a range of likely possible futures to see how they perform or how they would need to be adapted to continue to meet your management objectives.

This can be done with discrete scenario testing (i.e., comparing how a strategy performs under Future State A versus Future State B), with a dynamic model(s) that can simulate fluctuating future conditions, or a combination of the two. As an example, the Millennium Ecosystem Assessment used a qualitative discrete scenario approach to compare outcomes for two different general approaches to sustainable development (promotion of economic growth and public goods versus proactive management of ecosystems and their services) under two different basic futures (expanding globalization versus increasing regionalization) (ME Assessment 2005, Scenarios Assessment Report). This resulted in four different possible future states (see Figure 24 below), for which they then used interviews with international leaders and thinkers and other qualitative information to assess the risk of extreme ecosystem events (those affecting >1 million people) in each scenario.

Below we detail three additional examples of scenario and tradeoff analysis to inform environmental management decision-making in the face of tipping points.

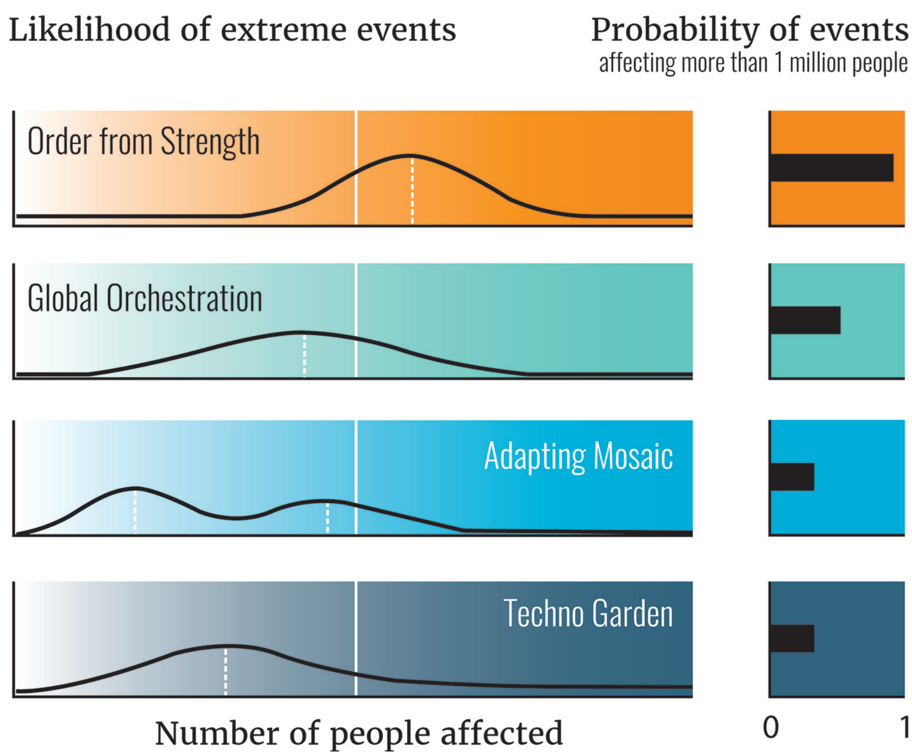


Figure 24, from the Millennium Ecosystem Assessment Scenario Assessment Report (2005) with permission.
Left column: Magnitude of extreme event (measured as the number of people affected) on the x-axis versus likelihood of events of a given magnitude, on the y-axis, for four different global development scenarios. Right column: Length of the bar indicates the annual probability of events that affect more than 1 million people.

Weighing tradeoffs associated with reducing sediment runoff to reefs in West Maui, Hawaii

Increased runoff of sediment and pollutants from land threatens coral reef ecosystems around the world. These land-based source pollutants (LBSP) have been linked to degradation on some Hawaiian reefs. As an example of how to quantitatively evaluate management options for reducing key drivers of reef change, we developed a decision support tool that analyzes the costs and benefits of different management strategies aimed at reducing LBSP (Oleson et al. 2017). Specifically, we examined the tradeoffs, in terms of management cost and sediment reduction, among potential agricultural road repair management actions in West Maui, Hawai'i. We identified the most cost-effective roads to repair (the most sediment reduction per dollar spent), and found significant cost savings associated with repairing these roads. We also found that the best environmental gains for lowest economic cost could be achieved if landowners cooperated, although the benefits of cooperation dissipate if landowners do not target cost-effective roads (See Figure 25 below).

Informing target-setting for marine spatial planning in Puget Sound

Levin and co-authors (2015) developed a social-ecological framework for scenario evaluation and target-setting in social-ecological systems. Demonstrating the approach in eelgrass ecosystems of Puget Sound, they illustrate how to determine people's preferences and willingness to accept specific management actions (i.e., risk tolerance). Puget Sound makes up a unique estuarine system that is valued for its beauty and ecological importance. Like other marine and estuarine ecosystems, Puget Sound supports a variety of human activities, leading to some degradation of the processes supporting its ecosystem. Eelgrass is a particularly important habitat in Puget Sound, highly valued for its ecological and economic benefits. The authors estimated changes in eelgrass in Puget Sound related to a variety of potential changes in human activities using expert elicitation and Bayesian network analysis to generate the relationships between changing human activities, different drivers, and eelgrass. They then developed seven scenarios based on alternative futures analyses of the system, including

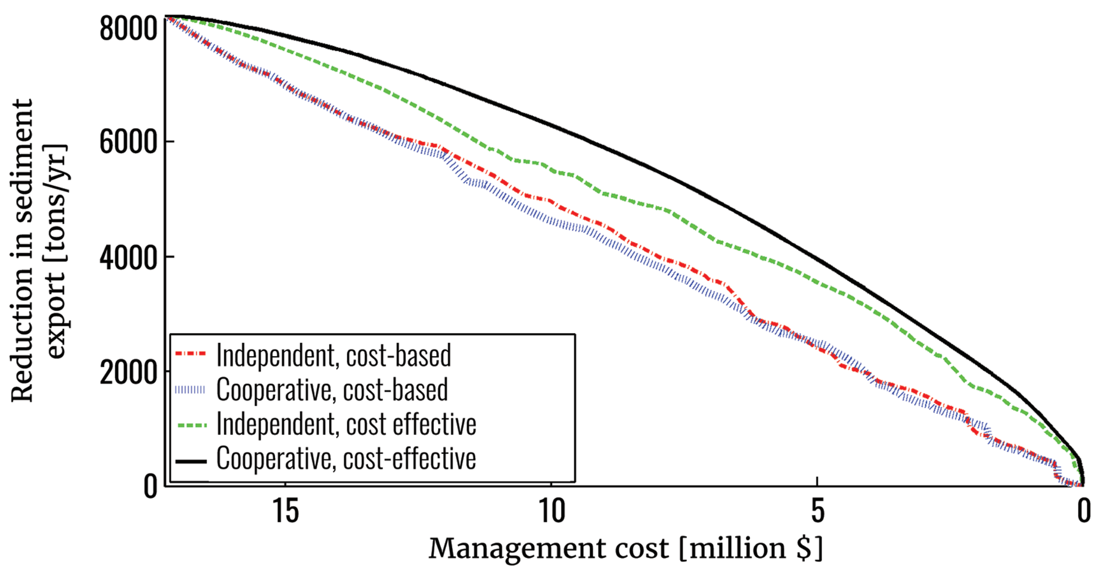


Figure 25, from Oleson et al. 2017 with permission. Each point represents a set of road segments to be repaired at a given cost, with a given reduction in sediment delivery to the coast. Colors represent whether landowners make decisions independently (red or green lines) or cooperatively (blue and black lines) and whether they choose roads for repair based on cost ($) or cost-effectiveness (tons of sediment reduced/$). The most efficient outcome is achieved with cooperative management targeting cost-effective road repairs (black line).

changes in growth management, transportation, and land use patterns, as well as projected changes in sediment and nutrient inputs, shoreline armoring and overwater structures. These seven scenarios projected changes in the state of the social-ecological system, linking the changes in eelgrass with changes to a food web model that evaluated how eelgrass influenced the ecological community. Applying these seven scenarios, the authors examined trade-offs among 16 metrics, including seven biological indicators, four human stressor metrics, two metrics of development, and three indicators of economic costs. To identify people's preferences and willingness to accept the social-ecological outcomes from these scenarios, the authors generated social norm curves, where stakeholder preferences are linked to the social-ecological state (represented by the 16 metrics) from each scenario (Figure 27). They interviewed 128 individuals representing major stakeholder groups in the region, exposing the participants to the outcomes of the scenarios using two approaches: (a) radar plots that visualize trade-offs among the metrics (Figure 23), and (b) photo-realistic images that provided visualization of the different states of the ecosystem (Figure 26). Participants were asked to score the desirability of each scenario on a Likert scale from -2 (completely unacceptable) to +2 (optimal state). This allowed the researchers to identify the minimally acceptable state, the unacceptable states, and the participants' overall most preferable state, which was an increase of between 10% and 25% of eelgrass (Figure 27). The outputs from this approach could be used to inform management targets in the region.

Figure 26, from Levin et al. 2015 with permission. Examples of the visualizations used to examine the desired state of the social-ecological system. Depicted are an (A) overview, (B) urban center, (C) outlying region (rural growth and open space), (D) shoreline, and (E) subtidal marine environment for a stylized Puget Sound metropolis. Two scenarios are illustrated: scenario 2 in which growth is unconstrained and population rapidly grows, and scenario 5 in which growth is managed through a set of land-use policies.

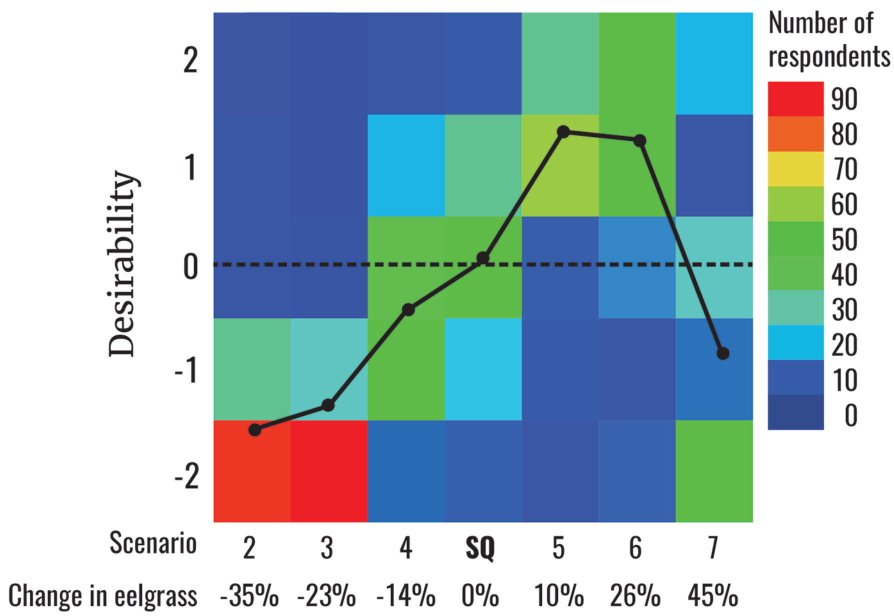


Figure 27, from Levin et al. 2015 with permission. A social norm curve showing desirability of seven development scenarios (and associated changes in eelgrass) on a Likert scale from -2 (completely unacceptable) to +2 (optimal state). The line depicts the average desirability of each scenario; the colors show the frequency distribution of responses to each scenario.

Investigating social preferences for herring management in Haida Gwaii

Building on the methods of Levin et al. (2015), our team conducted scenario workshops with stakeholders in Haida Gwaii to explore people's preferences around Pacific herring fisheries management. Interviews with Haida (the First Nation resident in Haida Gwaii for ~13,000 years) elders and community members informed our understanding of the linkages between herring and a variety of ecological, social and cultural dimensions (Poe et al. in prep). These linkages were further refined and quantified by Poe and colleagues through small focus group expert elicitation (Poe et al. in prep). Experts helped to quantify (on a 5 point Likert scale) the linkages between herring spatial distribution and biomass and each of four social benefits tied to herring for both Haida (via the traditional food fishery and/or commercial spawn on kelp fishery) and non-Haida stakeholders (via commercial spawn on kelp and/or gillnet or seine fisheries). The four benefits they scored were ability to practice harvest; access to herring eggs on kelp (k'aaw) for food and feasts; social relationships; and connections to herring, its places and the herring environment.

An existing Ecopath model of the ecosystem (Ainsworth et al. 2014) was modified to examine ecological changes that would result from changes in herring biomass under 13 different fishing scenarios (Levin et al. in prep). We then provided workshop participants with visual, graphical and written descriptions of how herring, other species, and social values could be expected to change under each scenario and asked them to rank the desirability of each scenario on a Likert scale. Aspects of governance, access, and the spatial distribution of fishing and processing activities were also included in the scenarios. Results of these workshops help to clarify community preferences for how herring fishing should be managed in Haida Gwaii.

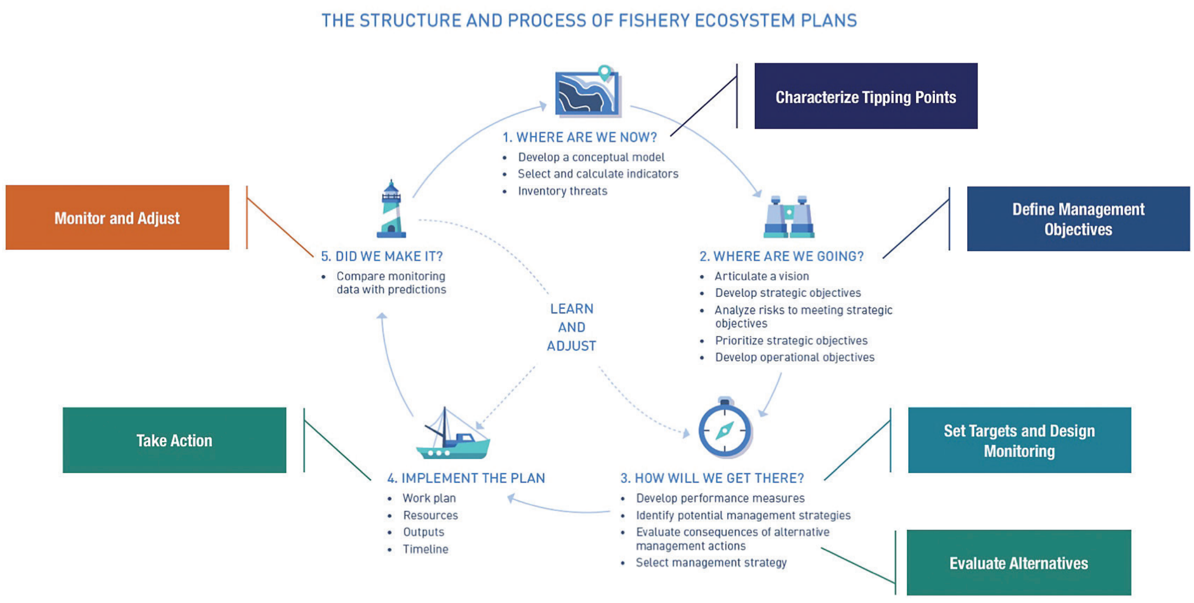
Conclusion

In this Guide, we have laid out four strategies for incorporating knowledge about ocean tipping points into your existing management decision-making. We have embedded these steps into a general adaptive management framework model that is widely used throughout natural resource management. This serves to not only make it easier to embed these steps into any ongoing adaptive management process you may be undertaking, but also to show that tipping points science can help you accomplish the tasks you may have already laid out in any adaptive management context. As an example of how these steps lend themselves to other resource management processes, in the box below we show how our four step process maps onto the Fishery Ecosystem Plan loop developed by the Lenfest Fishery Ecosystem Task Force in 2016.

Box 4. *Integrating with existing management processes*

The Fishery Ecosystem Plan Loop

The main recommendation of the Task Force report is that Fishery Ecosystem Plans (FEP) be developed to create a structured process for establishing ecosystem goals within fisheries management and translating them into action. The FEP Loop is presented as the conceptual framework for planning and implementation. While the terminology used in the FEP Loop and the OTP Process may differ, the ideas and order of operations included in these plans mirror one another closely.



Box 4 cont. *Integrating with existing management processes*

Where are we now? = Characterize Tipping Points
In both the "Where are we now?" as well as the Characterize Tipping Points steps, the first stage is to understand your system and where it is relative to key targets or limits.

Where are we going? = Define Management Objectives
In this step, one identifies management goals and defines measurable management objectives. A tipping point perspective can be integrated by stipulating that the system needs to stay within a certain range of conditions associated with desired ecosystem states, known as a "safe operating space".

How will we get there? = Set Targets and Design Monitoring, and Evaluate Alternatives
In this step, one establishes performance measures, sets target or limit reference points, and identifies potential management actions and their consequences. Note, this step includes activities from two Ocean Tipping Points strategies.

Implement the plan = Take Action
Once all of the potential alternative management options have been evaluated managers must select the management strategy that will be most beneficial for the entire system and implement it.

Did we make it? = Monitor and Adjust
Both frameworks emphasize the importance of monitoring the system, evaluating its response to management action, and adjusting accordingly.

From characterizing tipping points, to defining management objectives, designing monitoring programs, and taking action, we hope this guide has helped you identify ways you can incorporate tipping points science into your own ecosystem evaluation and management. The methods, themes, and concepts presented in this guide are not meant to be prescriptive, but instead offer new ways of addressing long-standing, commonly-encountered ecosystem management problems. While tipping points in marine social-ecological systems change the rules of the game, the tools and concepts presented here can help you to anticipate, avoid, or recover from these dramatic changes.

Above all else, we hope that this guide can provide an accessible and interesting foundation in tipping points science and concepts upon which to build more successful and adaptable management solutions.

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Glossary

Alternative Ecosystem States: When a single set of ecosystem conditions supports two or more different stable ecosystem states separated by an unstable threshold.

Conceptual models: Conceptual models represent ecological and/or social components and how they link to one-another, often with a focus on food web relationships. These models may also depict biophysical conditions and potential external drivers (e.g., nutrient input or shifting ocean temperatures) that are most likely to influence or alter those relationships.

Critical Transition: A theoretical term referring to a specific type of threshold in which a system passes a tipping point and transitions into an alternative ecosystem state or regime.

Driver: A force of change. According to ecological usage, any force associated with any natural or anthropogenic process, event or activity that causes a change in an ecosystem process, component, function, property or service. Throughout this guide we use "stressor" and "pressure" synonymously with "driver".

Early warning indicators: a specific type of indicator that provides information in advance of a regime shift. These indicators are most effective if they provide information that allows managers to be able to anticipate shifts with sufficient time to respond. Three common types of early warning indicators are listed below.

Critical slowing down and flickering: As a system approaches a threshold, the time it takes to recover from a disturbance increases due to loss of resilience (Scheffer et al. 2009) and the structure and/or function of the ecosystem starts to alternate between two states over a short time period (Dakos et al. 2012).

Autocorrelation: Change across ecosystems tends to become correlated in space and time prior to a tipping point (Biggs et al. 2009; Kéfi et al. 2014). This shift occurs when large-scale drivers, such as climate shifts, override feedback mechanisms that previously maintained stability and begin to dominate the ecosystem response.

Variance: The response of ecosystem components to drivers becomes more variable as a threshold is approached. Increased variance can be detected with little underlying knowledge of "normal" ecosystem dynamics (Carpenter and Brock 2006; Litzow et al. 2013), and can be detected in spatial and temporal analyses (Donangelo et al. 2010).

Ecosystem service: the goods and services provided by ecosystems that generate benefits to people (Granek et al. 2009). "Ecosystem services are the benefits people obtain from ecosystems. These include provisioning services such as food, water, timber, and fiber; regulating services that affect climate, floods, disease, wastes, and water quality; cultural services that provide recreational, aesthetic, and spiritual benefits; and supporting services such as soil formation, photosynthesis, and nutrient cycling." (Reid et al. 2005)

Ecosystem threshold: When a system crosses an ecosystem threshold a tipping point is triggered leading to a rapid change from one ecological condition to another. This large ecosystem-wide shift in the structure and function of the ecosystem is the result of a small change in environmental or human drivers (Bennett and Radford 2003, Groffman et al. 2006, Suding & Hobbs 2009, Huggett 2005). It's important to distinguish between such ecosystem thresholds and management thresholds (e.g., water quality standards), which may or may not be based on knowledge of an underlying nonlinear ecosystem response.

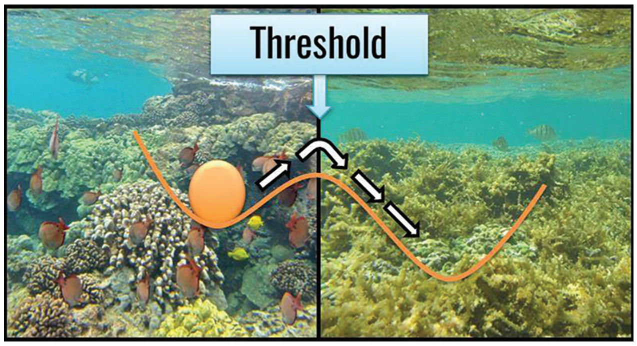

Figure A. Here an ecosystem threshold marks the transition from a coral dominated system to an algae dominated system, two regimes that are distinguished by key ecosystem attributes: coral cover, algae cover, and fish species diversity.

Feedback mechanisms: An ecological process that either reinforces or degrades the resilience of an ecosystem state (Briske et al. 2006). Positive feedbacks amplify the amount of change the system will experience in response to a small perturbation, whereas negative feedbacks dampen the effects of perturbations, counteracting the change (Fig. 5; Suding & Hobbs 2009).

Hysteresis: When the pathway of recovery of an ecosystem is different from its pathway of degradation (Suding & Hobbs 2009). Hysteresis is a concern when the driver which caused the regime shift has been removed but the system does not recover (Montefalcone et al. 2011), indicating that although the pre-threshold conditions have returned, the system remains in an alternative state. Thus, two alternative states are possible under the same external environmental conditions.

Indicator (of a threshold): A specific, well-defined, and measurable variable tracked through time which can communicate changes in ecosystem condition and provide an estimate of the location of an ecosystem relative to a threshold (Heinz Foundation 2008). Indicators simplify information about complex phenomena to improve understanding
(King 1997).

> *Leading indicator*: Measurements of a system that provide early warning of a change. Leading indicators are not necessarily good proxies for the changes taking place, but provide clues about the future (King 1997). In the context of regime shifts, suggested leading indicators that warn of an impending ecosystem shift include increased autocorrelation, rising variability, and 'flickering' between alternate ecosystem states.

> *Lagging indicator*: Measurements of a system that are taken after events, which indicate outcomes or results. They should attempt to provide a signal of the key changes in ecosystem interactions following the threshold (Herrera & Hovden 2008). For example, when measuring management performance, a lagging indicator would measure the number of times a threshold was crossed.

Reference point: A value of an indicator associated with a particular ecosystem state or condition that is often used to quantify management objectives.

> *Target* reference point: a value management aims to achieve (i.e., a socially desired ecosystem state, zone, or point) based on management goals. A target expresses a goal in quantitative, measurable terms that can be practically evaluated; e.g., the goal is swimmable water, the target is a maximum E. coli level.

> *Limit* reference point: a value management aims to avoid. e.g., if the goal is sustainable fisheries, the limit might be a maximum fishing mortality or minimum fish biomass values.

> *Baseline* reference point: a value associated with "initial" conditions, which needs context-specific definition. e.g. pre-industrial level biomass.

Regime shift: Rapid reorganization of a system from one ecosystem state to another (Carpenter & Folke 2006). These distinct ecosystem states are termed regimes and are characterized by a set of governing processes, species composition, and relationships among species and to external drivers.

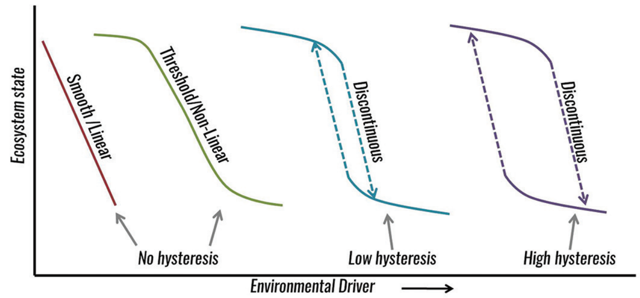

Figure B. Three types of regime shifts, defined by the shape of the relationship between the driver and the ecosystem state, modified from Dudgeon et al. 2010.

1. *Smooth or Linear*- characterized by a linear relationship between the driver (e.g. fishing effort) and the ecosystem state (e.g. fish abundance) (adapted from Lees et al. 2006).

2. *Threshold or Non-linear*- characterized by a non-linear relationship between the driver and the ecosystem state (adapted from Lees et al. 2006).

3. *Hysteretic* or *Discontinuous*- characterized by a non-linear relationship with hysteresis—in which the path from state A to B (degradation) is different from the path from B to A (recovery) and may be very hard to reverse (Scheffer et al. 2001, Collie et al. 2004, Lees et al. 2006).

Resilience: The capacity of an ecosystem to absorb perturbations while retaining its essential structure, function and feedbacks (i.e., stay in the same state, not cross a threshold) (Suding & Hobbs 2009, Folke et al. 2004). Ecosystem resilience is the capacity of an ecosystem to tolerate disturbance without crossing a threshold into a different regime (Resilience Alliance - http://www.resalliance.org/index.php/resilience)

Safe operating space: Ecosystem limits within which the risk of unwanted regime shift is low and resilience is high.

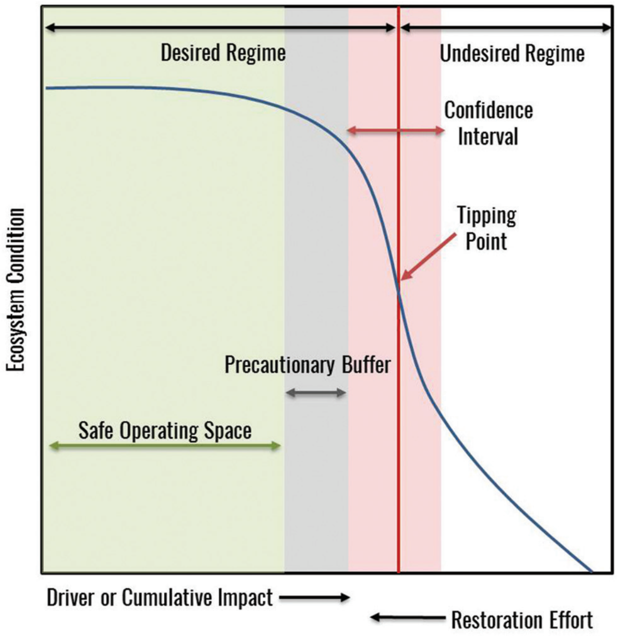

Figure C, adapted from Selkoe et al. 2015 with permission. The safe operating space (green) for management represents the range of driver levels with a tolerable level of risk of tipping into an undesired regime or ecosystem state and adequate to high resilience. If the risks associated with crossing the tipping point or costs of mitigation are very high or if the location of the tipping point is highly uncertain, the precautionary buffer (blue) should be increased.

Stressor: Used here as a synonym for Pressure and Driver.

Tipping point: The colloquial/loose synonym of threshold—a generally well-understood concept for communication with a broad audience that captures the non-linear and dramatic change associated with thresholds.

Vulnerability: The susceptibility of a system to harm or loss, due to exposure and sensitivity to a specific pressure (Turner et al. 2003, Chapin et al. 2009). Conceptually similar to resilience in that it characterizes the system's adaptive capacity, sensitivity to change, and ability to cope and recover, but unlike resilience, also includes consideration of the degree of exposure to specific threats.

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