Moving from A to B

EAFM EBFM

Guidelines for Practical Ecosystem-Based Fishery Management

A summary of findings from the Working Group on 'Benchmarks for Ecosystem Assessment'

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Key Terms & Concepts

Criticality analysis: analysis of network structure to identify nodes or segments (nodes and links) that are critical to performance of the network. If these critical components are lost the flow through the network would severely degrade causing the failure or fragmentation of the network.

Degree: the number of connections (in or out) the node of a network has.

Ecological (functional) traits: characteristics of species (morphological, physiological, or phenological) that influences a species' ecological processes, how it responds to environmental pressures and the species' role in an ecosystem's structure and function.

Ecological integrity: the capacity of an ecosystem to support and maintain ecological processes and biodiversity (content and structure).

Ecosystem structure: the network of biotic and abiotic components making up an ecosystem (note we focus only on the biotic and infer continuance of abiotic connections).

Ecosystem function: the combined set of ecological processes controlling the flux of matter (including nutrients) and energy through an ecosystem.

Ecosystem health: capacity of the ecosystem to maintain structure and function on ecological and evolutionary time scales.

(Google) PageRank: This index is a variant of the eigenvector centrality concept and is used by companies, such as Google, to rate the importance of websites (to improve search efficiency and web maintenance prioritisation). The index works by counting the number and quality (weight) of links to a node, more important nodes are cross link with and support more nodes.

Hub species: highly connected species (nodes in the network) that are found to tie the system together structurally and to facilitate trophic flow across a broad part of the system. The loss of these species would cause bottlenecks or splinter the network degrading its function.

Node: species in an ecological network (or functional groups in less resolved ecological networks), where connections between the nodes may be due to habitat dependency or feeding interactions.

Structural resilience: capacity of the network structure to continue functioning without degradation when nodes in the system are perturbed.

Topology: how the ecosystem is structured, what is connected to what.

Research Questions

- What are reliable indicators of ecosystem structure and function?
- Do these indicators work across many ecosystem types?
- How does the accuracy of indicators vary across data availability (e.g., data-rich vs. data-poor)?
- What are appropriate reference points, thresholds, or benchmarks associated with these indicators?
- How can these indicators be woven into existing fisheries management processes to achieve operational EBFM?

A Note from the Project Leads

Managers, scientists, and fishing communities are eager to move to ecosystem-based fisheries management (EBFM). But there is little practical guidance or agreement on indicators that can be used to measure the ecosystem properties that identify 'safe ecological limits' for fishing. Further, there is even less guidance on linking these indicators to decision-making. Current information is primarily focused on maintaining the productivity of an individual species or group of species, consequently using single species management and inconsistent incorporation of ecosystem data. As a result, many agree that the fisheries management system needs a fresh approach and clear recommendations on how to bring ecosystem concepts more fully into management of fisheries around the world.

Over the course of five years, we assembled and worked with an expert Working Group on "Benchmarks for Ecosystem Assessment." The purpose of the Working Group was to find indicators of ecosystem structure and function that could support EBFM and be used in as many different types of fisheries and ecosystems as possible. We joined researchers, managers, and policymakers from four different areas in Australia, India, Chile, and the U.S. Later in the project, we were approached by managers in the Gulf of Thailand and also applied our methods to these fisheries, further proving their utility in a wide variety of settings.

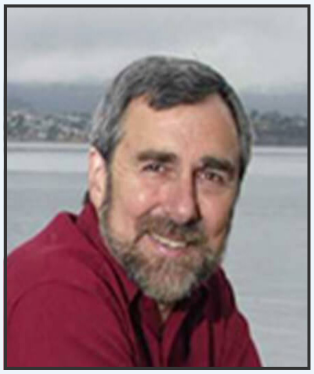
The perspectives shared from this diverse Working Group helped gain collective understanding of what it would take to move from ecosystem approaches in fisheries management (EAFM), which starts with a single (target) species approach with some consideration of ecosystem impact—to true EBFM, where predators, prey, habitats, and other influences on those species and ecological processes are included from the outset.

Through this process we learned that no group anywhere truly "does" EBFM. Rather, nations are attempting to retrofit ecosystems onto single species management processes and so are applying variations of EAFM. Although there is a keen desire to move to EBFM, decision makers often do not get the same exposure as scientists to processes and options from other locations. This hampers progress because decision-makers in many places do not know how to begin the transition to EBFM and have a lot of pressure not to misstep given the importance of fishing to so many livelihoods. This underlines the need for policy capacity building—just as there is a shortage of science skills in many locations, there is equally a knowledge gap around what management options are available.

The Working Group experiences also reinforce the importance of co-production between science and management. That is, producing science that aligns with management needs and processes, so that evolving management needs are scientifically achievable, and that together they deliver sustainable fishery production. These points may seem obvious but, much like EBFM, they are often hard to do. When done well, co-production is an immense opportunity to learn together, see what is possible with what we have, and discuss options free of the daily grind that often dominates thinking.

The ecosystem indicators we've identified work in combination with current data sets and allow for ways to monitor and respond to changes in ecosystem structure more directly. By sharing with others, we hope this offers a path forward, not only in the transition to EBFM, but also ways of understanding how to manage the extraction of resources from our oceans. We have already begun that journey working with new project partners—in Indonesia and elsewhere—to bring together these structural indicators and multispecies harvest strategies that will help put EBFM on an evidenced-based foundation for new systems.

Dr. Beth Fulton
CSIRO



Dr. Keith Sainsbury
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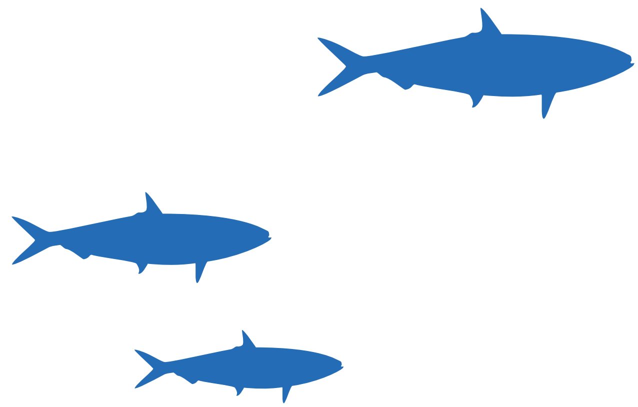
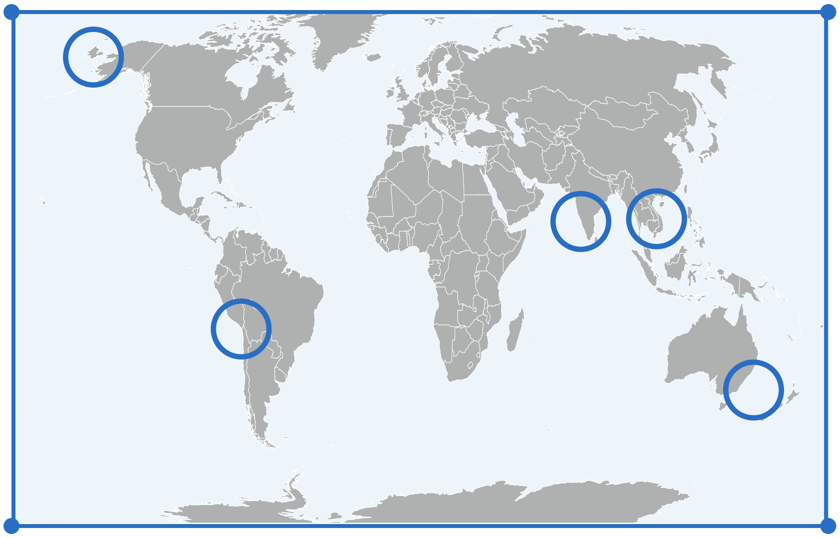
Lessons Learned

No group anywhere is truly doing EBFM, but many nations are trying.

Many nations around the world are doing their best to achieve and maintain sustainable fisheries. They try, however, to retrofit a system that is based on adding some ecosystem, bycatch, and habitat considerations into single-species management. This is a step in the right direction, but inhibits progress for incorporating multi-species, ecosystem-wide scientific methods into decision-making. With the best of intentions, the majority of those nations are following the same circuitous path to EBFM, via single species management and various forms of the ecosystem-approaches to fisheries management (EAFM).





The shift to EBFM cannot be done in siloes.

There is political will and a keen desire to make the move to EBFM, but decision-makers do not have the same exposure as scientists when it comes to understanding the process and its implementation. Generally, decision-makers have limited opportunity for exchange ideas and approaches with their management colleagues and scientists. But bringing decision-makers and scientists together at the start—as opposed to later in the process—helps meet the needs of researchers, mangers, and policymakers alike. This co-production facilitates a direct connection of decision-makers in different fisheries and nations, which can increase their breadth of experience and how to advance practical EBFM options.

When it comes to ecosystems, MSY does not work.

Maximum sustainable yield (MSY) is based on a single species estimate. It has been known for decades that it is impossible to simultaneously achieve the individual MSY for each species in an ecosystem. However, Multi-species Maximum Sustainable Yield (MMSY) can estimate system-level yield in fisheries and is a straightforward analogous concept to MSY that can assist in achieving EBFM. When MMSY is achieved not all species will be providing their individual MSY.

Nonetheless MMSY needs to be applied with care as research shows that very different MMSY levels exist for different ecosystem states, including ecosystem states created by past or future exploitation. Decision-makers and communities need to be clear about what ecosystem state they desire, each with its own implications for food supply, economic returns, and ecosystem integrity and resilience. Only then can an appropriate MMSY be defined and used.

Fisheries management does not need to be overhauled; it just needs to be adjusted.

Current fisheries management is very path-dependent, and it is difficult to break away from expectations based on existing and past management processes. Changes to achieve EBFM will be more rapid if we can re-use existing fisheries management approaches and infrastructure. In that context, ecosystem indicators that paint a fuller picture of the system's structure and its essential elements can be calculated with the data we have now. Rather than overhauling the entire fishery system, managers and scientists need to reframe thinking around reporting and using new or additional indicators.

Principles of this research can be applied in other settings.

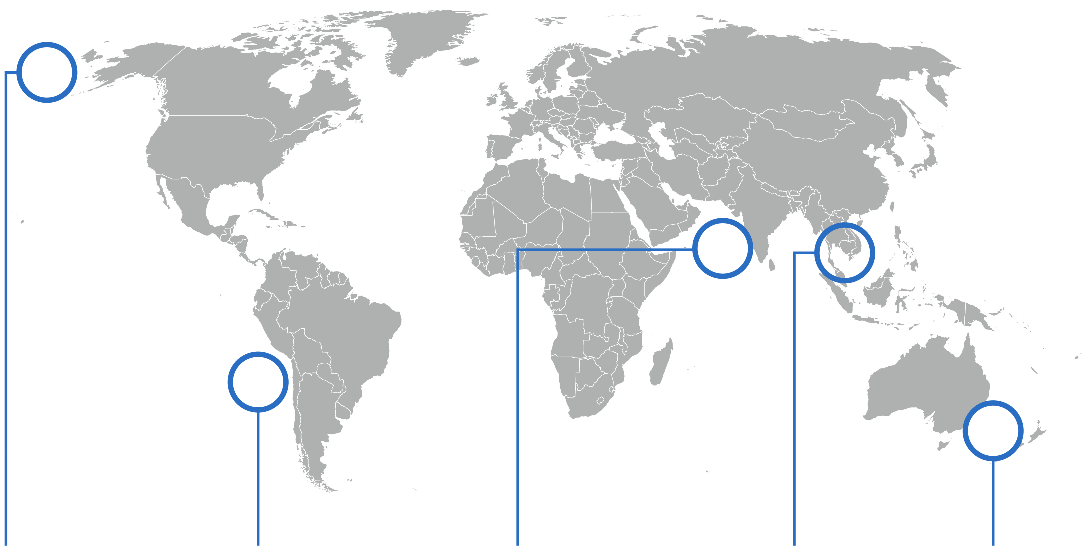
While the methods here are applied in fisheries management, their key concepts can be applied to other ecological impacts and management strategies. For example they allow us to integrate impacts of climate change and other human-driven disturbances of marine ecosystems into ecosystem-based planning.

The Process

1 Identify case study regions

Marine waters off the coasts of Alaska, U.S., southeast Australia, southwest India, and central Chile were selected as case study locations (Figure 1). The team also collaborated with managers for the Gulf of Thailand and included this region in the study to further test how easily the approach could be used in different contexts. These systems were chosen based on their contrasting ecological, economic, and social structures, their varying levels of available fisheries data, and a political willingness to move from EAFM to EBFM.

Profiles of case study regions



Aleutian Islands in the Bering Sea

A highly productive area that sees quite high catches but is still within a management system that uses individual species quotas. It also uses intentional caps on the amount of exploitation at the ecosystem level.

Northern-central Chile

A highly productive upwelling system, primarily fished with a quasi-commercial artisanal fishery. The formal management structure has historically taken a species-by-species approach to defining fisheries.

Kerala, India

A highly seasonal and productive tropical system that has long been fished by many thousands of fishers using a range of gears from very simple traditional gears through to highly mechanized offshore operations. The complexity the of the ecosystem has seen fisheries management arrangements focus on effort control measures.

Gulf of Thailand

A highly productive and diverse tropical ecosystem that has been fished intensively for decades.

Southeastern Australia

A low productivity but highly diverse area targeted by recreational and commercial gears of many types. Commercial fishing is under quota management control for the main commercial species with broader ecosystem considerations included via an ecological risk assessment approach.

2 Convene managers and policymakers

The Working Group consisted of an Advisory Committee of policymakers and managers, plus a Scientific Working Group of scientists from each of the case study regions. Co-production of practical and robust approaches across the case studies was facilitated through a series of working group meetings that rotated between the case study locations. Having all members present for discussions of both scientific progress and management considerations provided good understanding of needs, potential constraints, and possible solutions for implementing EBFM.

3 Identify candidate ecosystem indicators

The Working Group reviewed existing literature to identify candidate indicators from a broad array of fields dealing with complex systems. Beginning with fisheries, but also including fields such as finance, systems engineering and network ecology. The team found 181 indicators of the human dimensions of fisheries and more than 400 ecological indicators. These indicators were then screened for performance and connections to fisheries objectives. The indicators explained here focus on specific structural aspects of an ecosystem, but it is important to note that other methods such as Principal Component Analyses (PCAs) and heat maps can also illuminate transitions in the system through time, providing an undrestanding of how past fishing and management responses have reshaped the ecosystem.

A note on indicators: Decision-makers desire information on social and institutional aspects of fisheries, but economic aspects dominate the available indicators on the human dimensions of fisheries. Often the explicit connection of these indicators with fisheries objectives is lacking. Human and ecological indicators are not independent, and the quality of management and ecosystem health usually change together in fisheries. There is a fundamental need for meaningful and pragmatic objectives and indicators for both human and ecosystem aspects of fisheries.

4 Test the robustness of indicators and ecosystem assessments

For each type of ecological indicator, a small number of indicators were repeatedly mentioned in the literature and fewer still were recommended as reliable and relatively easily interpretable. These common indicators included catch and effort, abundance (usually relative biomass), size and age, habitat area, and network indices. Researchers tested the robustness of each indicator under different data levels and management scenarios. New indicators describing the structural aspects of connectivity, and how fishing pressure is being applied to that structure, provide a new and apparently reliable way of evaluating ecosystems and the effects of fisheries on them.

5 Apply the indicators to case study regions

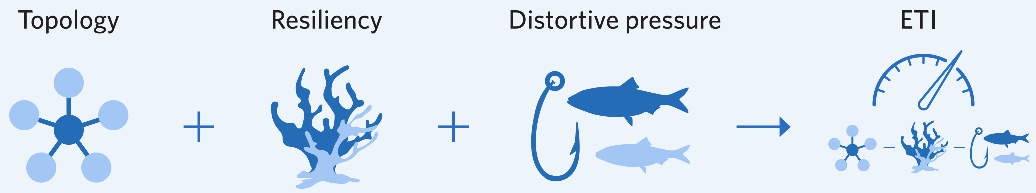
The selected indicators of ecosystem structure and function were applied to each case study region to examine a range of scenarios for how well they reflected ecosystem change and responsiveness. Discussions with decision-makers also made clear whether the information from these indicators provided useful information for fisheries decision-making.

Main Findings

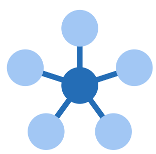
A Sounding Alarm for Ecosystem Health

Three dimensions of ecosystem structure are needed to define, understand, and measure the health of any ecosystem and how to conserve it. When combined, these indicators produce the Ecosystem Traits Index.

Ecosystem Traits Index (ETI)



Topology



Topology indicates how the ecosystem is structured and which species are most integral to this structure.
Some species in an ecosystem have a disproportionate impact on the ecosystem structure where they in effect tie the system together. The identity and role of these key species is based on their connectedness to other species and the habitat. Species that are considered a critical node in the web can be termed "hub species."

Hub species are not the same as keystone species.
Hub species are determined through a structural lens, as opposed to keystone species which are determined through an ecological lens. When compared to the keystone index, those species identified as "hubs" do not always align within the keystone framework. **This is important as it may change which species are prioritized for management attention.**

Hub species are identified using concepts of criticality analysis.
Researchers adopted concepts from other fields that study network structure and function. Criticality analysis is a method used in engineering, transport, and other forms of network maintenance to identify key "nodes" that need extra attention. For example, in a transportation network of highways and roads, a critical node might be a particular bridge that connects one piece of land to another. If that bridge is not maintained properly and lost, then the transportation network fails.

'Degree' and 'PageRank' methods work most reliably when determining hub species.
Hub species are identified using a combination of degree (the number of connections) and the PageRank index (originally developed to identify key internet pages). A range of other network indices were also used to check on system structure, but degree and PageRank were most reliable. Degree captures top predators' connection across the food web as well as basal groups that feed materials to a large number of other groups in the system. The PageRank index highlights centrally placed forage species that support the web as important prey species with connectedness across the web.

Extraction of hub species can result in large-scale trophic changes.
Removal of a hub species increases pressure to ecosystem structure. Too much pressure may result in system-wide trophic cascades, changing its structure and potentially causing the food web to fragment and collapse. In some cases this may trigger a regime shift- a shift from one state to another- changing the function of an ecosystem.

Resiliency

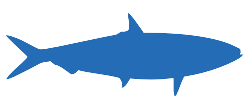
Network resiliency provides a deeper understanding of network structure and strength. Work by Gao et al. (2016), revealed universal patterns in the resiliency of complex systems, that is, their ability to recover after a disturbance. Using Gao's Index (see "Calculating Ecosystem Indicators and ETI"), it is possible to better understand how resilient a network or ecosystem is in relation to pressures that surround it.

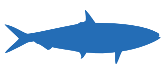
> "Ecosystem resilience is key to ecosystem sustainability and it can be measured."

Ecosystems with a strong, intact structure are generally deemed resilient through Gao's Index. This means the ecosystem is functioning at healthy levels and will likely bounce back should pressures be exerted on the system.

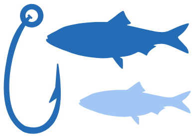
If the structure is weakened, an ecosystem may only have partial resilience, and is therefore at greater risk to collapse from surrounding or increased pressures on the system.

If the ecosystem is deemed to have little to no resilience, the structure has likely fragmented, and may not recover from further distortive pressures (external pressures on the system). New system structures can arise in these cases, but these structures will not be as extensive as in the previous ecosystem and so ecosystem function will be lower than previously.





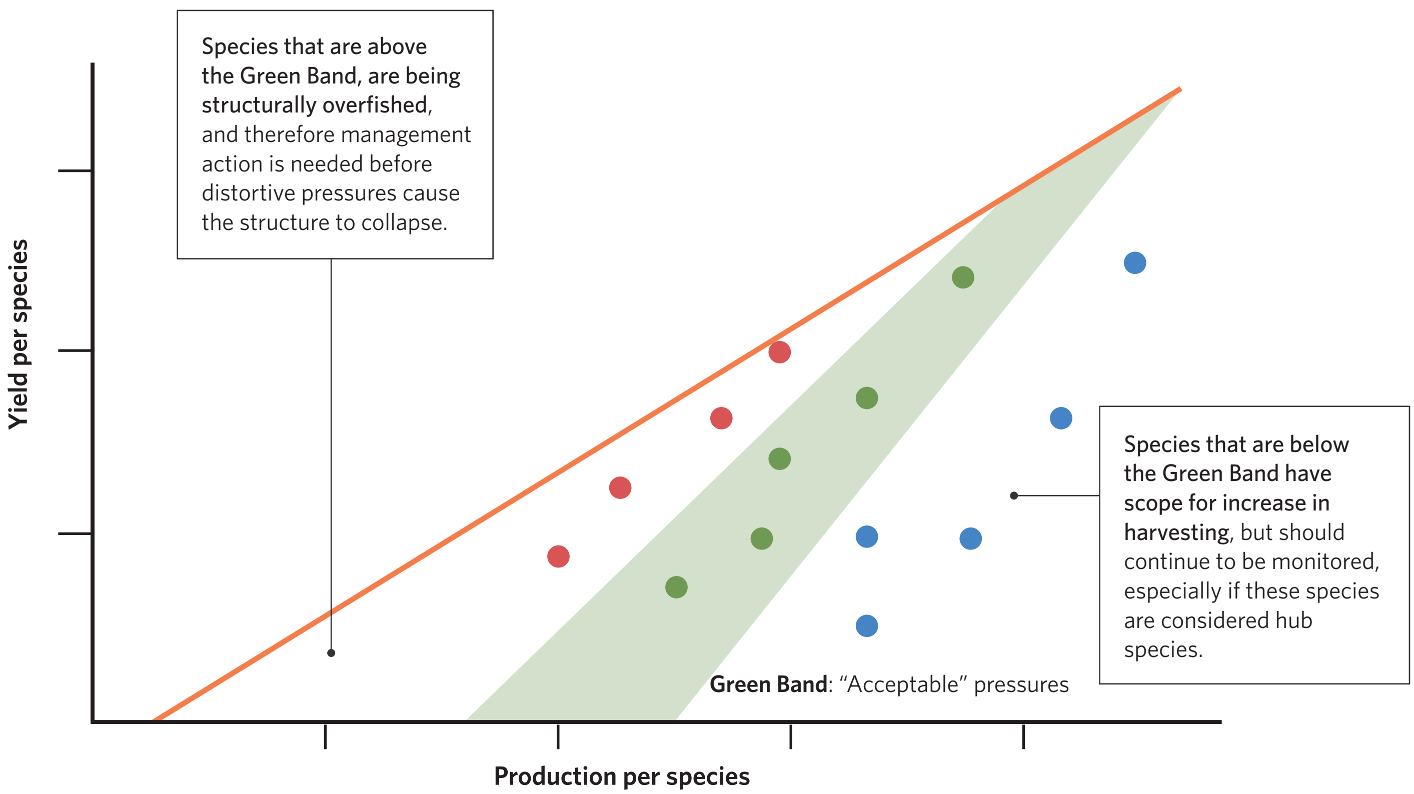
Distortive pressure

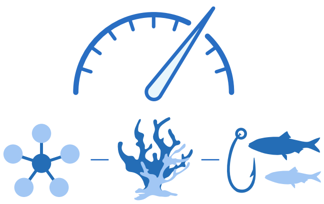


Distortive pressures can have varying effects on ecosystem structure.
Depending on the pattern of how pressure is put on the network (which nodes receive heavy pressure and which light), distortive fishing pressures can be weak or strong. Examples of distortive pressures might be extractive activities (e.g., fishing, logging, invasive species causing increased or changed predation), additive strategies (e.g., restoration or protection), or extreme weather events (e.g., hurricanes or heat waves). Identifying the acceptable level of distortive pressure on a system can help managers understand when action is needed.

Plotting fishing pressure on an ecosystem against its unfished profile gives you a range of acceptable harvest rates.
When biomass and production are plotted against the unfished profile of a system, this can tell us the acceptable level of pressure on a system – with "acceptable" being close to the pattern of mortality the system structure evolved under. The Working Group termed this the "Green Band" method, which can be used to define the tolerable level of pressure in a plot of catch against production.

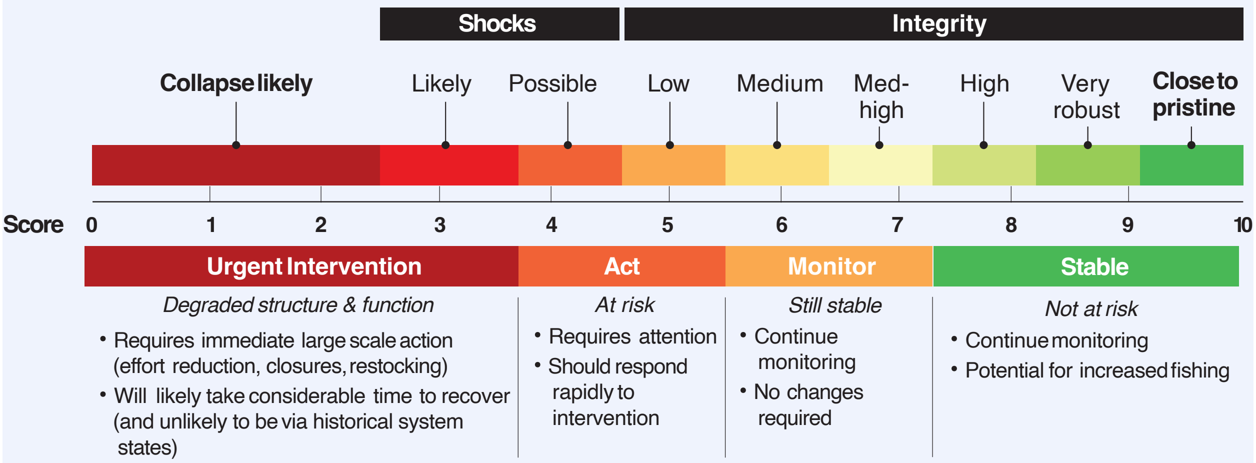
The "Green Band" method characterizes when distortive pressures are too much.
When data—or modelled values—for the catch and production of a species are marked on the plot as described described below, the ones that are within the "Green Band" are considered to be fished at a level aligned with the natural system. Extraction of species within the Green Band is not resulting in distortive pressure on the ecosystem structure.





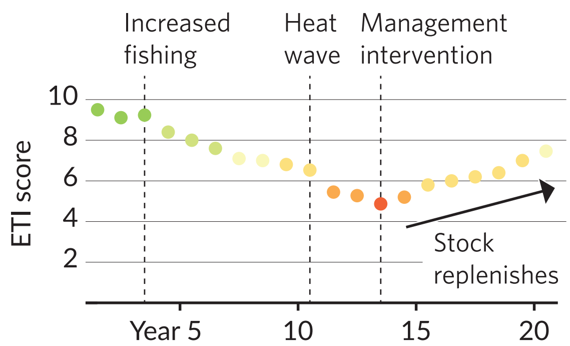
When combined, these indicators generate the Ecosystem Traits Index (ETI). These indicators can be calculated on their own which can help define targeted management actions. But when combined, they produce a qualitative score of ecosystem traits and health. The Working Group termed this as the Ecosystem Traits Index, or ETI. An ecosystem's ETI score signals its spectrum of health, from pristine to when it is at risk for collapse.

ETI can act as a warning system.
Think, a forest fire warning system, but for ecosystems. A high ETI score signals a healthy ecosystem structure and function. A low score indicates one or more indicators are out of balance and this requires further investigation- taking a closer look at each indicator will help managers understand where action is needed and what actions to consider.



ETI can be tracked through time.

Tracking the ETI scores of an ecosystem through time allows managers to understand whether or not a management or policy decision is moving an ecosystem to its desired state. This comparison can be made in a range of different contexts, from ecosystems dominated by fishing to the impacts of climate change or other non-fishery pressures (e.g. introduced species, changes in coastal habitats).



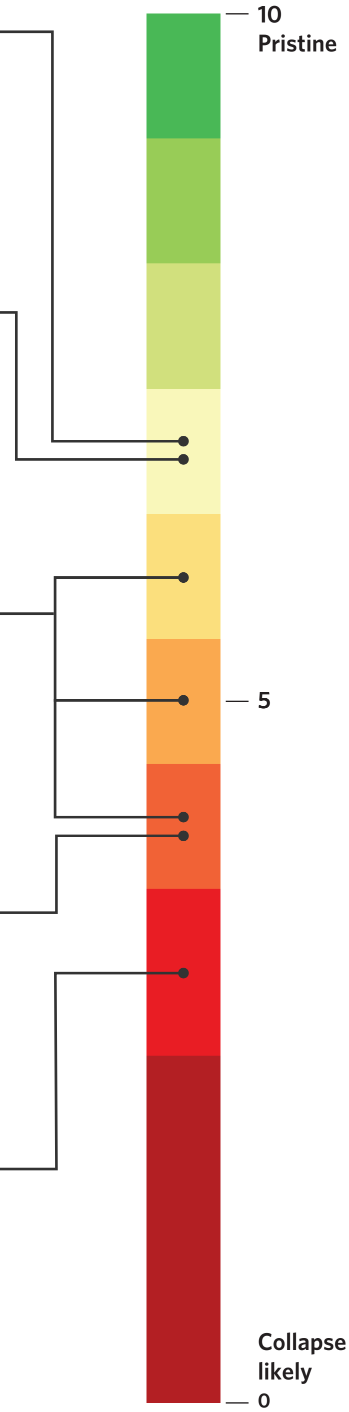
ETI is only just beginning to be used.
It may be revised as decision makers use it and researchers gain experience in calculating and communicating it. This is typical of these kinds of summary indicators – the Australian fire warning system has had many revisions to improve its ease of use. For now though the ETI has 10 risk scores.

Applying Indicators to Case Study Regions

	Network Topology: Hub Species	Network Resilience: Gao's Index	Distorti
Southeast Australia	• Demersal Sharks • Mesopelagics • Squid • Macrobenthos • Large Zooplankton • Gemfish	Partial resilience	A smaller portion of species c fishery sit inside the green ba and past fisheries targets have are being made to rectify this strategies. Some vulnerable sp
Aleutian Islands in the Bering Sea	• Atka mackerel • Sandlance • Benthic Amphipods • Pelagic Amphipods • Euphausiids	Partial resilience	In the Aleutian Islands in the E green band- likely a result of t system. However, not all grou were under distortive pressure
Kerala, India	• Large Pelagics - inshore • Medium bento pelagics - shelf • Squid • Cuttlefishes	Partial resilience, trending downward toward non-resilient threshold	Kerala is in a similar situation the green band in the upper m the region is putting distortive further management action is
Northern-central Chile	• Hake • Anchovy • Zooplankton	Partial resilience, trending downward toward non-resilient threshold	In Chile, very few fished group action is needed to remove dis
Gulf of Thailand	• Coastal tuna • Large piscivores • Macrobenthos • Large Zooplankton	Partial resilience, near to resilient threshold and trending away from non-resilient threshold	While fishing pressure has eas pressure on the system, with c **Note**: In the case of the Gulf of Th MMSY to evaluate fisheries option ecosystem states, and therefore it indicators helped define objective

: What they Found

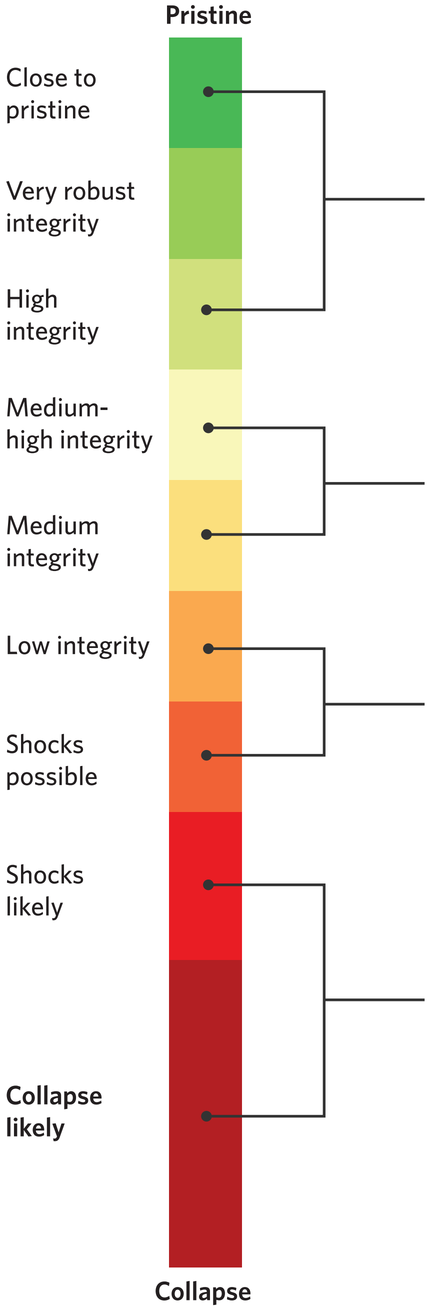
ve Pressures on the Network	Qualitative ETI Score
onsidered less important by the southeastern Australian nd or are slightly under pressure. However, both current e spent time under distortive pressure and attempts in current fisheries management targets and harvest pecies are not doing well.	Medium-high integrity
Bering Sea more of the species were inside or below the he precautionary ecosystem cap used in the management ps were in good condition. A number of vulnerable species e from incidental interactions with the fisheries.	Medium-high integrity
to Chile, where a number of groups sit outside of nargin. This reflects how intense fishing pressure in e pressure on the ecosystem structure and indicates needed to remove the pressures.	Medium integrity to shocks possible
ps sit within the green band, indicating further management stortive pressure on this system.	Shocks possible
sed somewhat over recent years, there is still significant distortive catches for many species putting them above the green band. ailand, managers are already using aggregate species indexes such as ns. The research team found that MMSY values can shift under various was imperative to be clear on the desired state. These ecosystem s around ecosystem state to set sustainable limits.	Shocks likely (stepping back from collapse likely due to the reduction in fishing pressure since 2013)



Using ETI:
Recommendations for Managers

1 Use ETI to signal when a system is at risk.

ETI scores can be easily translated to visual cues. For example from the ETI score, the following interpretations can be made:



Ecosystems with ranks of High to Pristine integrity are assumed to be stable and are not at risk under current environmental conditions and fishing pressure.

Ecosystems with medium to medium-high integrity do not need immediate action or changes in management. Most ecosystems with well managed and sustainable fisheries will have these scores, but ETI should be monitored so that managers can be quickly alerted if their condition deteriorates.

Ecosystems with ranks of Low integrity or Shocks possible should be paid special attention and should respond well to management responses.

ETI scores in the red zone from "Shocks likely" or "Collapse likely" signal an ecosystem where structure and function are badly degraded. Immediate management action, such as large-scale effort reduction, fishery closures, and similar management constraints are required. Ecosystems in these states can respond but will take many years of management to rebuild the ecosystem back to more desirable levels, such as to medium integrity, and the recovery path may be different to the path followed when exploitation was increased.

2 Use "métiers" to steer how pressure is applied in an ecosystem.

Fishing métiers are groups of fishers using similar gear in similar areas and catching similar species. Individual métiers have specific ecosystem footprints and changing the fishing effort or catch through different métiers can change the sustainability and impact of fishing on the ecosystem. Such changes in the fishing by different métiers can give sustainable catches without weakening ecosystem structure. For example the fishing through métiers that cause distortive pressure can be decreased while the fishing by métiers that do not impact vulnerable species or species above the "Green Band" can be increased. When the ETI signals that management responses are needed, managers can use the associated ecosystem indicators within the ETI to help inform their decisions. For example:

- **Prioritize harvest strategies by identifying hub species.**
  Managers should explicitly use topology in harvest strategies by prioritizing hub species as groups to be tracked and they should pay special attention to their status. This could include setting a target and limit reference levels to be precautionary to ensure that these critical species are not over-exploited.

- **Use Gao's Index to identify when pressures on an ecosystem are unsustainable.**
  Classifying the resilience of a system lets managers know if the existing pressures are unsustainable.

- **Determine which pressures are unsustainable using the Green Band method.**
  Managers can understand which species are experiencing the greatest pressures by using the Green Band method. This highlights which species are under greatest threat and where fishing effort or pressure from specific gear types should be alleviated. This is a very responsive indicator and can quickly show if the pressure on the system is already sustainable or if is moving toward a sustainable outcome.

3 Improve interpretation of catch composition.

Catch composition changes as ecosystem state changes, and some fisheries have transitioned through several different ecosystem structures during their development. Recognizing which ecosystem state correlates with the desired ecosystem resilience, food security, and fishery profitability can help managers set specific management objectives. If the desired ecosystem state does not match the current ecosystem state, then managers can decide what interventions are needed.

4 Use indicators as part of system-wide multi-species assessments.

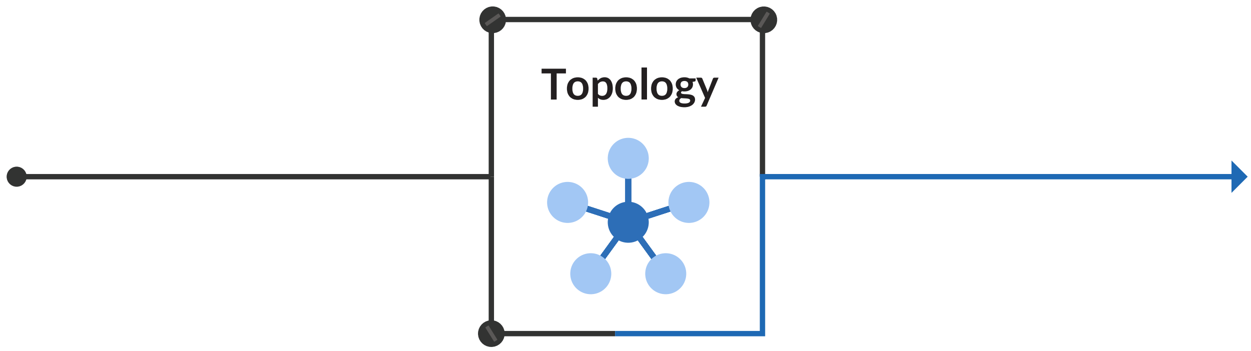
Multispecies and aggregate production models are used for fishery assessment in some areas, allowing them to estimate MMSY. However, it is important to recognize these results will shift if the ecosystem structure changes. Therefore, it is important to strategically identify goals and limits for fishery management. These ecosystem indicators can be shown alongside curves for the multispecies production models, highlighting trade-offs associated with differing amounts of exploitation at a whole fishery scale, as evidenced in the Gulf of Thailand (Fulton et al., 2022).

5 Use ecosystem indicators to frame decision-making.

In the Aleutian Islands in the Bering Sea, scientists and managers reported indicators as part of annual reporting cycles to help frame management decisions. This approach can be applied in any setting and supports increased transparency and consistency around quota setting with ecosystem state.

Additional Resources

Calculating Ecosystem Indicators and ETI



What is it?

When determining the health or strength of a system, it's important to first understand its structure and how various elements are connected. In ecosystems, food webs determine network structure. Loss of a "key" species from a food web can cause cascading effects like the loss of more species, or the collapse of the ecosystem. These species are often referred to as "keystone species." Another way to look at the network and its vulnerabilities is a criticality analysis. Looking for critical nodes, or connections, that if lost would cause bottlenecks or splinter the network, ultimately degrading its structure, and thus, function. When applied to a food web we have termed these critical nodes "hub species".

Hub species are ranked by importance to the ecosystem structure through their **Hub Index Score**, explained below. When compared to the keystone index, those species identified as "hubs" did not always align within the keystone species framework. This is an important finding, as for some cases, it changed which species were recommended for management attention.

Citation:

Fulton, E. A., & Sainsbury, K. (2024). Food web structure, the hub index and identifying species of ecological significance. Ecological Indicators, 166, 112378. https://doi.org/10.1016/j.ecolind.2024.112378

Why is it important?

This approach is broad enough to be applied to different management processes but specific enough to provide information specific to the system of management concern. Calculating the **Hub Index** for species reveals two aspects of ecosystem structure.

1. The first, **degree score**, highlights species with high connectivity—those that have many "local" connections (high local centrality). These were often top predators that feed widely across much of the ecosystem directly connecting many sub-webs, or key basal species that support the food web. This is important, as mesopelagic species have high connectivity but typically received the least attention within fisheries. While they are not yet a commercial target, there is growing interest and a large biomass available. Their role as hub species means that management should be particularly cautionary should fishing begin on them.

2. Secondly, the **Page Rank Index** often highlighted forage species such as large zooplankton, forage fish, and invertebrates as important prey species that support the web structurally both directly and indirectly. These species had high global connectivity, which further underscores the importance of forage fish as a critical component of network health and structure.

Once identified, management can track hub species through time and space. This will inform which species should receive special attention as losing those species would have a disproportionate effect on the ecosystem, potentially fracturing its structural integrity.

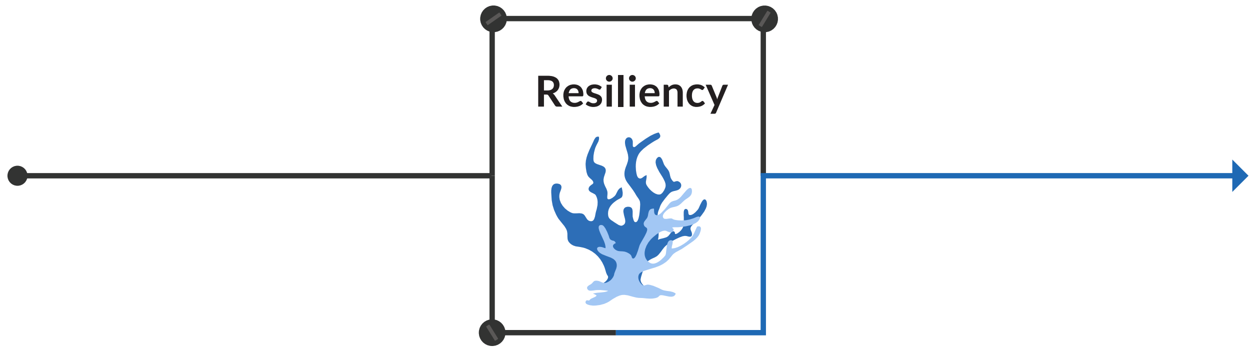
How it's calculated

Calculating the criticality analyses involves calculating standard network metrics for each species in the ecosystem, as well as the Page Rank Index. For each system analyzed, each of the nodes (species/functional groups) in the network are ranked based on each of their scores. A "Hub Index" Score is given to each species using the formula:

$$Hub_{Index} = min\ (R_{degree}, R_{degree\_out}, R_{pagerank})$$

Where R_{degree} is the rank for that species or group based on its degree (sum of connections in and out of the group, for example, the number of its predators and prey), $R_{degree\ out}$ is the rank for that species or group based on its degree out (the number of predators the group has) and $R_{pagerank}$ is the rank for that species based on the number and quality (weight) of links to that species (species that are cross linked, supporting many other species achieve a higher page rank).

In each case, a score of 1 indicates the highest score for that measure in the network. The species ranked in the top 5% for the network based on this score are considered **hub species**. The 5% breakpoint was chosen based on when the network properties of a fished system are distorted as these species are lost from the system, which occurred when around 5% of the species (ordered based on the hub ranking) had been lost from the system. We verified the same level of distortion did not occur if a random 5% of species were lost (the effect was two to thousands of times larger when hub species were depleted).



What is it?

Work by Gao et al. (2016) revealed universal patterns to the resilience of complex systems and provided a method for calculating the resilience of a system from its network structure. **Gao's index uses two main measures of the network**.

1. The first is **network heterogeneity of flow**, sometimes called degree heterogeneity, which measures the number of links for each node in the network. Heterogeneity is measured by the variance of the distribution of the degrees in the network, where the degree is the number of nodes that can be reached from a reference node in one step, and links are weighted by their strength.

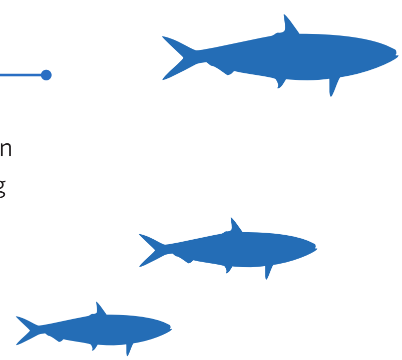
2. The second is the **density of network connections** and is measured by the ratio of the total numbers of links between nodes to the maximum number of links that are possible, with a maximum value of 1 if all nodes were connected to all other nodes. Plotting the heterogeneity of the flow in the system against the density of network connections on a chart tells us whether an ecosystem is resilient, partially resilient, or in danger of collapse.

Citation:

Gao, J., Barzel, B. & Barabási, AL. Universal resilience patterns in complex networks. Nature 530, 307–312 (2016). https://doi.org/10.1038/nature16948

Why is it important?

This analytical framework means that the behavior of different networks can be collapsed into a single resilience function, making it useful for comparing within ecosystems through time and also between ecosystems.



How it's calculated

Anyone interested in the details of the derivation of the resilience index should consult the original Gao et al. (2016) paper, especially the supplementary materials, but in summary the resilience of a food web is governed by three topological characteristics: symmetry S, the heterogeneity of the flow in the system H and the network density <s> (in this case calculated as the average weighted degree).

Gao et al. (2016) showed that specific dynamics of how a network responds to perturbation (e.g., loss of a node or link, pressure on the nodes) are fully accounted for by the changes caused in a measure they refer to as β_{eff} (literally the effective state of the system in the space of all possible conditions β) Gao et al. (2016) explain how the changing value of β_{eff} summarizes the system state within a universal "resilience function"—a mathematical construct based on the dynamics of complex systems of many types. Gao provides an equation for the transition surface of β_{eff}, which separates resilient from non-resilient states and is given by the following equation:

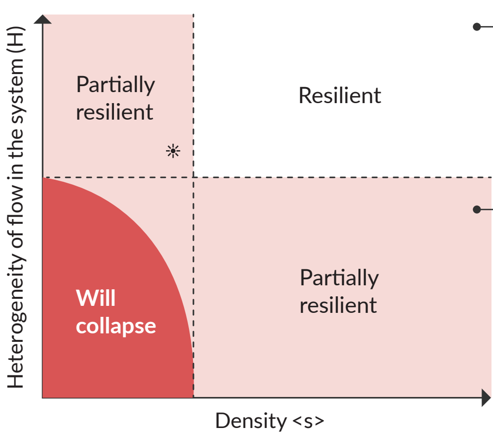
$$\beta_{eff} = \langle s \rangle + S\mathcal{H} = \langle s \rangle + \frac{\langle s^{in} s^{out} \rangle - \langle s^{in} \rangle \langle s^{out} \rangle}{\sigma_{in}\sigma_{out}} \cdot \frac{\sigma_{in}\sigma_{out}}{\langle s \rangle}$$

as $$S = \frac{\langle s^{in} s^{out} \rangle - \langle s^{in} \rangle \langle s^{out} \rangle}{\sigma_{in}\sigma_{out}} \quad \text{and} \quad \mathcal{H} = \frac{\sigma_{in}\sigma_{out}}{\langle s \rangle}$$

Where s^{in} and s^{out} are weighted degrees (in and out) and σ^{in} and σ^{out} are the variance of the marginal probability density functions P(s^{in}) and P(s^{out}) respectively. In this case the weights assigned to a connection between species in the network is the consumption of the prey by the predator.

The value for resilience used in our work—the **resilience score (*R*)**—is based on where the network sits in (*H*, <*s*>) space versus the β_{eff} surface. When plotted:

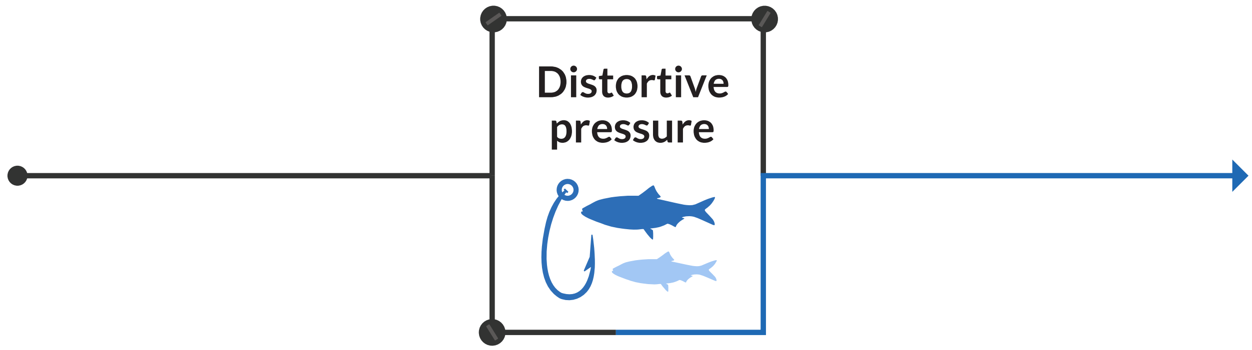
Figure 1



Points in the upper right are considered completely resilient (as they are above the intercept points of the threshold surface in both dimensions).

Points in the light red zone are considered only partially resilient, as they score poorly on one or other dimension and a perturbation could more easily see them fall into the non-resilient region (dark color area on the plot). For example, a system sitting in the light pink region of the plot with a low <s> score (such as the * on the plot) could drop into the nonresilient zone due to an extreme event disrupting basal productivity (as this would see the *H* score drop, and the point would end in the dark region).

As this resilience score acts as a scalar for the final composite index of Basic Ecosystem Traits Index (ETI), fully resilient systems are given the score 1.0, partially resilient 0.8 and non-resilient 0.5. If this does not prove sufficiently conservative these thresholds could be changed to 1.0, 0.5 and 0.25 respectively.



What is it?

The final aspect to consider is the distortive pressure put on an ecosystem. Ecosystems have evolved to withstand pressures that are placed on them from natural processes such as predator-prey dynamics, weather patterns, and species interactions. Pressure applied to the system outside of these dynamics will create a pattern differential that potentially distorts the system structure.

In the marine environment, we can assume that an ecosystem is capable of sustaining pressures in an unfished profile—represented by the biomass—productivity profile. Fishing pressures can distort this profile, but if management is to avoid this then they must determine the proper fishing pressure that can be applied to the system. The "**Green Band**" method identifies which stocks are receiving the greatest distortive pressure in the system, thereby informing when and where management actions should take place.

Citation:

Fulton, E.A. "The Green Band": Using Production and Catch to Judge Distortive Pressure on an Ecosystem. In preparation.

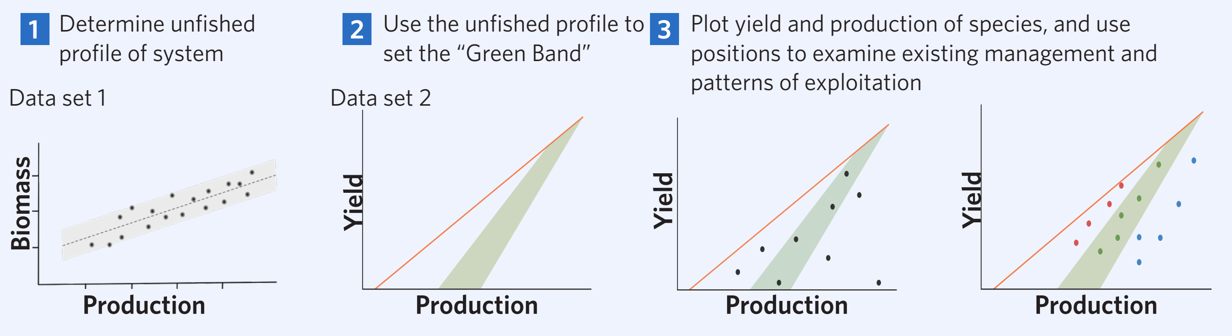
Why is it important?

At its simplest, the Green Band can be used as a snapshot to judge the current pressure on an ecosystem. The plot can also be tracked through time to understand whether fisheries management is moving stocks toward or away from the Green Band (Figure 3).

How it's calculated

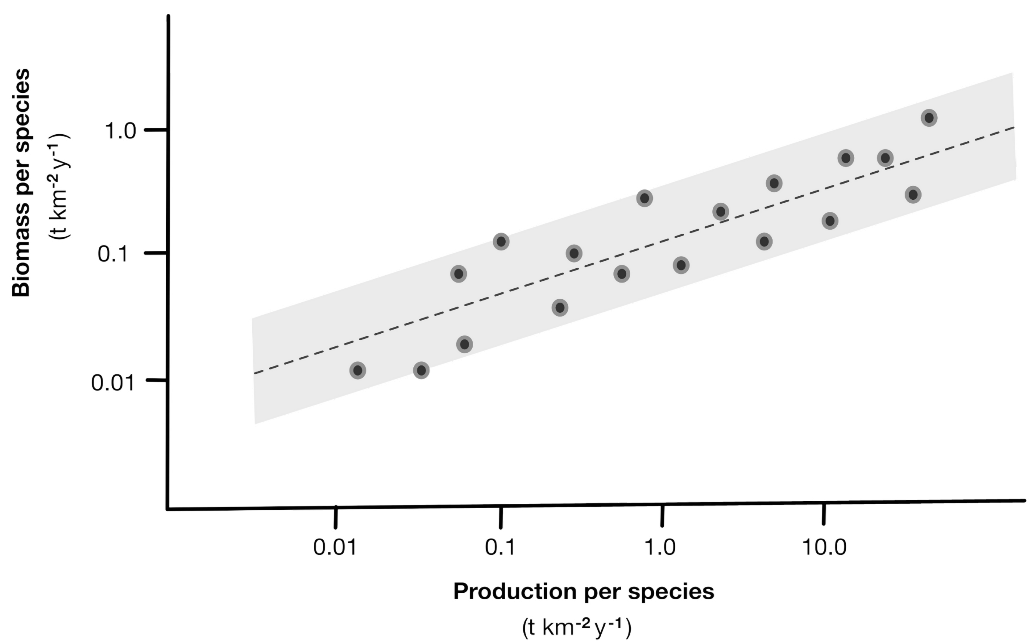
The Green Band Index is calculated by plotting the fishing pressure on an ecosystem against its unfished profile using the following steps:

Figure 2. Overview of steps

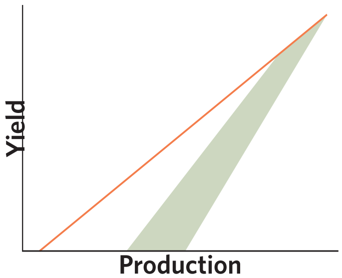


1 Calculate the "unfished" profile of a system.

In log-log space calculate the linear regression between biomass and production per group.



2 Define "acceptable" distortive pressures, i.e., the Green Band.

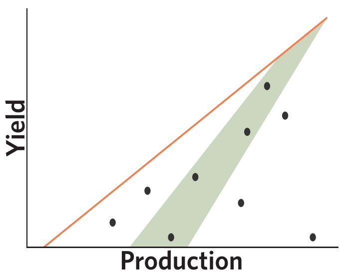


Use the slope of the regression line in Step 1 to define the "acceptable" pressure levels in the fished system on a plot of catch versus production. The slope of the green band is given by 1+ a where a is the slope of the regression line from Step 1 and the upper bounds of the green band given by:

$$Y_{bound} = min\ (0.5P,\ P^{\,1+a})$$

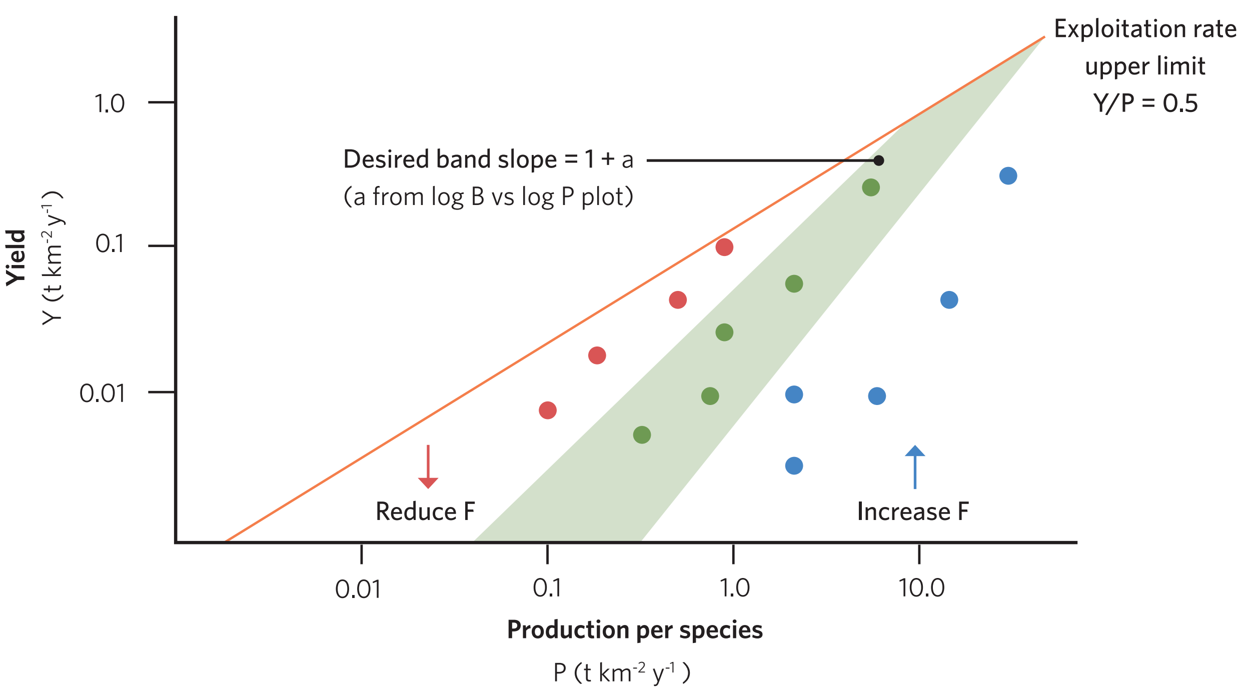
The width of the green band is typically set based on the degree of variance (spread of points either side) of the regression line in Step 1 (with values for the lower bound typically within two orders of magnitude of the upper bound).

3 Plot the species vs. the Green Band



Use the position of species to judge whether existing management and patterns of exploitation are putting distortive pressure on the ecosystem.

- Species fished with a level of pressure aligned with that of the natural system and require no further action.
- Species structurally "overfished" and harvest rates should be reduced.
- Species have scope for an increase in harvesting.

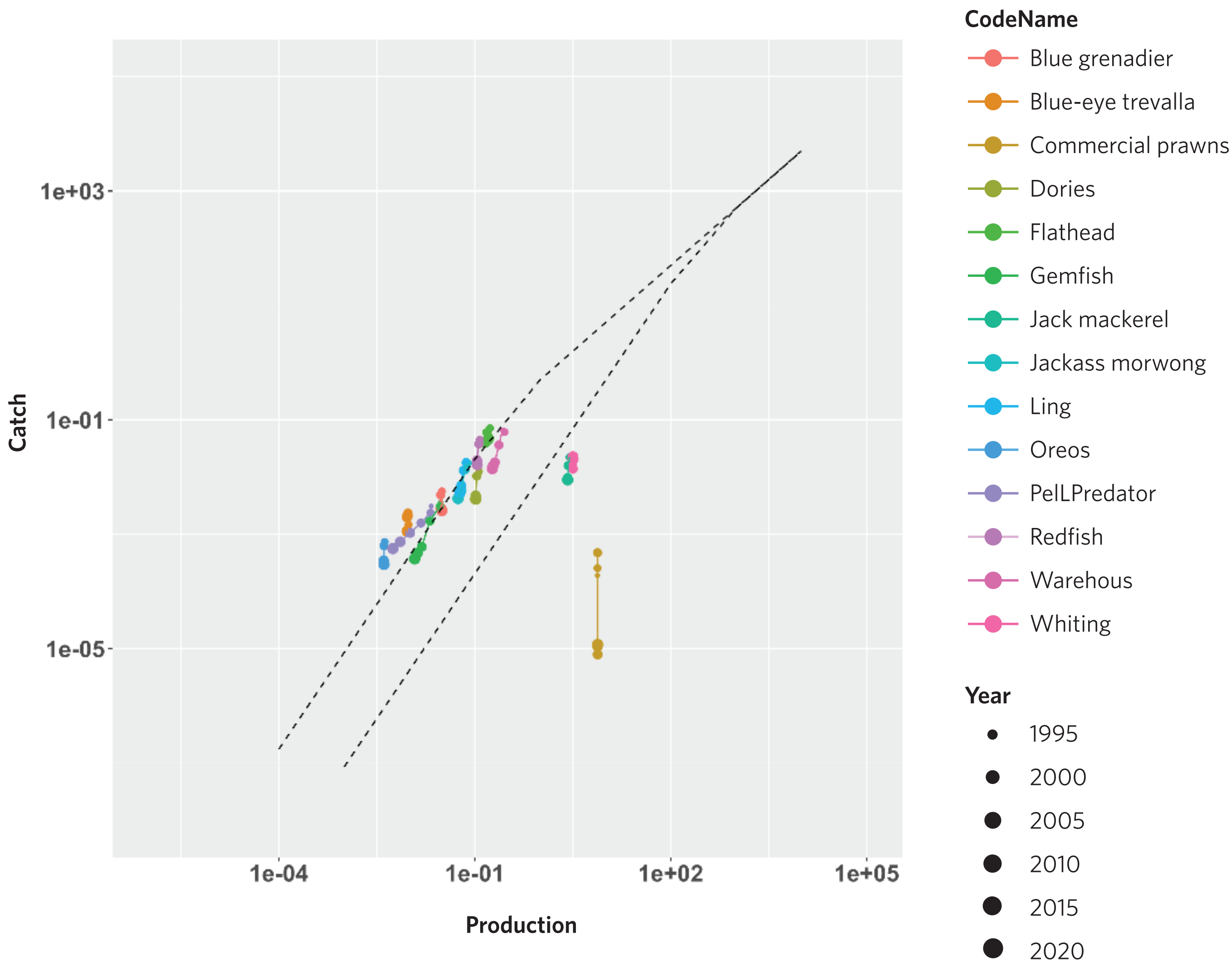


Example of Green Band application to one fishery

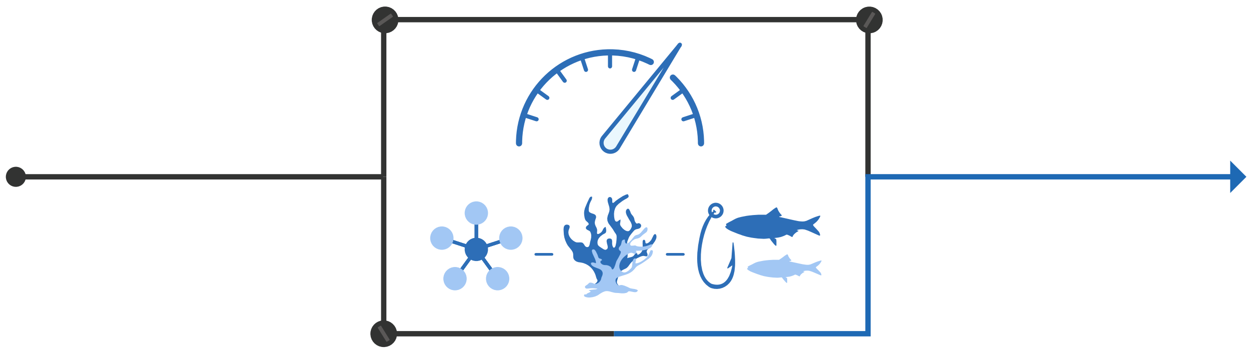
At its simplest, the Green Band can be used as a snapshot to judge the current pressure on an ecosystem. The plot can also be tracked through time to understand whether fisheries management is moving stocks toward or away from the Green Band (Figure 2).

Figure 3

Plot of the catch and production (in t km^{-2} yr^{-1}) through time for the main target species in the SE Australian fishery. Note that while management has moved many of the structurally overfished stocks toward the desired area (marked by the dashed lines), a number of species are still yet to reach the "green band."



The Index of Ecosystem Traits and Health (ETI)



Citation:

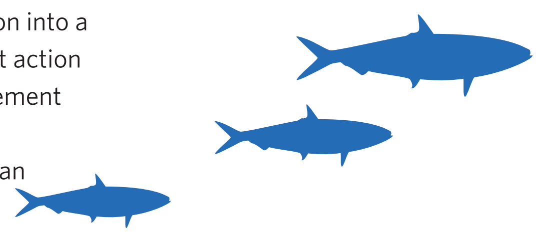
Fulton, E.A. and Sainsbury, K. A composite index of ecosystem robustness - the Ecosystem Traits Index (ETI). In preparation.

What is it?

The indicators outlined above can be calculated on their own, but when combined, they produce a qualitative score of ecosystem traits and health. The Working Group termed this as the Ecosystem Traits Index, or ETI. An ecosystem's ETI score signals its spectrum of health, from pristine to when it is at risk for collapse.

Why is it important?

ETI is a robust method that distills complex ecosystem information into a powerful visual tool that can signal when and where management action is needed. It can also be a valuable tool in projecting how management options may influence an ecosystem, as well as a way to evaluate whether or not past management or policy decisions are moving an ecosystem toward its desired state.



How it's calculated

Each species or taxonomic group is classified into a species category, and for each category there is a target relative biomass depletion and a statistical weight of importance. The target depletion and statistical weights may be altered in different situations.

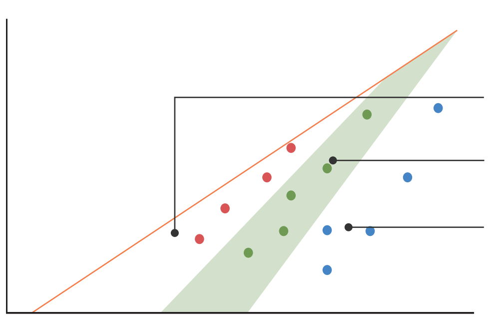
Table 1

Classification	Description	Target relative biomass levels (vs $B_{unfished}$)	Weights
Vulnerable	Slow growing, late maturing species susceptible to fishing pressure (such as marine mammals, seabirds and large sharks)	0.5-0.7	1
Habitat	Biogenic habitat forming species	0.3-0.6	1
Target	Primary target species of a fishery	0.4-0.5	0.5
Byproduct	These species have some value and are landed by fisheries but are not the main targeted species	0.35-0.4	1
Bycatch	Species that are not retained by the fishery	0.2-0.4	0.1
Robust	Fast growing, short lived species (such as productive invertebrates like cephalopods or microfauna like zooplankton)	0.4-0.5	0.1
Hub	Species identified as being a hub species using the method described above (based on Degree and PageRank scores)	0.6-0.7	1

Each of these species are rated based on its position relative to the Green Band and current relative biomass. Note that the relative biomass scoring is intentionally set conservatively, as these are the levels that allow for some impacts of fishing while also maintaining long term ecosystem structure and function in ecosystem models used here in concept testing. Alternatively, less conservative, and less constraining values could be used, such as limit reference points from environmental legislation.

Table 2

Qualitative scoring schemes for position relative to the green band and for relative biomass. Default target biomass levels are given in Table 1.



	Green Band scoring system	Relative biomass scoring scheme
Fail	Above green band	Below target levels
Acceptable	In green band	Within target band
Light	Below green band	Above target band

A matrix of the "green band status" vs "relative biomass" is populated with the number of groups per green band-relative biomass combination scores. This is used to determine the proportion of each category sitting in each part of the matrix below. Each combination is then given a combination score ($\mathcal{K}$).

Table 3

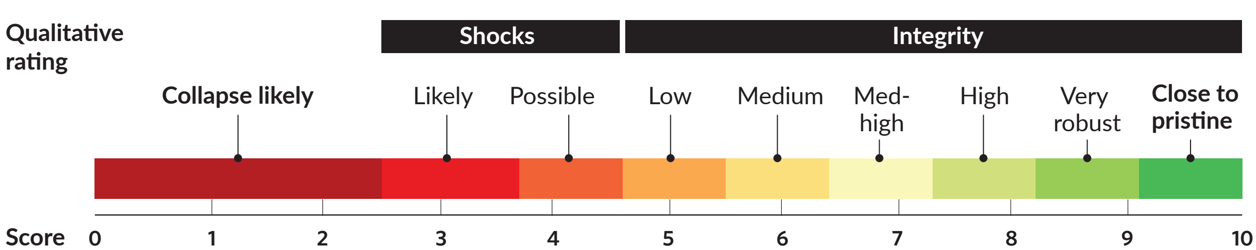
Matrix of possible combinations of fail (F), light (L) and acceptable (A) values of the Green Band (GB) and relative biomass (RelB). and the associated . "combination score" for use in equation 4, for different categories of species.

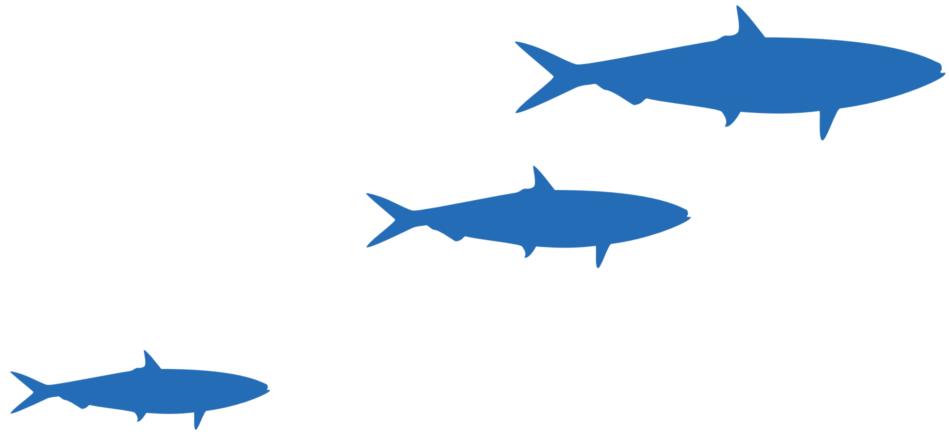
GB-RelB	Vulnerable	Habitat	Target	Byproduct	Bycatch	Robust	Hub	κ
F-F								0
F-A								0.25
F-L								0.5
A-F								0.375
A-A								1
A-L								1.5
L-F								0.75
L-A								2
L-L								2.5

Using the values of the combinations scores and the Gao's resilience score, calculate the final composite index score.

$$ETI = R\left(\sum_j W_j\left[\sum_i \frac{\kappa_i N_{i,j}}{N_j}\right]\right)$$

Where i is the green-band-relative biomass (RB-RelB) combination (the row of Table 3), j is the species classes (columns vulnerable to hub in Table 3), Nij are the values in the cells of the matrix in Table3; Nj is the total number of species in class j; $\mathcal{K}$j is the combination score (effectively a scalar of how healthy that combination of distortive pressure and relative biomass is, provided for reference in Table 3); Wj is the weighting given to species class j (see Table 1); and R is the Gao resilience score.





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