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Report of Working Group 28 on Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors

NORTH PACIFIC MARINE SCIENCE ORGANIZATION

PICES

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Report of Working Group 28 on Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors

edited by
Motomitsu Takahashi and R. Ian Perry

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Front cover:
Examples of multiple pressures on the ecosystems of the Western and Eastern Pacific coasts. From top: aquaculture and industry, Seto Inland Sea (Photo credit: Kazuhiko Mochida), *Noctiluca* sp. red tide, Seto Inland Sea (Photo credit: Naoki Yoshie), killer whale (*Orcinus orca*) and tanker sharing waters in the Strait of Georgia (Photo credit: Rachael Merrett), a marina in Nanaimo Harbour (Photo credit: R. Ian Perry).

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Motomitsu Takahashi and R. Ian Perry
Co-Chairs, Working Group 28

Executive Summary

Marine ecosystems are complex and dynamic systems which experience many and diverse pressures (the Working Group chose to use the term ‘pressures’ rather than ‘stressors’ to recognize that positive or negative outcomes from pressures may occur). Multiple pressures on marine systems are common, whereas marine systems which experience single pressures are rare. Yet most analyses of marine systems have focused on single pressures, or at best included two or three pressures (*e.g.*, fishing and climate change), which sometimes are considered to interact, and other times are considered to have no interactions. The development of indicators to describe ecosystem conditions, which are necessary to evaluate how ecosystems are changing and to create management measures to modify these changes, is challenged by these multiple pressures and their interactions. These issues motivated PICES to establish a Working Group on the *Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors* (Working Group 28). This Working Group met during PICES Annual Meetings from 2011 to 2015, and worked on seven Terms of Reference. The key Terms of Reference were:

- Review existing frameworks to link stressors to impacts/change, assessing their applicability to North Pacific ecosystems and identify the most appropriate for application to North Pacific ecosystems.
- Identify and characterize the spatial (and temporal) extent of critical stressors in North Pacific ecosystems, both coastal and offshore, and identify locations where multiple stressors interact.
- Review and identify categories of indicators needed to document status and trends of ecosystem change at the most appropriate spatial scale (*e.g.*, coastal, regional, basin).
- For 1 to 2 case studies, identify and characterize how ecosystems respond to multiple stressors using the indicators identified above.
- Publish a final report summarizing the results.

This report describes the analyses, findings, and recommendations of Working Group 28 in the context of these key Terms of Reference.

To develop indicators of marine ecosystem responses to multiple pressures, some type of framework or organizing scheme is needed to connect pressures to impacts and to the resulting changes in the ecosystem, which can then be characterized by some sort of indicator. Eight frameworks which have been applied to North Pacific ecosystems were reviewed. Five of these frameworks are considered as ‘multi-sector impacts’ frameworks, and include: pathways of effects, driver-pressure-state-impact-response, ecosystem simulation models, and marine health and geospatial methods. Three approaches are considered as ‘management’ frameworks, as they explicitly require management objectives to guide the selection of variables to explore alternative management actions and scenarios and to evaluate trade-offs among these alternative scenarios. Each framework has advantages and disadvantages in the extent of system knowledge and data required, their optimal spatial and temporal scales, and the effort required for their development. Experimental evidence for the impacts of multiple pressures on different marine ecosystems is rare because of the logistical difficulties of controlling and evaluating many interacting factors in such systems. The expert elicitation method is appropriate for marine ecosystems of the North

Pacific and may be the only way to adequately assess more than three simultaneous pressures, in particular when sufficient data are not available to develop ecosystem simulation models.

Multiple pressures on North Pacific marine ecosystems are identified, with a focus on coastal systems of PICES member countries and the open North Pacific. All marine ecosystems in the North Pacific appear to experience more than one pressure, which means that multiple pressures are to be expected. In general, pressures on North Pacific marine systems tend to be similar throughout the region; differences in pressures among regions relate to the type of ecosystem being examined. For example, coastal systems surrounded by millions of people have similar pressures around the North Pacific, but these are different from the pressures experienced by open ocean systems which are far from major population centers. Pressures on North Pacific marine ecosystems include climate change (broadly driving changes in temperature, circulation, sea level rise, and the timing and amounts of freshwater flows into the ocean), climate variability (*e.g*., variability at seasonal to multi-year scales, which include weather systems, monsoon characteristics, *etc*.), ocean acidification, excessive (and sometimes harmful) algal blooms, and hypoxia. Anthropogenic pressures include (depending on the ecosystem) nutrients, organic and inorganic pollutants, oil and gas development, other pollutants (*e.g*., plastics, pharmaceuticals), human population density and coastal development, land use changes, fishing, invasive species, and shipping.

These frameworks and identified pressures and habitats were used to explore the main pressures and their impacts in two similar coastal marine ecosystems in the North Pacific: the Seto Inland Sea, Japan, and the Strait of Georgia, Canada. Using an expert elicitation method, the studies revealed there are similar intense pressures on each ecosystem, such as coastal development (a local pressure) and ocean warming (a large-scale pressure). Most habitats had more than two pressures: for the Strait of Georgia the most common number of pressures per 4 km^2 planning unit was 20 to 25. This makes assessment of the impacts of multiple pressures impossible using standard experimental approaches.

A large part of this report presents the concepts and rationale behind developing ecosystem indicators of responses to multiple pressures, drawing from global examples but with a focus on the North Pacific. Indicators should be chosen based upon defined criteria, conceptual models linking indicators to pressures and drivers, and defined strategic goals and ecological or management objectives. Indicators should be complementary, non-redundant, integrate responses to multiple pressures and reflect the status of the ecosystem. Identifying indicators and evaluating multiple pressures on marine ecosystems requires a variety of approaches, such as empirical analyses, expert opinion, and model-based simulations. The ultimate goal is to identify a meaningful set of indicators that can be used to assist with the management of human interactions with marine ecosystems.

Working Group 28 examined many sets of indicators proposed for or already in use in North Pacific marine ecosystems. Two ‘toolboxes’ are recommended for use by PICES member countries, the first being an integrated set of indicators for North Pacific ecosystems, and the second being a selection of statistical and modelling techniques to identify which indicators are most appropriate for the multiple pressures of any specific marine ecosystem. Many of these indicators are directly measurable but several, in particular relating to features of ecosystem function and resilience, can only be derived from statistical or model analyses.

The Working Group identified a core set of indicators for use in North Pacific marine systems. This core set includes ENSO-related indices (Multivariate ENSO Index; Oceanic Niño Index), Pacific Decadal Oscillation, North Pacific Gyre Oscillation Index, sea surface temperature anomalies by season, sea level pressure anomalies by season, winter maximum sea ice area or extent, freshwater discharge, nitrate, pH, dissolved oxygen, contaminants (PCBs, POPs, total mercury), harmful algal bloom area or frequency, spawning stock biomass of selected species, slope of the size spectrum, species richness, taxonomic diversity, number of taxa representing 80% of the biomass; chlorophyll a, crustacean plankton biomass, gelatinous plankton biomass (or volume), small pelagic fish biomass, demersal fish biomass, piscivorous fish biomass, top predator biomass, total primary production, total landings, mean trophic level of landings, taxonomic diversity of landings, and landings (biomass) of selected species.

To apply these indicators to assess marine ecosystem responses to multiple pressures, issues of data availability and the characteristics of good indicators need to be considered. Methods to identify which indicators may be best suited to assess multiple pressures in particular systems are presented as Toolbox 2. These range from expert elicitation to statistical to model-based approaches, each with their own strengths and weaknesses. Finally, the importance of clearly communicating indicators is discussed.

1 Introduction

Motomitsu Takahashi[1] and R. Ian Perry[2]

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1.1 Context

The issue of understanding and predicting the effects of multiple pressures on ecosystems is one of the most important challenges in ecological studies today (Tockner *et al*., 2010) and a "worst-case" scenario for ecosystem management (Piggott *et al*., 2015). Characterizing ecosystem responses to multiple pressures, for example by the use of ecosystem indicators, is a third significant challenge. These matters motivated PICES to establish a Working Group on the "Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors", which was numbered as Working Group 28. This Working Group met during PICES Annual Meetings from 2011 to 2015, working on seven Terms of Reference (Appendix 1). The key Terms of Reference, and those forming the bases for this Scientific Report, are:

- Review existing frameworks to link stressors to impacts/change, assessing their applicability to North Pacific ecosystems and identify the most appropriate for application to North Pacific ecosystems.
- Identify and characterize the spatial (and temporal) extent of critical stressors in North Pacific ecosystems both coastal and offshore and identify locations where multiple stressors interact.
- Review and identify categories of indicators needed to document status and trends of ecosystem change at the most appropriate spatial scale (*e.g*., coastal, regional, basin).
- For 1 to 2 case studies, identify and characterize how ecosystems respond to multiple stressors using indicators identified above.
- Publish a final report summarizing results.

The members of the Working Group are identified in Appendix 2. This report describes the analyses, findings, and recommendations of Working Group 28 in the context of these key Terms of Reference.

An early discussion within the Working Group concerned the appropriate term for what it is that impinges upon ecosystems and causes them to change. Several terms have been used in the literature, for example, drivers, pressures, and stressors. The Working Group chose to use the term 'pressures', recognizing that 'stressors' had a connotation of causing mostly negative outcomes, whereas 'drivers' is colloquial English shorthand for 'drivers of change' which therefore implies a change will result. In contrast, 'pressures' was readily understandable across languages and included the concept that positive outcomes could also occur. The Working Group noted that pressure in this context can have four aspects (Oesterwind *et al*., 2016): i) an objective or desired outcome, ii) the relationship between the pressure and the changes that have been induced, iii) the type of pressure, and iv) the specification of the pressure (*e.g.*, 'fishing' may be separated into different gear types). Oesterwind *et al*. (2016) further recognized the different scales and manageability of pressures, for example, those local and manageable *versus* those outside the system, widespread, and unmanageable.

1.2 Single versus multiple pressures

Considerable discussion took place within the Working Group as to whether, and how, indicators of ecosystem responses to multiple pressures would differ from indicators of ecosystem responses to single pressures. In some situations they may not be different. However, the expectation was that multiple pressures will be common in most North Pacific marine ecosystems, whereas single pressures will be rare. The difference in the mode of action between single and multiple sector pressures and impacts was conceptualized as the difference between single pressure impact chains *versus* multiple sector impact webs (Fig. 1.1).

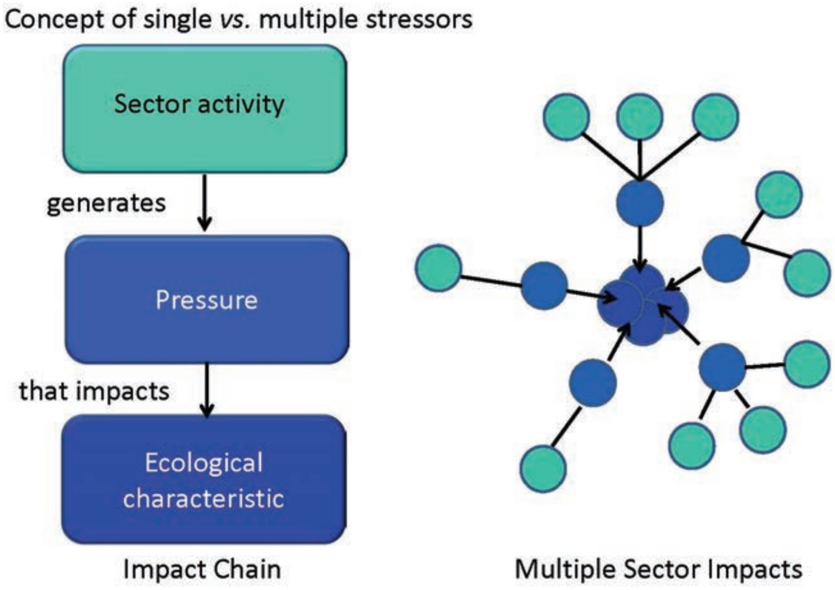

Fig. 1.1 Cartoon showing the conceptual differences between a single sector (and therefore, single indicator) impact chain *versus* multi-sector (and therefore, potentially a multiple indicator) impacts. Modified from Knights *et al*. (2013). Reproduced with permission of Wiley.

1.3 How important are the effects of multiple pressures on marine ecosystems?

Beginning with the expectation that most marine systems will be subjected to multiple pressures, and the conceptual differences above between single and multiple pressure impacts, what indicators can be developed to observe changes in ecosystems with multiple pressures? The 'gold standard' in deriving indicators of the responses of ecosystem components to multiple pressures comes from controlled experiments, usually conducted in laboratories where all conditions can be controlled. The effects of multiple pressures on ecosystems can be "greater than, less than, or qualitatively different from the sum of the effects that would be predicted" if each pressure occurred on its own (Breitburg and Riedel, 2005, p. 168; see also Fig. 1.2). A number of authors have applied meta-analytical methods to multiple pressure laboratory experiments on marine organisms, often resulting in different conclusions. Crain *et al*. (2008) did a meta-analysis of 171 studies involving two or more pressures in marine and coastal systems. They found that cumulative effects were additive in 26%, synergistic in 36%, and antagonistic in 38% of the studies. The overall interaction effect was synergistic but the interaction type varied by response level (population, community), trophic level, and pressure pair. Adding a third pressure changed the interaction effects significantly in two-thirds of all cases. They concluded that synergistic effects of multiple pressures were likely common in marine ecosystems. In contrast, Darling and Côté (2008) conducted a meta-analysis of 112 studies that examined the effects of multiple pressures on animal mortality in marine, freshwater, and terrestrial systems. They found that, on average, mortalities resulting from two pressures were present in only one-third of the studies they examined, but that non-additive interactions of all kinds occurred in three-quarters of the experiments examined. Darling and Côté (2008) concluded that 'ecological surprises' (*e.g.*, Fig. 1.2C-D) may be more common than what single additive effects might predict. Przeslawski *et al.* (2015) carried out a meta-analysis of the responses of the early life stages (embryo to larva) of several marine organisms to the combined effects of multiple pressures associated with global change (*i.e.*, with a focus on laboratory manipulations of temperature, salinity, and pH). Two of their findings were that: 1) Synergistic interactions (65%) were more common than additive (17%) or antagonistic (17%) interactions and 2) Interaction types vary among pressures but tend to be consistent within phyla.

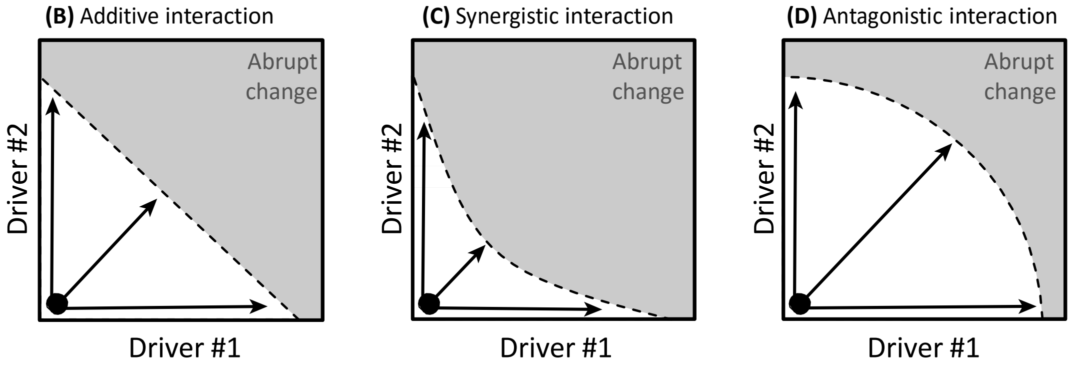

Fig. 1.2 Schematics of how two pressures can interact to produce abrupt ecological changes. Pressure (Driver) combinations unlikely to produce abrupt change are in white. Additive interactions (linear) are illustrated in (B). Synergistic interactions (C) increase the likelihood of abrupt change, while antagonistic interactions (D) reduce the likelihood of change. Modified from Ratajczak *et al*. (2018). Reproduced with permission of Cell Press.

Hunsicker *et al*. (2016) analyzed 75 studies, representing 728 single pressure–response relationships in marine pelagic ecosystems to search for evidence of non-linearities in these relationships. They found that non-linearities in single pressure–response relationships are common in marine pelagic ecosystems (occurring in at least 52% of the relationships they examined), and concluded that non-linear relationships in such interactions should be the default assumption.

There are several reasons why such a diversity of responses of pressures on ecosystem impacts may occur. Piggott *et al*. (2015) suggested that a consensus on the operational definitions of synergistic and antagonistic interactions of multiple pressures is lacking. For example, if pressure effects are opposite, then what is synergistic for one pressure is antagonistic for another pressure. Piggott *et al*. (2015) suggested a new class of "mitigating synergism" in which cumulative effects are reversed and enhanced. Gunderson *et al*. (2016) describe how the impacts of multiple pressures on marine ecosystems depend on the magnitude and relative timing of each pressure, with interactive effects more likely when the pressures occur more closely together in time. They state that experimental designs have exposed organisms to pressures simultaneously and at constant intensities, which will tend to favour synergistic effects. They recommend that multi-pressure studies should use more natural exposure regimes at temporal and spatial scales appropriate to the organisms and their life stages being studied. Obviously, this may be very difficult to achieve for many wide-ranging species and ecosystems.

1.4 Guide to this report

This report of the findings of Working Group 28 is organized by sections, each of which addresses one or more of the Working Group's Terms of Reference (Appendix 1). Section 2 presents several frameworks linking pressures to impacts and changes in use, or proposed for use, in the marine ecosystems of the North Pacific. This addresses Term of Reference 4. Section 3 describes the multiple pressures on North Pacific marine ecosystems, with a focus on coastal systems of PICES member countries and the open North Pacific. This addresses Term of Reference 1. Section 4 presents case studies which identify multiple pressures on North Pacific marine ecosystems, specifically in the Seto Inland Sea, Japan, and the Strait of Georgia, Canada. This addresses Term of Reference 6. Section 5 presents the concepts and rationale behind developing ecosystem indicators of responses to multiple pressures, drawing from global examples but also with a focus on those in the North Pacific. This addresses Terms of Reference 2, 3, and 5. Section 6 presents indicators that have been proposed or are in use for ecosystems of the North Pacific, and includes two toolboxes for use by PICES member countries: toolbox 1 with an integrated set of potential indicators, and toolbox 2 with a set of tools for selecting indicators for multiple pressures that are appropriate for a particular ecosystem and situation. This addresses Terms of Reference 2 and 3. Section 7 provides conclusions and recommendations.

Working Group membership, an expert judgment survey for case studies, session/workshop summaries and meeting reports from annual and inter-sessional meetings, and articles featured in PICES Press are presented in Appendices 2 to 5.

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2 Frameworks Linking Pressures to Impacts and Changes in North Pacific Marine Ecosystems

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2.1 Introduction

Understanding how multiple pressures can impact marine ecosystems is much more complicated than understanding the impacts of single pressures on selected marine components. This is because of the many more pressures involved, of the many more ecosystem components (or ‘endpoints’, *e.g.*, Labiosa *et al*., 2014), and therefore, the multiple and interacting pathways that connect pressures with endpoints. As noted in Section 1, such interactions can be additive, synergistic, or antagonistic. In addition, experimental testing and manipulation is very difficult for more than three factors, and usually is restricted to a small subset of the potential suite of pressures and endpoints. Wernberg *et al*. (2012) reported that of 110 marine climate change experiments published between 2000 and 2009, 65% tested only single climate change factors, 54% examined temperate organisms, 58% looked at only single species, and 73% examined benthic invertebrates. Field experiments can include consideration of more components, but usually require long time series of data to be able to separate the effects of individual pressures. For example, Hecky *et al*. (2010) used paleolimnological (sediment core) methods to identify decadal-scale multiple pressures which altered food web conditions in Lake Victoria, Africa, leaving its ecosystem vulnerable to change in wind stress and warming. This section focusses on key frameworks for characterizing ecosystem responses to multiple pressures in the North Pacific Ocean. As noted above, tracking the influence and impacts of pressures on endpoints in the presence of multiple interactions is complex. As a consequence, a number of approaches have been proposed, which are reviewed in the next section. This review is then followed in the following section by a review of key studies which have identified multiple pressures on North Pacific marine ecosystems.

2.2 Frameworks linking multiple pressures to changes in North Pacific marine ecosystems

A number of frameworks and approaches have been developed to examine the interacting and complex nature of connecting multiple pressures to impacts and changes in marine ecosystems. These include experimental and statistical approaches, with the former being more relevant for a few (*e.g.*, up to three) pressures and endpoints, and the latter being useful for more pressures and endpoints but with more intensive data requirements.

2.2.1 Pathways of Effects models

At their simplest, Pathways of Effects (PoE) models for multiple stressors are an extension of multiple pressures of single pressure–endpoint relationships to multiple pressures. A PoE model represents the connections (cause and effect) between a driver (*e.g.*, a human activity), the pressures generated by that driver, and their impacts on the ecosystem (O *et al.*, 2015). They are usually developed as conceptual models derived from the literature or observations. They can be very flexible and adaptable to the questions being considered, including aspects of scale, detail, and objectives (users). In the context of integrated and ecosystem-based management, three categories of PoE models have been proposed: 1) holistic models, 2) endpoint models, and 3) activity or sector-based models (O *et al.*, 2015). A holistic model provides an overview of relationships by limiting the details to focus on the (often human) activities of interest, the pressures that derive from these activities, and the ecosystem or societal components of concern (Giguère *et al.*, 2011). Such models can be useful to remind users of the many potential and interacting drivers, pressures, and endpoints in a system beyond those of immediate concern. An endpoint PoE model starts from the 'other' end, *i.e.*, with the endpoint or ecosystem component(s) of interest, and builds the model backwards. Activity-based PoE models focus on the relationships between a particular activity, its pressures, and their impacts (Fig. 2.1; O *et al.*, 2015). The latter two types of PoE models can also be constructed for particular areas ('area-specific' PoE models). In principle, area-specific PoE models can be constructed for any spatial scale, although the complexity of the model will likely expand with larger scales (O *et al.*, 2015). Such models have been developed by Fisheries and Ocean Canada as central frameworks for ecological risk analyses. O *et al.* (2015) provide an example of the use of activity-based PoE models in an ecological risk assessment framework for ecosystem-based oceans management in Pacific Canada. Their approach builds on the Australian Ecological Risk Assessment for the Effects of Fishing (ERAEF) framework (Hobday *et al.*, 2011). Specifically, it provides a transparent and science-based approach to describing (in particular, anthropogenic) impacts for ecosystem-based management.

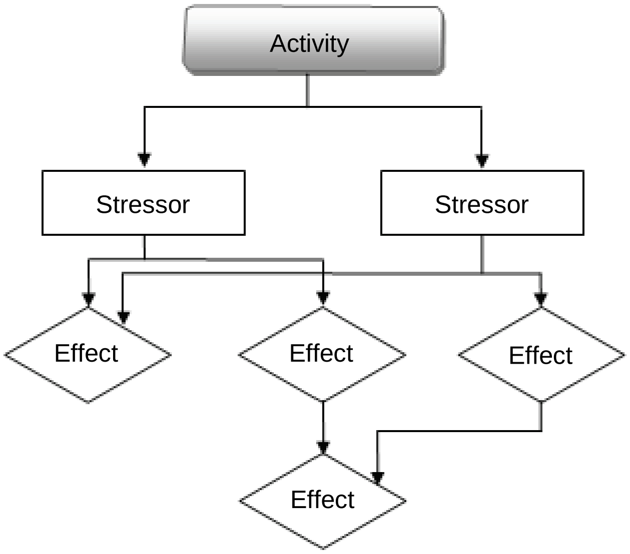

Fig. 2.1 Example of a generic activity-based Pathways of Effects model, for a single activity with more than one pressure. From O *et al.* (2015).

Knights *et al*. (2013) evaluated the links between sectors, pressures, and ecological characteristics (impact chains), assembled them into a network, and then used network topology statistics and clustering to group similar chains and generalize to a smaller number of pressure types (*e.g*., does Sector A generate the same pressure types as Sector B?). This approach was able to combine and identify fewer and more simplified measures involving groups of, rather than individual, pressures (Knights *et al*., 2013). They applied this to the biodiversity and food web descriptors of the European Union's Marine Strategy Framework Directive (MSFD: http://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm) and, based on the 19 sectors included in their study, were able to reduce the 7,066 impact chains to 1,462, which have the potential for detrimental effects on European marine ecosystem components. Various forms of PoE models underlie the cumulative effects assessment process used to evaluate large environmental projects and multiple pressures, in particular for marine contaminant issues (*e.g*., Adams, 2005; Judd *et al*., 2015).

2.2.2 Driver-Pressure-State-Impact-Response models

Many examples of Driver-Pressure-State-Impact-Response (DPSIR) models have appeared in the literature over the past few years for a variety of terrestrial and marine ecosystems. They include simpler versions, such as Pressure-State-Response (PSR) models (*e.g*., Niemeijer and de Groot, 2008), and more complex models which have been expanded to include human well-being (*e.g*., Müller and Burkhard, 2012) and societal impacts *via* ecosystem goods and services (Atkins *et al*., 2011). Patricio *et al*. (2016) provide a discussion of DPSIR and similar recent frameworks. The DPSIR framework is similar to, but is a more complex version of, pathways of effects models. The DPSIR approach formalizes the relationships between a driver, the pressures that result from this driver, the changes of state caused by these pressures, the impacts (usually to human activities or values) caused by these changes of state, and the responses by human societies that are (usually) directed to the drivers to mitigate the impacts (Fig. 2.2). Indicators can be developed to track and summarize the impacts of the pressures at changing the ecosystem states. When applied to multiple drivers and pressures, the resulting connecting pathways can become very complex (Fig. 2.3). For example, Perry and Masson (2013) used a DPSIR conceptual model to identify linkages among a suite of natural and anthropogenic drivers of changes in the Strait of Georgia, Canada. They used this network to identify pathways of effects among variables, and which of these variables had sufficient time series data to apply multivariate statistical methods to identify a small set of ecosystem indicators. Kelble *et al*. (2013) proposed replacing the Impacts module with an Ecosystem Services module, which would enable the DPSIR conceptual framework to include positive as well as negative ecosystem changes.

Labiosa *et al*. (2014) describe five advantageous features of the DPSIR approach: 1) identification of likely causal linkages between human activities and changes in ecosystem states, 2) capability to simplify these complex linkages, 3) use as convenient tools for communicating these complex relationships and potential solutions among scientists, policy makers, and the public, 4) they provide a framework for identifying indicators, and 5) they allow for understanding of how response actions may influence the desired states. Labiosa *et al*. (2014) specifically used the DPSIR concept as a tool to facilitate communication of linkages, definitions, and assumptions among scientists and policy makers with respect to an assessment of the pressures on the Puget Sound, Washington State, ecosystem.

The linkages mapped out within a DPSIR model lend themselves well to the application of sophisticated statistical analyses techniques. Several of these techniques can be used to assist with the identification of ecosystem indicators, for example, network nodes with high influence or leverage on the outcomes of the network, and operationalizing the network to predict outcomes when provided with different input values for the drivers or pressures. An example of both of these uses is provided by Araujo *et al*. (2013), who applied the DPSIR concept to develop a probabilistic (Bayesian) network to evaluate the effects of biophysical conditions and hatchery production on the early marine survival of Coho salmon (*Oncorhynchus kisutch*) in the Strait of Georgia. An advantage of this probabilistic approach is that it can use information from the literature, expert elicitation, model outputs, and field observations to supplement time series data (as the latter are almost always insufficient). Another advantage is that results from this approach can be presented as probabilities, meaning they are better able to include uncertainties in data and model structures, and are often easier for decision makers to understand.

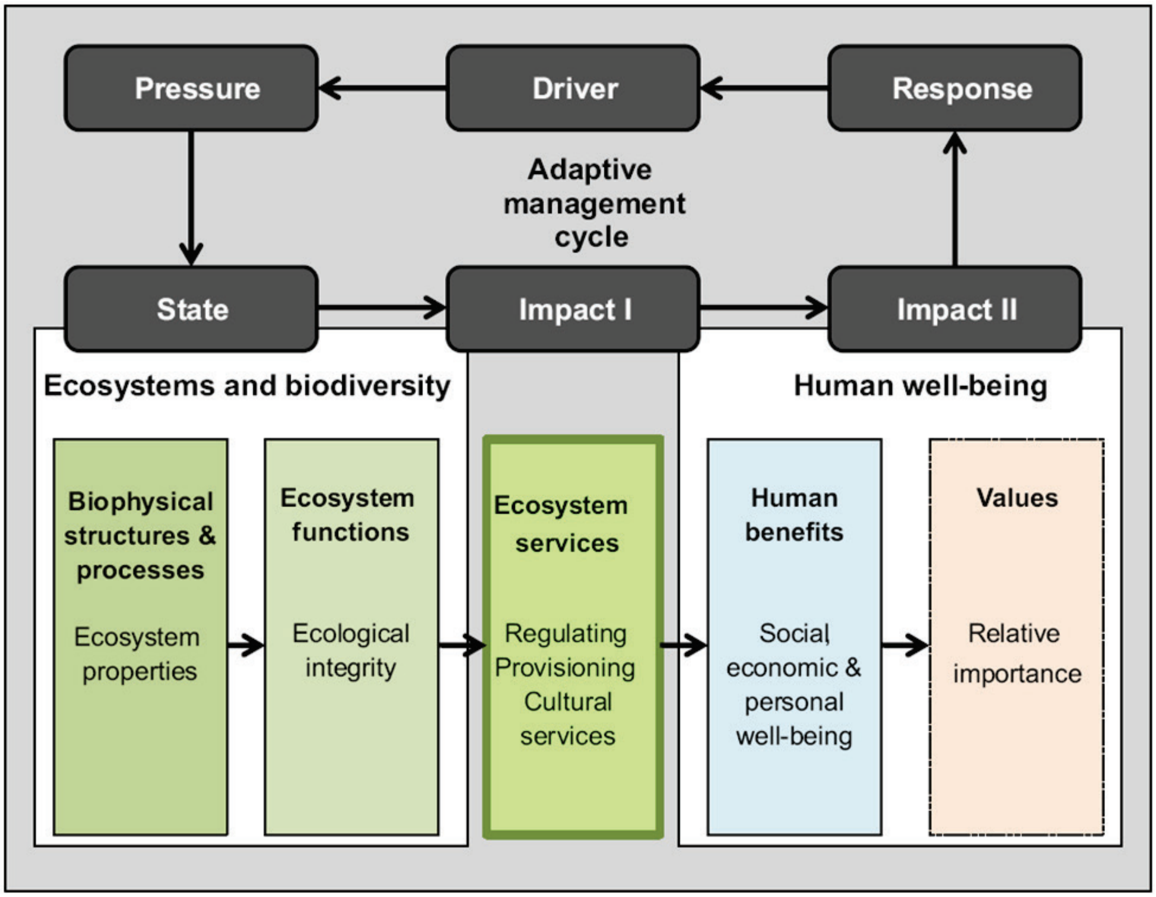

Fig. 2.2 A schematic Driver-Pressure-State-Impact-Response framework for assessing impacts of multiple drivers and pressures. This version has separated the Impacts into those relating to ecosystem services and those relating to human benefits and values. From Müller and Burkhard (2012). Reproduced with permission of Elsevier.

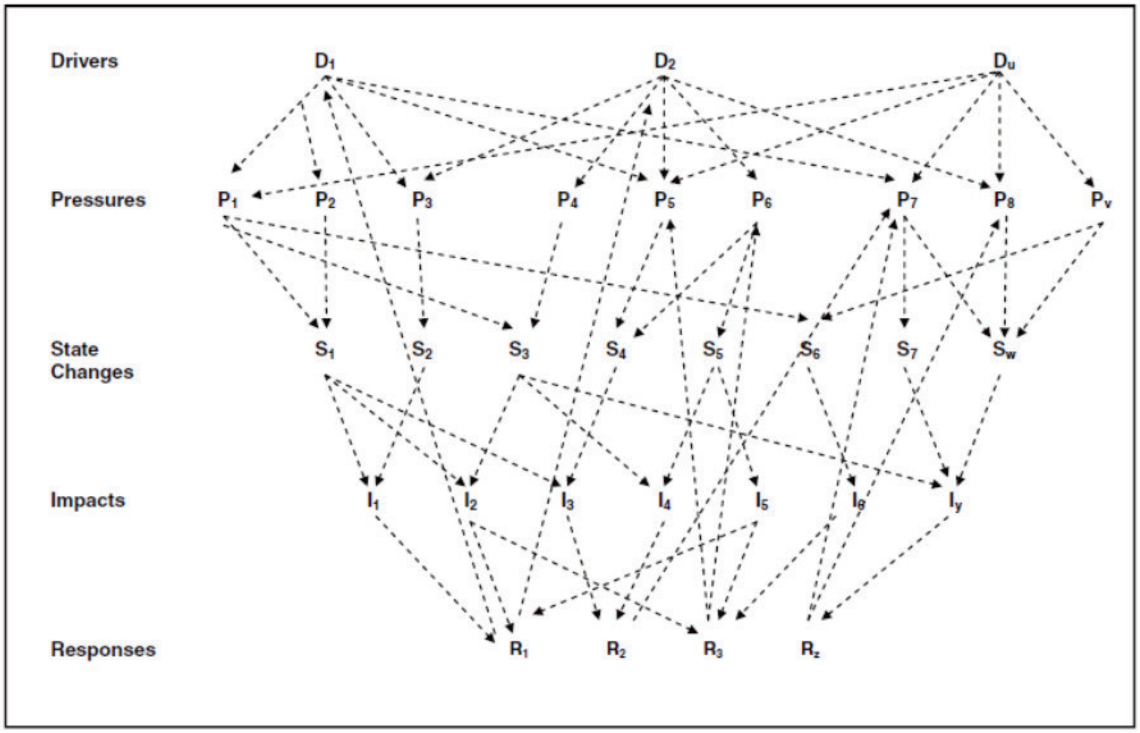

Fig. 2.3 A conceptual example of multiple interactions from multiple drivers in a Driver-Pressure-State-Impact-Response framework. From Atkins *et al*. (2011). Reproduced with permission of Elsevier.

2.2.3 Ecosystem simulation models

The construction of ecosystem simulation models has a long history, often using many different approaches in many different locations (*e.g*., Plagányi, 2007). Although usually not constructed for the purpose of exploring multiple pressures and identifying indicators of ecosystem responses, they essentially are mechanistic network models and can therefore, be used for these purposes, similar to DPSIR models. One of the most widely used ecosystem food web models is Ecopath, and its time-dynamic extension Ecosim (collectively Ecopath with Ecosim, EwE; Christensen and Walters, 2004), which is based on mass balance relationships and defined trophic interactions. The influences of non-biological pressures are usually approximated by functions describing their effects on the growth and mortality of the biological components and their food web connections. Colléter *et al*. (2015) indicate that 25 to 35 EwE models have been constructed for the two Food and Agriculture Organization (FAO) statistical areas in the North Pacific at the time of this writing. Table 2.1 identifies selected models in these areas. Samhouri *et al*. (2009) used six of these models constructed for marine ecosystems along the west coast of North America (U.S. and Canada; Table 2.1) to identify and evaluate the performance of potential indicators of ecosystem food webs. They focused on 22 features which define ecosystem food web structure and function, such as connections and energy recycling. From this analysis they concluded that no single indicator adequately described all ecosystem attributes, and that lower trophic level and higher productivity (*i.e*., higher turnover) groups tended to perform better as indicators.

Table 2.1 Selected Ecopath and/or Ecopath with Ecosim (EwE) models constructed for the North Pacific. From Zhang *et al*. (2007), Christensen *et al*. (2014, Supplementary material; reproduced with permission of Inter-Research Science Publisher), and Radchenko (2015).

Country	**Location**	**Number of model groups**
Canada	British Columbia: shelf	53
	British Columbia: northern shelf (*)	53
	British Columbia: southern shelf	27
	Strait of Georgia (*)	27
	West coast of Vancouver Island (*)	15
China	Bohai Sea	13
	East China Sea	38
Japan	Seto Inland Sea	19
	Western North Pacific	50
	Tohoku coast	46
Korea	East Sea	103
	East China Sea	138
	Yellow Sea	108
Mexico	Baja California	18
	Gulf of California: central	27
	Gulf of California: northern	34
	Gulf of California: Bay of La Paz	32
Russia	Sea of Okhotsk	48
United States – Alaska	Aleutians Islands (*)	40
	Eastern Bering Sea	36
	Western Bering Sea	34
	Southeast Alaska (*)	40
	Prince William Sound	19
United States – Oregon	Oregon coast	54
United States – California	Northern California Current (*)	29
United States – Hawaii	Hawaii	16
	Kaloko, Honolulu	26
Open Pacific Ocean	Central Pacific Ocean	26
	Eastern Tropic Pacific Ocean	39
	Western Tropical Pacific Ocean	20
	Northeast Pacific Ocean	56

(*) indicates models used by Samhouri *et al*. (2009) in their evaluation of ecosystem indicators derived from EwE models.

In some studies, EwE models have been used to generate time series of ecosystem properties that are otherwise difficult or impossible to measure directly (*e.g.*, total system throughput, mean path length, *etc*.). Using this approach and by applying ecological network analysis methods, Tomczak *et al*. (2013) calculated indices of ecosystem change and regime shifts in the Baltic Sea as a result of forcing by climate and fishing. Tecchio *et al*. (2015) used a similar approach based on EwE models to assess the cumulative impacts of fishing and climate change (modelled as inputs of organic matter) to three deep sea ecosystems in the Mediterranean Sea.

2.2.4 Marine health approaches

In Japan, concepts of healthy marine ecosystems have been used as frameworks linking multiple pressures to impacts in marine environments, and for the identification of indicators. Programs such as the Health Examination of Coastal Seas (HECS; Ocean Policy Research Foundation, 2006) and the Action Plan for Healthy Material Circulation in Coastal Seas (Healthy Coastal Sea Plan; HCSP) aim to monitor, recover, and sustain healthy ecosystems and material circulations in Japanese coastal waters.

HECS was launched in 2001 by the Ship and Ocean Foundation of Japan to revise former assessment programs that had been focused on water quality. Although these former programs and relevant laws started in the 1960s and 1970s and succeeded in reducing severe environmental problems such as heavy metal pollution and eutrophication, ecosystems and material circulation were not necessarily sustained. For example, increasing coastal reclamation resulted in losses of tidal flats, where direct nutrient loads were relaxed and various fisheries resources were exploited. In this context, HECS identified two primary indicators to be monitored: the stability of ecosystems, and the smoothness of material cycles. These two primary indicators were divided into several secondary indicators. The stability of ecosystems included species composition, habitat area and composition, and habitat quality. The smoothness of material cycles included primary productivity, effective nutrient loading (considering flushing time scale), sedimentation/decomposition, and carbon/nutrient removal through harvesting (Fig. 2.4). HECS was a framework assessment that consisted of several steps, analogous to a human health examination. Higher-level inspections were conducted if the preliminary inspections yielded negative diagnoses (Fig. 2.5). Monitoring and assessment based on HECS was applied to 88 semi-enclosed coastal waters of Japan until 2006 (Ocean Policy Research Foundation, 2009). This framework itself did not include solutions to problems, *i.e*., it did not provide any treatment to those problems. This point was updated by HCSP (Ministry of the Environment, 2013) which was launched in 2006 by the Ministry of the Environment.

Similar to HECS, HCSP aimed to achieve a healthy state of coastal seas, which was defined as the state in which ecosystems and material circulations were sound and sustainably yielded living marine resources. Updated from HECS, HCSP had four general stages: PLAN, DO, CHECK, and ACTION. The PLAN stage included a seven-step process, with each step linked to work of the DO/CHECK/ACTION stages (Fig. 2.6). DO, CHECK, and ACTION stages were controlled based on the road map (STEP 5), the monitoring plan (STEP 6) and the adaptive management policies (STEP 7), respectively (Fig. 2.6). Various indicators were considered in HCSP, which were structured by three viewpoints: material transport, quality conversion, and availability to living organisms, and were further aided by more detailed subcategories regarding mechanisms. A large number of potential indicators were suggested, leading to a reduced number of practical indicators (Fig. 2.7).

HCSP did not intend to make the Ministry of Environment conduct all surveys and make management decisions for each coastal area, but expected that local people, including local government, residents, non-governmental organizations, non-profit organizations, fishermen, businessmen, and researchers, would carry out this work. For this reason, HCSP distributed a guidance document, which was written based on experiences in three model regions: Harima-nada Sea and Mitsu Bay in the Seto Inland Sea, Mikawa Bay, and Kesennuma Bay (Healthy Coastal Sea Plan Committee for Mikawa Bay, 2013; Healthy Coastal Sea Plan Committee for Northeastern Harima-nada Sea, 2013; Healthy Coastal Sea Plan Committee for Mitsu Bay, 2014).

Other approaches to using a marine ecosystem health concept to identify indicators for multiple pressures, such as by the Helsinki Commission (HELCOM) and the Marine Strategy Framework Directive of the European Union, are discussed in Section 5.

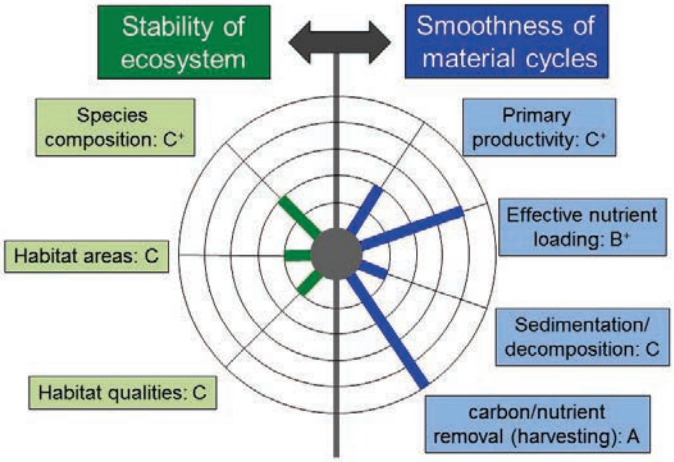

Fig. 2.4 An example of a ‘medical chart’ for Ise Bay, Japan. Adapted from Ocean Policy Research Foundation (2006).

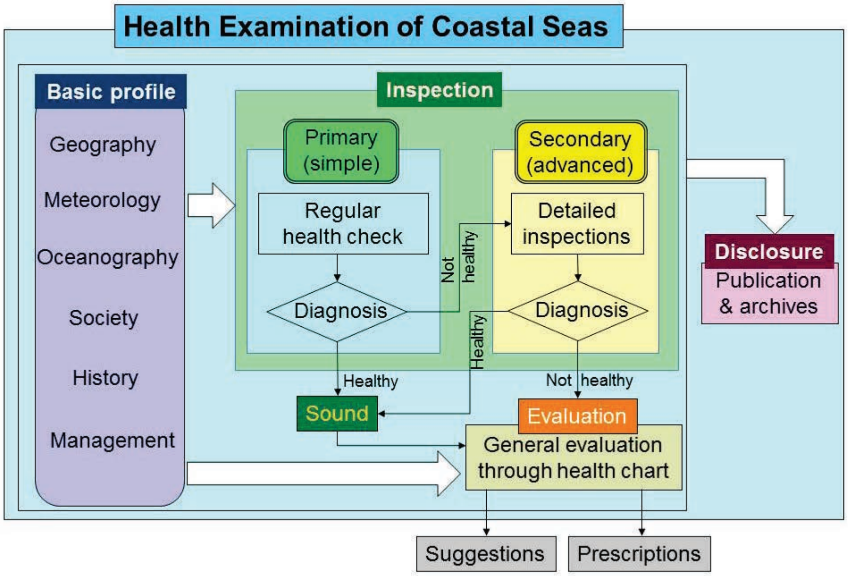

Fig. 2.5 Health Examination of Coastal Seas (HECS) framework used in Japan. Adapted from Ocean Policy Research Foundation (2006).

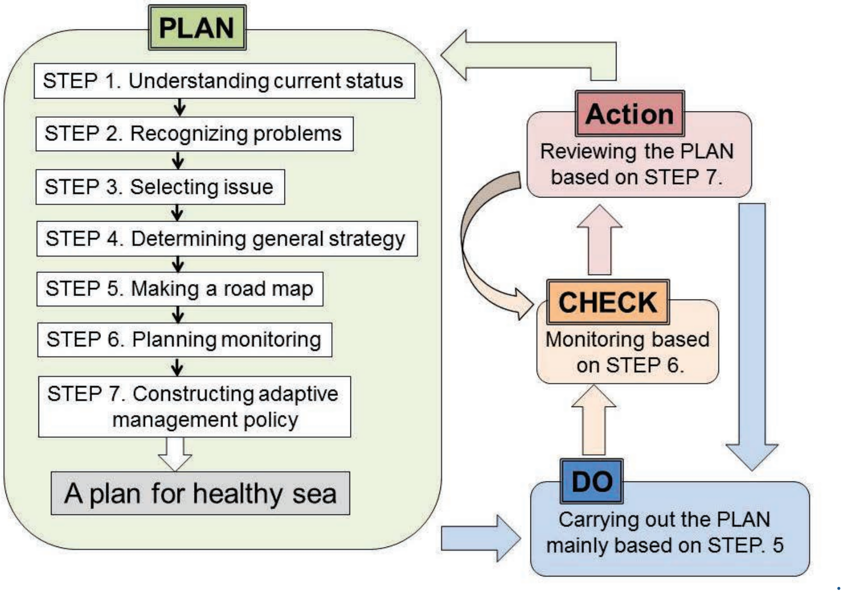

Fig. 2.6 The PLAN (with seven steps), DO, CHECK, ACTION framework of the Healthy Coastal Sea Plan (HCSP). Adapted from the Ministry of the Environment, Japan (2013).

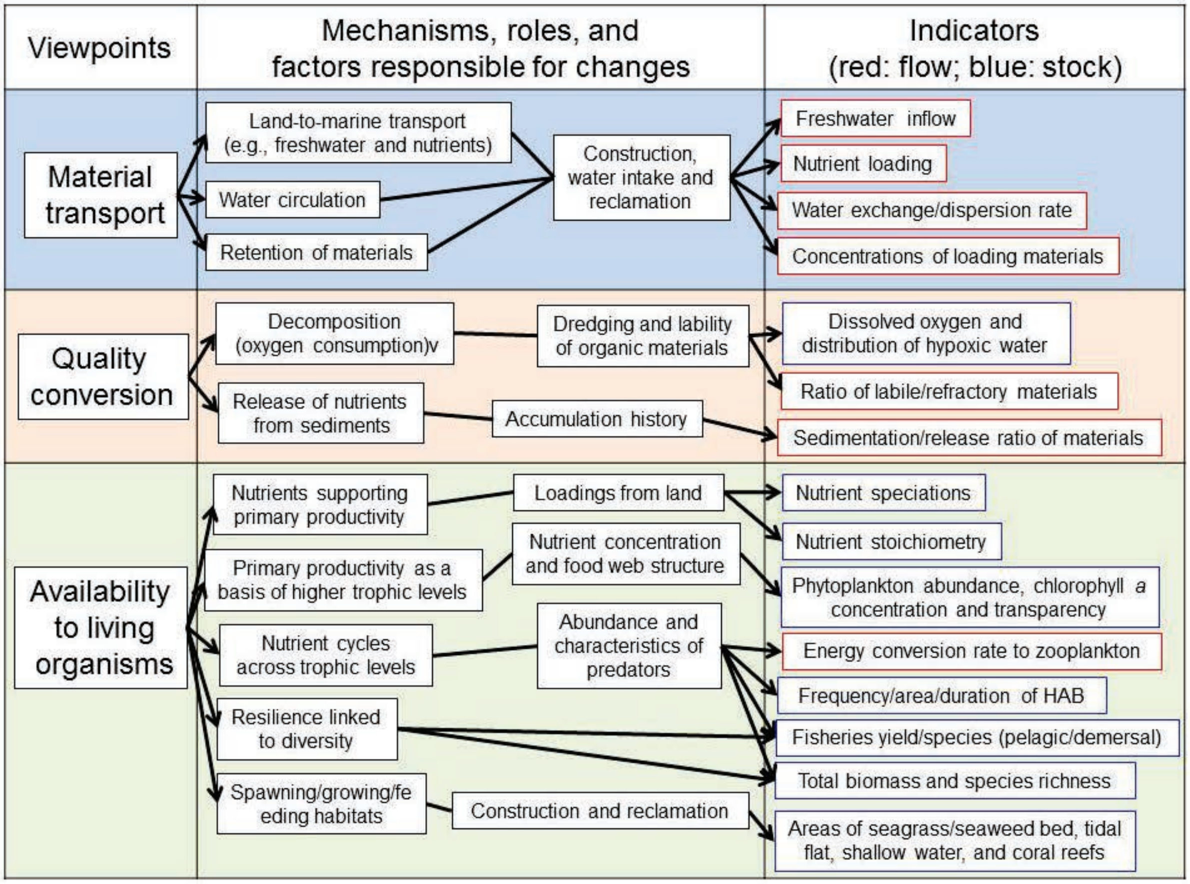

Fig. 2.7 Indicators of marine ecosystem health for Japanese coastal seas derived from the HCSP framework. Adapted from the Ministry of the Environment, Japan (2013).

2.2.5 Geospatial methods

Geospatial methods to understand the cumulative effects on marine ecosystems are relatively recent developments, but have been expanding rapidly with improvements in computer-based spatial analysis techniques. A key study is that by Halpern *et al.* (2008) whose methods have been followed by most other studies of this type. The general approach is to first represent the habitat (marine, terrestrial) of the region at the spatial scale chosen for the analysis ('pixel' or 'grain' size). The second step involves overlaying data on the intensity of pressures at each pixel. A weighting is then applied representing the vulnerability of the habitat in each pixel to each pressure in that pixel. The intensity of each pressure scaled by the vulnerability of the habitat to that pressure is then summed over all pressures to derive a cumulative impact score for all pressures on the habitat in each pixel. Note that, to date, all studies of this type have assumed additive interactions among pressures, as this has been the easiest to assess. Stelzenmüller *et al.* (2010) examined how the assumption of other forms of interactions among ranked pressures influenced the model outcomes. These were: 1) equal importance of pressures, 2) linear decrease of importance of pressures, 3) logistic decrease of importance of pressures, and 4) ranking of importance of pressures derived from a simulated expert consultation, which they defined as four alternative scenarios (*e.g.*, Fig. 2.8). When applied to marine habitats around the British Isles, they found that all scenarios produced similar locations with increased risk of cumulative impacts. They also found that the logistic weighting scheme was very sensitive to changes in the importance and ranking of pressures in comparison to the linear weighting scheme.

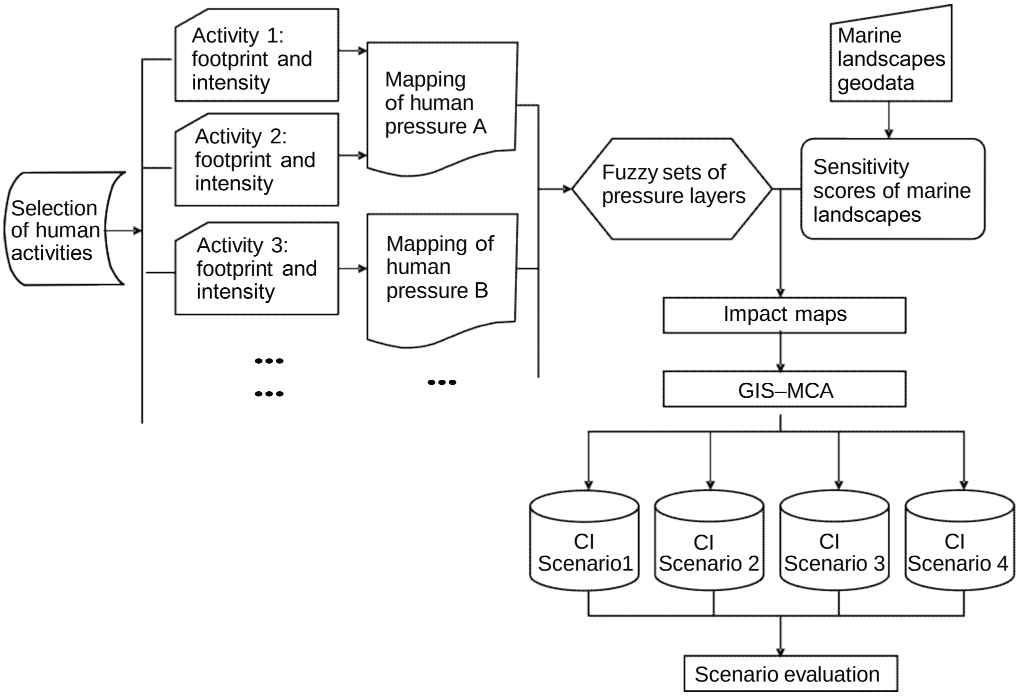

Fig. 2.8 Conceptual geospatial modelling framework developed by Stelzenmüller *et al.* (2010) to identify the pressures imposed by multiple human activities, their interactions with habitat and ecosystem features, and the alternative scenarios to evaluate their interactions. Reproduced with permission of Inter-Research Science Publisher.

Selection of the weighting functions for pressure X on habitat Y in each pixel has usually been done using expert elicitation because of a lack of observational and experimental data. These weighting functions are often based on several characteristics: spatial scale of the pressure, frequency (time scale) of the pressure, the functional level of the ecosystem that is affected by that pressure, the resistance of the ecosystem feature to that pressure, and the time required for the ecosystem feature to recover from the impacts of that pressure (Halpern *et al*., 2007). Studies using this approach will often begin with the weightings developed by Halpern *et al*. (2008) for marine habitats globally, but then revise them for the particular situation and location of the study. This cumulative effects mapping approach seems better suited to anthropogenic pressures applied in discrete (and mapable) locations, but less well suited to broad slowly changing (spatially or temporally) 'background' physical conditions such as temperature (*e.g*., as a result of global warming).

2.2.6 IFRAME

Researchers in Korea have elaborated an ecosystem approach to fisheries management to include management performance and the impacts of multiple pressures such as climate change and fishing. The Integrated Fisheries Risk Analysis Method for Ecosystems (IFRAME; Zhang *et al*., 2011) tracks climate change impacts on flows of energy through the marine food web (using food web simulation models, *e.g*., see sub-section 2.2.3) and includes resource management scenarios to understand the impacts on fish availability and mortality. It focusses on four management objectives: sustainability, biodiversity, habitat quality and quantity, and socio-economic status (Fig. 2.9), and developing an integrated suite of indicators for these objectives. There are three key components of IFRAME (Fig. 2.10), relating to assessment (constructing the structure of the ecosystem), forecasting future ecosystem structure under various climate and management scenarios, and management, which involve assessing the risks of different management actions. Zhang *et al*. (2011) used IFRAME to identify and track four indicators of sustainability, four of biodiversity, three for habitats, and six for socio-economic objectives. However, Zhang and Kim (2010) noted that IFRAME needs sufficient data for input variables, related indicators, and reference points to work successfully. If these constraints can be met, IFRAME can help to minimize uncertainties about the effects of climate change and help formulate effective measures for fisheries management (Zhang and Kim, 2010).

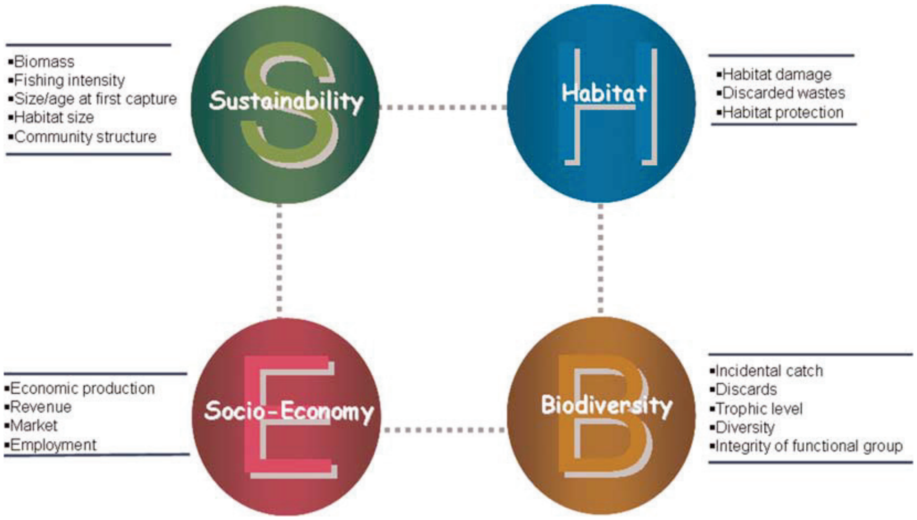

Fig. 2.9 The four key identification of objectives (circles) and corresponding attributes (lists) of IFRAME. From Zhang *et al*. (2011). Reproduced with permission of Oxford Journals.

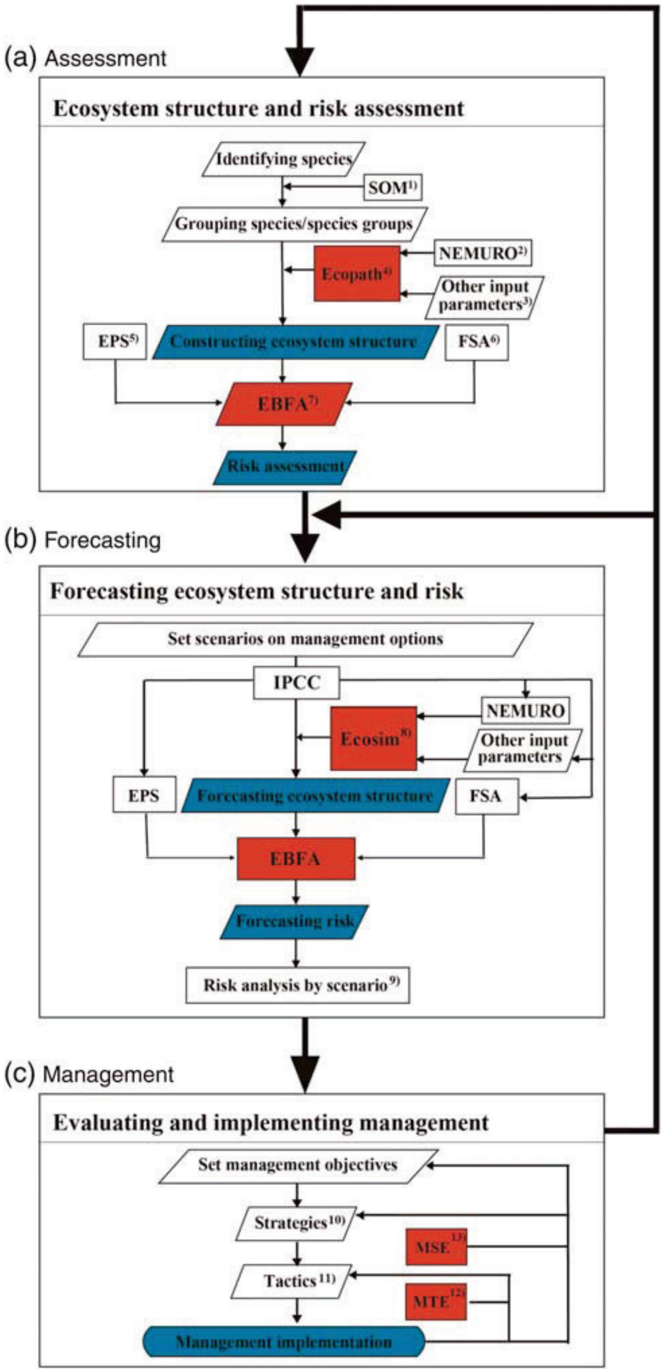

Fig. 2.10 Flowchart illustrating the three key components of IFRAME: a) assessment, b) forecasting, c) management. Notes: (1) SOM (self-organizing mapping): species grouped by swimming ability, size, depth, body shape, habitat, feeding, food, and longevity; (2) NEMURO model estimations of biomass and production of phytoplankton and zooplankton; (3) biomass, catch, production–biomass ratio, consumption–biomass ratio, and diet composition; (4) ecosystem structure model (here *via* Ecopath); (5) egg production per spawner; (6) management and fishery socio-economic analyses (FSA) scenarios; (7) ecosystem-based fisheries assessment; (8) ecosystem simulation model; (9) based on management improvement index (MI); (10) translate objectives to strategies; (11) translate strategies to tactics; (12) management tactics evaluation; (13) management strategy evaluation. From Zhang *et al*. (2011). Reproduced with permission of Oxford Journals.

2.2.7 Integrated Ecosystem Assessments

An Integrated Ecosystem Assessment (IEA) is another framework to apply ecosystem-based management concepts and to include management objectives explicitly in the process. Developed in the United States (Levin *et al*., 2009), IEAs are currently being applied in Alaska, the California Current System, and the U.S. Pacific Islands, Additionally, they are being applied in U.S. Atlantic waters, and other regions, including Europe. The U.S. National Oceanic and Atmospheric Administration's Integrated Ecosystem Assessment Program describes the primary objective of an IEA which is to make comprehensive information available to inform management decisions, and includes (https://www.integratedecosystemassessment.noaa.gov):

- Assessments of status and trends of the ecosystem condition, including ecosystem services;
- Assessments of activities or elements in an ecosystem that can stress the ecosystem;
- Prediction of the future condition of the ecosystem stress if no management action is taken;
- Prediction of the future condition of the stressed ecosystem under different management scenarios and evaluation of the success of management actions in achieving the desired target conditions.

As practiced in the U.S., an IEA is a cyclical process involving defining goals and targets, developing indicators, using these to assess the status and trends of the ecosystem, analyzing uncertainties and risks, and evaluating potential management strategies (Fig. 2.11; Samhouri *et al*., 2014). Setting management objectives and defining goals is Step 1, and the key to a successful IEA. This involves a diverse group of participants to define a broad vision and objectives for ecosystem-based management, the spatial scales of interest, and the ecosystem components to be considered (Levin *et al*., 2014). Step 2 involves defining ecosystem indicators and, where possible, their reference levels. To date, this has been accomplished in different ways, but usually includes developing an often long list of potential indicators, which is then screened against selection criteria such as being directly observable, having a theoretical basis, being easily understandable, cost effective, supported by available time series, and sensitive and responsive to changes in the ecosystem (Levin *et al*., 2014; see also Rice and Rochet, 2005, Kerschner *et al*., 2011, James *et al*., 2012). When available, ecosystem models can be used to evaluate the diagnostic characteristics of proposed indicators (Levin *et al*., 2014). Section 5 discusses the development of ecosystem indicators in more detail, with a focus on responses to multiple pressures.

Ecosystem reference levels then provide the desirable (in the case of targets) or undesirable (in the case of limits) conditions for resource use and management goals. The intent is to identify thresholds or inflection points that warn of significant changes to ecosystem states, or of conditions to be avoided – all in the context of the overall goals established in Step 1. The setting of ecosystem reference levels is a topic of active international research (*e.g*., PICES Working Group 36 on *Common Ecosystem Reference Points across PICES Member Countries*; https://meetings.pices.int/members/working-groups/wg36). Collectively, in Step 3 these selected indicators and their defined reference levels enable an evaluation of the overall status and trends within the ecosystem, relative to the initial goals and targets (Samhouri *et al*., 2014).

The subsequent two steps then involve analyses of the uncertainties and risks posed to the ecosystem features that are indexed by the indicators by human activities and natural processes, and ultimately evaluations of management options and strategies to consider trade-offs and the potential to reach the defined objectives (Samhouri *et al*., 2014). Embedded throughout the latter steps is a continuous process of monitoring and evaluation (Levin *et al*., 2014). Examples of IEAs in U.S. Pacific waters include Levin *et al*. (2013) and Harvey *et al*. (2018) for the California Current System, and Gove *et al*. (2016) for the West Hawai'i region.

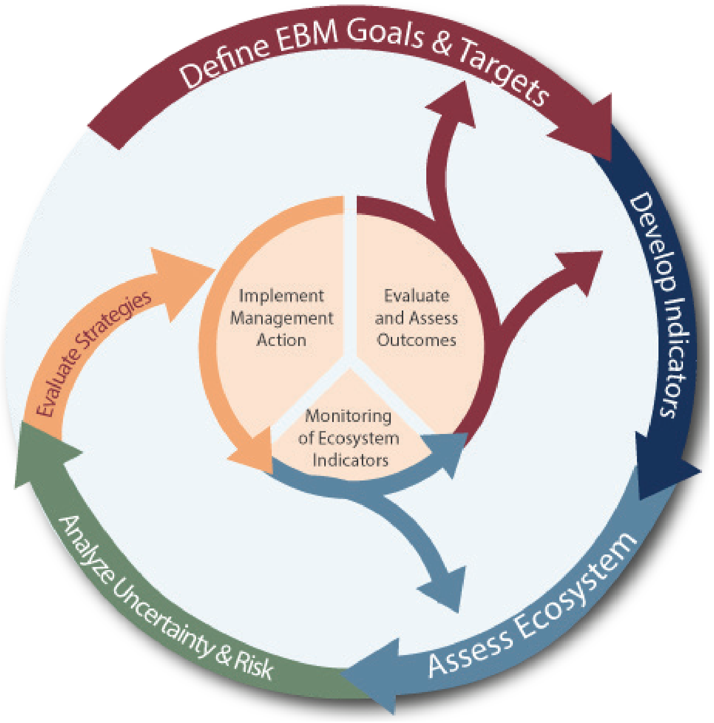

Fig. 2.11 Conceptual schematic of the Integrated Ecosystem Assessment (IEA) process as practiced at the U.S. National Oceanic and Atmospheric Administration. From Samhouri *et al*. (2014). Reproduced with permission of Oxford Journals.

2.2.8 Ecosystem services

Ecosystem services, and specifically marine ecosystem services, have become important concepts in discussions of the management of marine resources, their multiple pressures and objectives, and how to value and assess trade-offs. PICES has recognized this importance and recently created a Working Group to address marine ecosystem services (Working Group 41 on *Marine Ecosystem Services* (MES); https://meetings.pices.int/members/working-groups/wg41).

The Millennium Ecosystem Assessment defined ecosystem services as “the benefits people obtain from ecosystems” (Millennium Ecosystem Assessment, 2005) and identified four ecosystem service categories: provisioning, regulating, supporting, and cultural. It has been argued, however, that supporting services are embedded within the other three categories (*e.g*., Hattam *et al*., 2015). Lillebø *et al*. (2016) omitted supporting services as a specific group, and used a tiered approach to link pressures to their impacts on human well-being of selected European marine ecosystems. These tiers consisted of 1) identifying ecosystem services, 2) identifying ecosystem service indicators, and 3) mapping ecosystem services in the areas of interest. They also recommended model-based approaches to the mapping of ecosystems services, which can be used to assess uncertainties in quantification and valuation.

One of the model-based approaches recommended by Lillebø *et al*. (2016) was the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST). Guerry *et al*. (2012) describe marine InVEST as a new tool to assess (*i.e*., map, model, and value) multiple services provided by marine ecosystems, including simulations of changes in a suite of services under different management scenarios. It is a flexible and scientifically grounded computer-based tool that 1) is focused on ecosystem services, 2) is spatially explicit, 3) provides outputs in biophysical, monetary, and non-monetary terms, 4) is scenario driven, 5) reveals relationships among multiple services, and 6) has a modular approach which accommodates varying extents of system knowledge and data.

InVEST is designed for use in a decision-making process which involves diverse participants to define questions and services of importance to different groups of people (Fig. 2.12). The tool includes modules to address questions relating to future changes and impacts which may result from different management scenarios. The critical component is the ability of marine InVEST to link various services models to illustrate how a change in one service may impact the delivery of several other services (Guerry *et al.*, 2012). As such, it provides the capability to move from single pressure perspectives to cumulative impacts and benefits to society, including simulation of alternative management scenarios and their trade-offs.

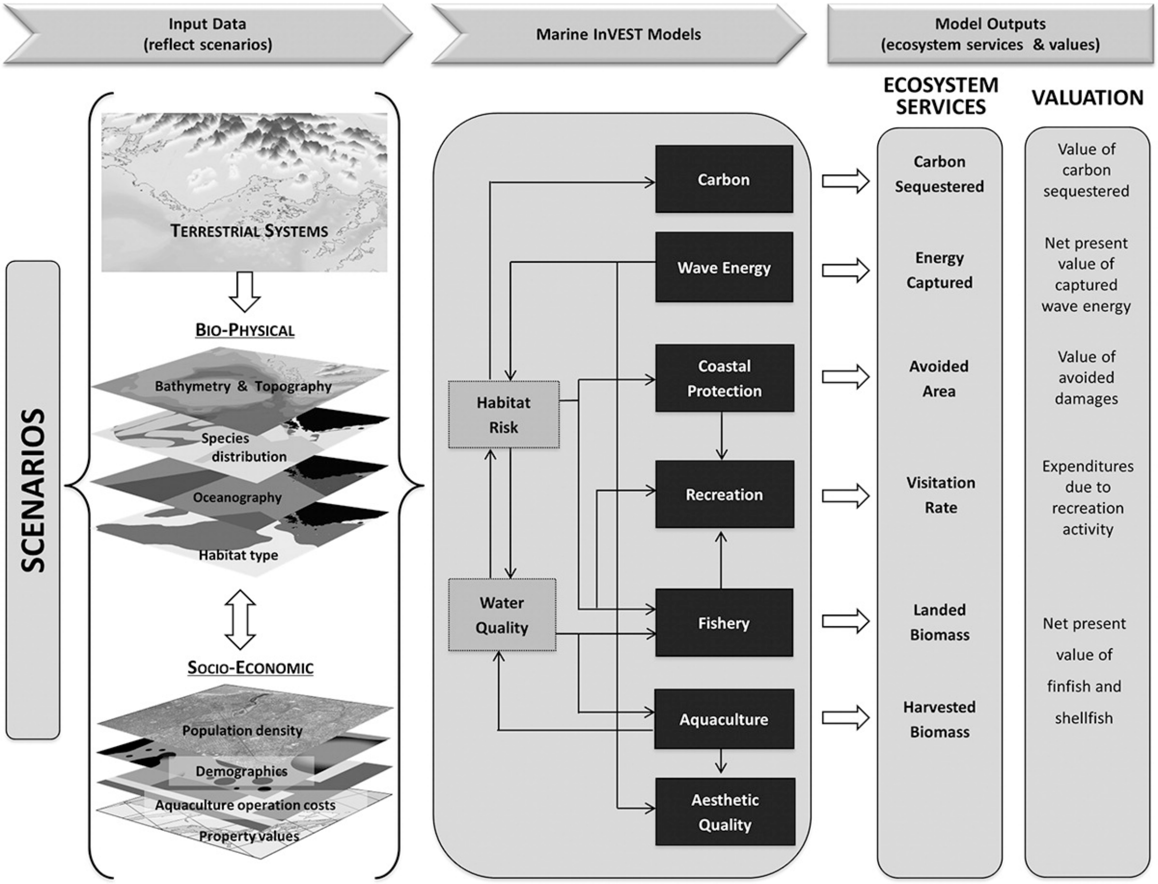

Fig. 2.12 Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) evaluates how alternative management or climate scenarios produce changes in the flow of ecosystem services. Ecosystem service outputs are expressed in biophysical or socio-economic units. From Guerry *et al.* (2012). Reproduced with permission of Taylor & Francis.

2.3 Comparisons among frameworks

The approaches described in this section all have the ability to describe and represent the influences of multiple pressures on marine ecosystems. There are, however, clear differences among them. The first five (sub-sections 2.2.1 to 2.2.5) are analytical and statistical approaches which assist with organizing and identifying relationships among multiple-sector pressures and ecosystem features. They can be considered as ‘multi-sector impacts’ frameworks. In contrast, the latter three approaches (sub-sections 2.2.6 to 2.2.8) can be considered as ‘management’ frameworks that specifically include and can produce management-relevant decision-support outputs. The latter may also be considered ‘toolboxes’, which bundle several methods and approaches (some of which may include the former multi-sector impacts frameworks) to provide explicit support for management decisions.

All of these frameworks have common, and sometimes specific, challenges to their application as described in the following sub-sections.

2.3.1 Data needs and uncertainty

Developing networks of interacting multiple pressures and ecosystem features can generate hundreds or thousands of linked interactions and information requirements. Observational and experimental data are usually available for only a small number of these linkages. Information for some additional links can be derived by analogy with similar situations and species elsewhere; however, many links and information needs remain data-poor. Researchers have usually addressed this problem by resorting to expert elicitation to fill the remaining key information gaps. In this approach, experts are asked to assess, for example, the strength of the effects of X and Y, and the proportion of Y that is directly affected by X (and *vice versa*). There are many different approaches to obtain expert elicitation for assessing the potential ecosystem impacts of multiple pressures. The approach used by Halpern *et al.* (2008) was to assemble a (relatively small) group of experts to assess all interactions. A more complex approach is to have interactions scored by only those few experts (sometimes only one) who are most familiar with that interaction or situation (*i.e.*, experts in that particular subject). As a consequence, this approach to expert elicitation can be biased towards linkages that are sufficiently well understood or studied and for which information and experts are available to carry out the evaluation (McManus *et al.*, 2014). The most complex approach is to adopt a more social science technique with an open format and targeted elicitation and workshops. For example, Teck *et al.* (2010) designed an expert survey for the California Current System that focused on estimating values for the five vulnerability criteria selected by Halpern *et al.* (2007; see also sub-section 2.2.5 above) and asked each expert to indicate their assessment of the relative importance of vulnerability using a discrete choice approach.

Considerable uncertainty is embodied in such methods for providing data for these models and frameworks. Uncertainty is inherent in the amount of individual stress produced by a particular activity or pressure, in how this stress impacts ecosystem features, in the nature of the interactions among the stresses produced by multiple activities and pressures, and in how the ecosystem features change and interact as a result of these pressures (Clarke Murray *et al.*, 2014). Uncertainty was explicitly included in the pathways of the effects-based ecological risk assessment model of O *et al.* (2015), which included expert elicitation of uncertainties about the examined interactions. McManus *et al.* (2014) developed an ‘uncertainty index’ to summarize the input from each expert as to their uncertainty for each stressor–endpoint pair. In their approach, uncertainty is not assessed as a separate factor but is captured directly as part of expert ratings through use of a probability scale. For any approach, as the number of pressures, ecosystem features, and resulting linkages increases, adequately accounting for the uncertainty in all these interactions can be daunting.

2.3.2 Spatial and temporal scale

The utility of these frameworks can also differ by scale. Since the stresses resulting from multiple pressures and activities can combine and accumulate in many different ways, ecosystems are subjected to direct and indirect effects, from both near-field and far-field sources. This can make the selection of the appropriate spatial boundaries (*i.e*., what is in or out of the analysis) difficult (Clarke-Murray *et al*., 2014). In many cases, such a selection is based on existing political boundaries rather than ecological features, in part because similar data may not be available on the other side of the political boundary. The selection of key species in a study also complicates issues of spatial scale in cumulative impacts research (Clarke-Murray *et al*., 2014). For example, a study of the cumulative impacts on Pacific salmon would require a very different spatial scale from a study focused on northern abalone, even though these animals may overlap in some parts of their ranges.

Selecting the temporal scale for analyses of multiple pressures also reflects a balance among pressures, ecosystem features, and available data (Clarke Murray *et al*., 2014). Data for many anthropogenic pressures may not be available at the desired time steps, and so must be aggregated over longer time intervals. In addition, ecology is an historical science, and the ecosystem that occurs in any particular place represents the outcomes of ecological, environmental, and anthropogenic processes over a long period of time. This means that existing ecosystems already represent a balance among, and adjustments to, previous multiple pressures. The ‘shifting baseline’ problem (*e.g*., Pauly, 1995) is a frequent concern in cumulative pressure assessments.

For the multiple sector impact frameworks described in this section, the larger the spatial and/or temporal scales being assessed, the more sectors and pressures that need to be considered and therefore, often the larger the number of ecosystem features. As a consequence, since the number of links among nodes scales as the product of the number of parent and child nodes, the amount of required information increases greatly. Consequently, these multiple-sector impact frameworks may be more efficient and tractable for local to small-regional applications with relatively few (or relatively focused) pressures and ecosystem features. Although not unlimited in their capacity to include information on multiple pressures and ecosystem components, the approaches defined as ‘management’ frameworks appear to be more integrative and reductionist, and therefore more appropriate for use at multiple spatial scales and in situations with more complex sets of pressures and ecosystem features.

For geospatial methods, spatial scale is an explicit attribute of the approach, although combining data among many different scales of spatial resolution is not a trivial problem, often requiring many assumptions. Including the temporal dimension can also be a significant problem because many spatial data sets are aggregated from observations collected over (sometimes long) time intervals. Most spatial data sets also do not extend more than one to two decades into the past for the resolution needed for cumulative impacts mapping.

Table 2.2 provides a summary and comparison of the broad features and applicability of the eight frameworks discussed in this section for linking pressures to impacts and changes in North Pacific marine ecosystems.

Ultimately, small-scale mechanistic studies using different frameworks can provide insight into the causes and cumulative effects of multiple pressures (in particular whether they are additive, synergistic, or antagonistic). When combined with broad-scale assessments, the overall results can be used to identify the shapes of relationships (linear, non-linear) to help decision makers identify appropriate indicators, reference points, and management levers for the impacts of multiple pressures on North Pacific marine ecosystems.

Table 2.2 Summary and comparison of the features of the eight frameworks discussed in this section for linking pressures to impacts and changes in North Pacific marine ecosystems.

Framework	**Type of framework**	**Data needs**	**Management objectives**	**Spatial scale**	**Effort to develop**
Pathways of effects models	Multi-sector impacts	Minimal	Not required explicitly	Local to regional	Minimal to moderate
Driver-Pressure-State-Impact-Response models	Multi-sector impacts	Minimal	Not required explicitly	Regional to large	Minimal to moderate
Ecosystem simulation models	Multi-sector impacts	Intensive	Not required explicitly	Regional to large	Intensive
Marine health approaches	Multi-sector impacts	Moderate	Not required explicitly	Local to regional	Minimal to moderate
Geospatial methods	Multi-sector impacts	Moderate	Not required explicitly	Local to global	Moderate
IFRAME	Management	Intensive	Required explicitly	Regional to large	Moderate to intensive
Integrated Ecosystem Assessments	Management	Moderate	Required explicitly	Regional	Moderate to intensive
Ecosystem services	Management	Moderate	Required explicitly	Local to regional	Moderate to intensive

2.4 Summary and recommendations

Linking multiple pressures to impacts and changes in North Pacific marine ecosystems is complex, in part because of the potentially large number of pressures, even larger number of interactions, and often low system knowledge and available data. A conceptual framework is essential to organize an approach and to systematically work through and record decisions of what to include, and why. This section reviews eight such frameworks that are available in the literature and which have been applied to North Pacific waters. Five of these frameworks can be considered as 'multi-sector impacts' frameworks: pathways of effects, driver-pressure-state-impact-response, ecosystem simulation models, and marine health and geospatial methods. Three approaches can be considered as 'management' frameworks, as they explicitly require management objectives to be developed to guide the selection of variables, exploration of alternative management actions and scenarios, and often evaluation of trade-offs among these alternative scenarios. Such management frameworks described in this section are the Integrated Fisheries Risk Analysis Method for Ecosystems (IFRAME), Integrated Ecosystem Assessments, and ecosystem services approaches. Each framework has advantages and disadvantages with respect to the extent of system knowledge and data required, the optimal spatial and temporal scales, and the effort required for their development. All frameworks are appropriate for identifying potential indicators of ecosystem responses to multiple pressures.

Recommendation

The selection of a framework for any analysis of indicators for multiple pressures must be done carefully and with full consideration of the advantages and disadvantages of each approach and of the goals of the assessment. Analyses should consider multiple pressures as the default.

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3 Multiple Pressures on North Pacific Marine Ecosystems

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3.1 Introduction

The scientific literature describes many studies of environmental and anthropogenic pressures on marine ecosystems. Typically, these studies examine the effects of single pressures, for example, warming temperatures, fishing, pollution, or eutrophication, on different components of marine ecosystems. Fewer studies have examined multiple and interacting pressures and their impacts on multiple ecosystem components, often considering only a few pressures, such as climate change and fishing (*e.g.*, Perry *et al.*, 2010a). With recent developments in computer-based spatial mapping and spatially-explicit data bases, several studies have examined the spatial distributions of multiple pressures on marine ecosystems. This section provides a review of key studies identifying multiple pressures on marine systems, and their spatial distributions, in the North Pacific.

To facilitate the discussion of multiple pressures on ecosystems generally, the biodiversity research community has developed a ‘taxonomy’ of pressures on ecosystems (Table 3.1). This taxonomy is dominated by terrestrial-based pressures, which is not surprising considering the strong terrestrial focus of many biodiversity studies, but it does include anthropogenic and environmental marine pressures. It serves as a starting point for defining pressures impacting North Pacific marine ecosystems.

Table 3.1 Biodiversity-based taxonomy of pressures on ecosystems (both terrestrial and marine). Based on Salafsky *et al*. (2008).

Category	**Sub-category**
Residential and commercial development	Residential and commercial development
Agriculture and aquaculture	Agriculture, livestock grazing Timber harvesting Finfish and shellfish aquaculture
Energy production and mining	Energy production Energy emissions Mining
Transportation and service corridors	Roads Shipping and ports Utility corridors
Biological resource use	Aquatic (*e.g.*, harvesting) Terrestrial (*e.g.*, harvesting)
Human intrusions and disturbance	Recreational activities Marine shoreline Freshwater shoreline Derelict fishing gear Military exercises
Natural system modifications	Dams and culverts Freshwater floodgates Marine water tidegates
Invasive and other problem species	Invasive species
Pollution	Stormwater pollution Unmanaged runoff Industrial and domestic wastewater Toxic contaminants Oil spills
Geological events	Earthquakes/Tsunamis Landslides Volcanoes
Climate change and severe weather	Climate change and severe weather

3.2 North Pacific: Climate-related pressures

Physical and chemical properties of marine systems determine the general habitat characteristics and distributions of marine organisms. They are probably more important in marine than terrestrial systems because of the lack of fixed topological and biological features (*e.g.*, mountains and valleys, forests and grassy plains). Marine ecological classifications in the North Pacific based on physico-chemical features (*e.g.*, Reygondeau *et al*., 2013) typically define most of the North Pacific as belonging to the North Pacific Subarctic Gyre (east and west), the North Pacific Polar Front, and the east and west North Pacific subtropical biomes. Therefore, any changes to the properties or locations of these biomes represent an environmental or climate pressure. Bopp *et al*. (2013) considered warming, acidification, deoxygenation, and primary productivity of marine phytoplankton as four of the major (climate-related) pressures on open ocean ecosystems, globally. They modelled the potential changes in these properties as a result of different Intergovernmental Panel on Climate Change (IPCC) representative concentration pathways (RCPs) over the 21st century, using 10 Earth System Models. Mean global changes to the 2090s (compared to the 1990s) under the business-as-usual scenario (RCP8.5) are projected to be +2.7°C for sea surface temperature, –0.33 units for sea surface pH, –3.45% for O_2 concentrations, and –8.6% for integrated (upper layer) primary productivity. The North Pacific is projected to be one of the most impacted regions for these multiple pressures in combination. Much of the North Pacific and its adjacent seas are projected to experience sea surface warming of greater than 3.5°C, pH decreases of 0.35 units, and subsurface (200–600 m) declines in oxygen of about 20 mmol m^{-3} (Fig. 3.1). No significant declines are projected for net primary productivity, however. In the North Pacific, freshwater (as changes in salinity) should also be included as an important habitat characteristic, and for its role in defining the depth of the permanent pycnocline in this region. Using data from Argo floats and other sources, Ren and Riser (2010) found that significant freshening of the upper water of the North Pacific has occurred over the past two decades.

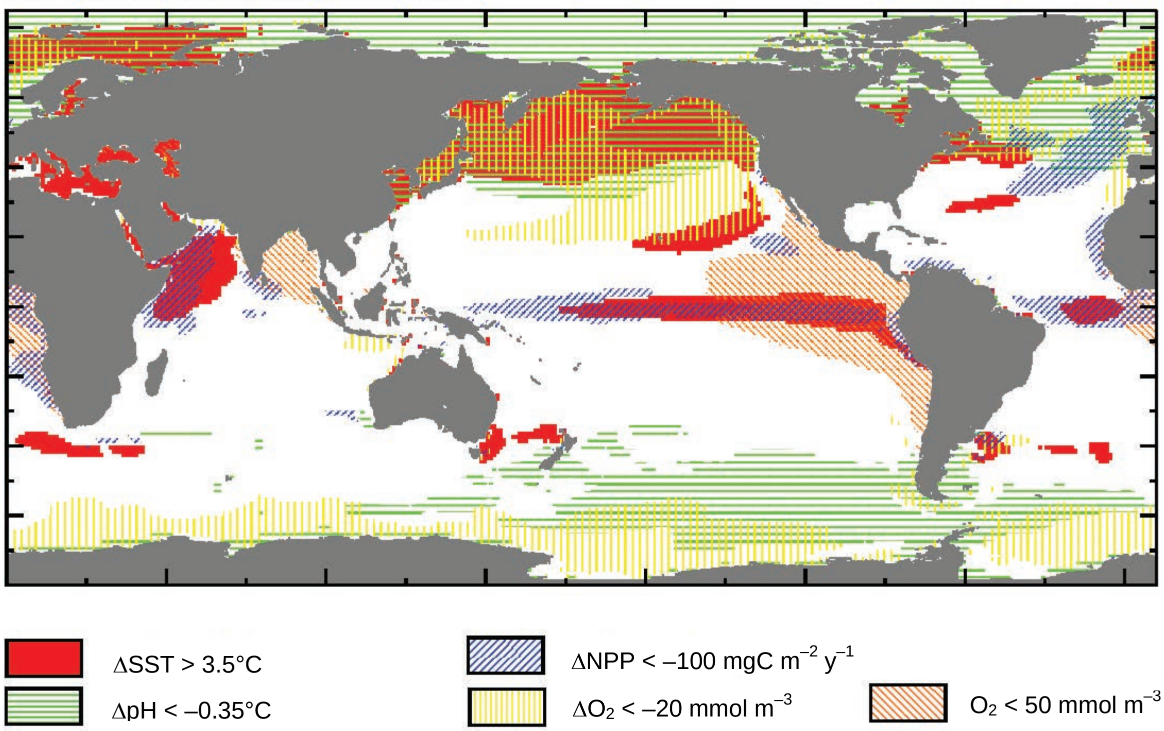


Fig. 3.1 Change in multiple climate-related stressor intensity in 2090–2099 relative to 1990–1999 under the business-as-usual scenario RCP8.5. NPP is net primary productivity. From Bopp *et al*. (2013). Reproduced with permission of Copernicus Publications for the European Geosciences Union.

3.3 North Pacific: Anthropogenic pressures

In most areas of the North Pacific, however, climate change impacts are occurring in addition to a long list of more direct anthropogenic pressures (*e.g.*, Perry *et al*., 2010b). For example, fishing can complicate the projected impacts of climate change on fish populations. By changing the characteristics of these populations, such as by removing older age classes and spatial sub-units, fishing can cause them to become more sensitive (*i.e.*, less resilient) to climate variability at interannual to inter-decadal time scales (*e.g.*, Perry *et al.*, 2010a). As a consequence, marine ecosystems under intense exploitation can evolve towards stronger bottom-up control and greater sensitivity to climate forcing. Macdonald *et al.* (2003) discussed how similar interactions among climate change, intensive fishing, habitat modifications, nutrient imbalances, and exotic species introductions can alter contaminant pathways. Such interactions can be direct, for example, by impacting the pathways themselves, or indirect by influencing the chemical nature and biological availability of contaminants (Fig. 3.2).

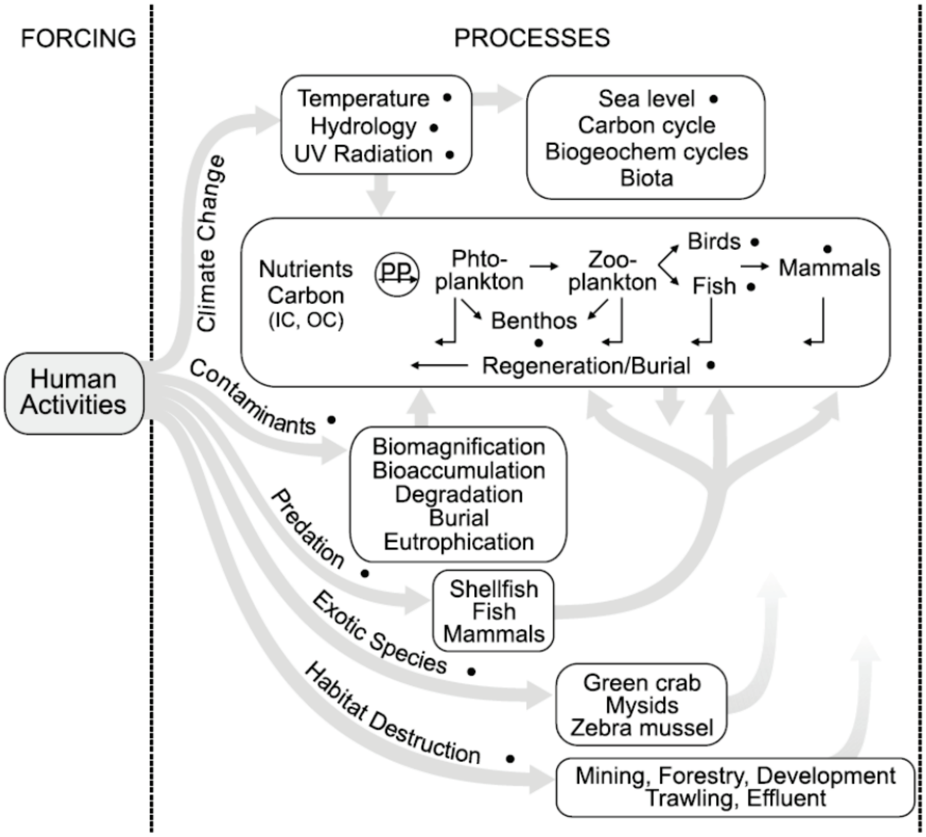


Fig. 3.2 A schematic diagram illustrating how multiple pressures may affect marine ecosystems. The central panel illustrates how released contaminants can enter aquatic food webs from a variety of sources. The black dots indicate many nodes at which time series data can be collected, depending on the objectives. From Macdonald *et al*. (2003). Reproduced with permission of Canadian Science Publishing.

A major step forward in the spatial identification of multiple pressures on marine ecosystems was provided by Halpern *et al*. (2008). They defined a set of 14 anthropogenic and three climate-related pressures and 20 different habitat types (Table 3.2) for which they used a spatial analysis (see sub-section 2.2.5) to identify marine areas with higher and lower potential impacts. Their scheme to infer impacts was relatively simple, using an additive approach among the multiple pressures conditioned on the pressure intensity, the occurrence of a particular habitat type, and a weighting factor for the impact of each pressure on each habitat. Specifically,

$$I = \sum_{i=1}^{n} \sum_{j=1}^{m} P_i \times E_j \times \mu_{i,j}$$

in which P_i is the log-transformed and normalized values of a pressure in assessment unit i, E_j is the presence or absence of an ecosystem component j, and $\mu_{i,j}$ is the weight score for P_i in E_j.

Table 3.2 Pressures and habitat types defined by Halpern *et al*. (2008) for assessment of cumulative impacts on the global ocean.

Pressure	Habitat type
Nutrients (fertilizer)	Coral
Organic pollutants (pesticides)	Seagrass
Inorganic pollutants (impervious surfaces)	Mangrove
Direct human (population density)	Rocky reef
Pelagic, low-bycatch fishing	Shallow soft
Pelagic, high-bycatch fishing	Hard shelf
Demersal, destructive fishing	Soft shelf
Demersal, non-destructive, low-bycatch fishing	Hard slope
Demersal, non-destructive, high-bycatch fishing	Soft slope
Artisanal fishing	Hard deep
Oil rigs	Soft deep
Invasive species	Seamounts
Ocean pollution	Pelagic waters
Shipping	Deep water
SST	Rocky intertidal
UV	Intertidal mud
Ocean acidification	Beach
	Salt marsh
	Kelp forest
	Suspension-feeder reef

Stock (2016) provides open source software for consistent use of this approach. For the North Pacific (Fig. 3.3), the oceanic areas had ‘medium’ impacts, due mostly to climate change effects (temperature, acidification, UV radiation), commercial fishing, shipping, and related contaminants. Areas of the Sea of Okhotsk had ‘low’ impacts, whereas ‘very high’ impacts were identified for the Aleutian Islands–Bering Sea shelf break, parts of the Kuroshio Current system, and the Yellow Sea and East China Sea regions.

Halpern *et al*. (2015) published an update of their analysis, using data available for the five years subsequent to their original study (Halpern *et al*., 2008). They found that nearly 66% of the global ocean and 77% of national jurisdictions had increasing human impacts, and that 10% had ‘very low’ impacts with decreasing pressures (Fig. 3.4). Increasing impacts since 2008 were located in tropical, subtropical, and coastal regions, whereas decreasing impacts were located in the Northeast and Central Pacific and the eastern Atlantic. Overall, they found that countries with greater increases in coastal populations had increased impacts compared with 2008, although there was no relationship with absolute population size. They concluded that on a global basis, increases in climate change pressures (sea surface temperature anomalies, ocean acidification, and UV radiation) were the causes of most of the increases in cumulative impact scores. The lack of change of sea surface temperature in the Northeast Pacific compared with the Northwest Pacific is seen clearly in Table 3.3. It is well known that the Northeast Pacific was unusually cool in comparison with the global ocean from 2008 to 2012 (Crawford, 2013) but changed in 2013 and 2014 to become exceptionally warm (Crawford, 2015; Di Lorenzo and Mantua, 2016). This implies that a revision using data since 2013 would likely show a strong increase in cumulative pressures for the Northeast Pacific.

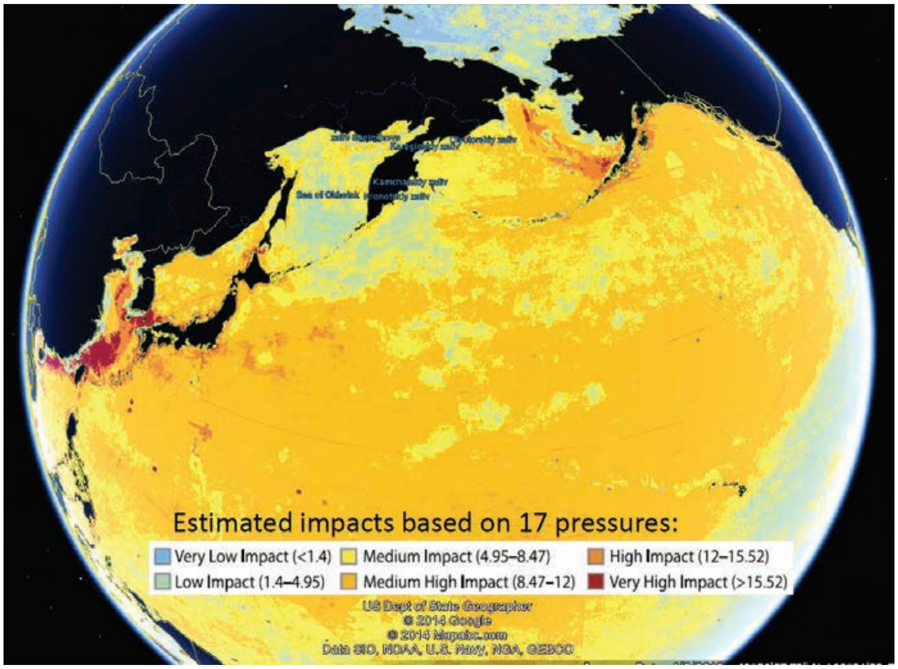


Fig. 3.3 Impacts of multiple pressures on the North Pacific, as estimated by Halpern *et al*. (2008). Projection courtesy of B. Halpern (https://www.nceas.ucsb.edu/globalmarine2008).

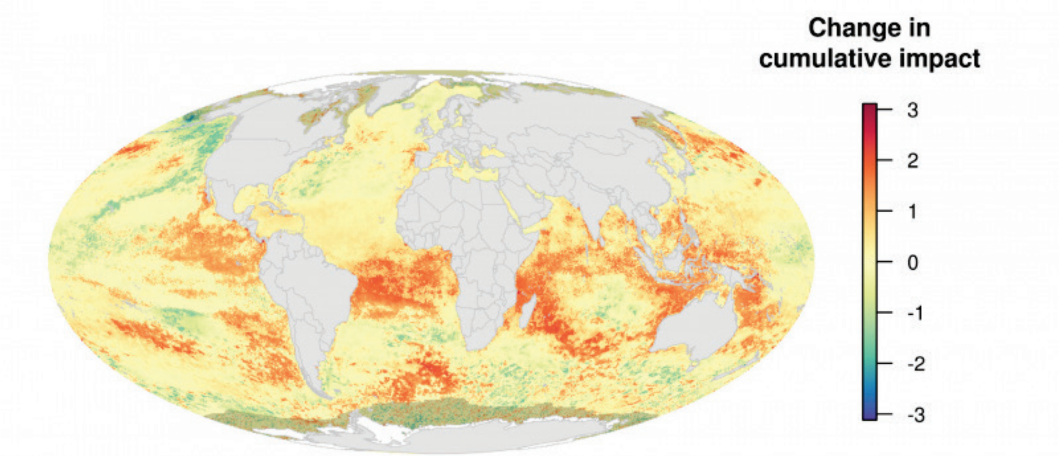


Fig. 3.4 Change in cumulative impacts of multiple pressures in the North Pacific between 2008 and 2013. From Halpern *et al*. (2015). Reproduced with permission of Springer Nature.

Table 3.3 Average difference in impact scores for each stressor and for cumulative impacts between 2013 and 2008 for each FAO high seas region in the North Pacific, and for each Large Marine Ecosystem in the North Pacific. From Halpern *et al*. (2015). Excerpted with permission of Springer Nature.

	Average cumulative impact scores	**Demersal destructive fishing**	**Demersal nondestructive high bycatch fishing**	**Demersal nondestructive low bycatch fishing**	**Direct human impact**	**Light pollution**	**Nutrient pollution**	**Oil rigs**	**Organic pollution**	**Pelagic high bycatch fishing**	**Pelagic low bycatch fishing**	**Sea surface temperature**	**UV**
FAO High Seas Region													
Pacific, Northwest	0.30702	-0.00335	-0.01593	-0.01354	0	0	0	0	0	-0.00003	-0.00485	0.32369	0.02116
Pacific, Northeast	-0.21884	0.00005	0.00006	0.00009	0	0	0	0	0	0	0.00007	-0.22001	0.00090
Pacific, Western Central	0.14476	-0.00133	-0.00609	-0.00623	0	0	0	0	0	-0.00001	-0.01077	0.16382	0.00543
Pacific, Eastern Central	0.06779	-0.00061	-0.00269	-0.00422	0	0	0	0	0	-0.00279	-0.00593	0.07419	0.00984
Large Marine Ecosystem													
Oyashio Current	0.59495	0.00387	0.00096	0.00145	-0.00005	-0.00001	0.00011	0	0.00000	0	-0.00033	0.55272	0.03722
Sea of Okhotsk	0.51545	0.05522	0.01600	0.01742	0.00006	0.00002	0.00013	-0.00001	-0.00002	0	-0.00005	0.39570	0.03233
Gulf of California	0.36010	-0.00279	-0.00051	-0.00375	0.00043	0.00000	0.00055	0	0.00230	-0.00012	-0.00018	0.37922	-0.01142
Kuroshio Current	0.12531	-0.00993	-0.00997	-0.00889	-0.00025	-0.00011	-0.00039	0	-0.00013	-0.00133	-0.00273	0.15070	0.00877
West Bering Sea	0.10304	0.01491	0.00383	0.01150	0.00006	0.00001	0.00014	0	0.00001	0	0.00000	0.06433	0.00851
East China Sea	0.04817	-0.03266	-0.02918	-0.01215	-0.00020	0.00003	0.00083	0.00000	0.00016	-0.00273	-0.00148	0.09658	0.02956
Yellow Sea	0.03570	-0.02900	-0.03394	-0.01397	-0.00011	0.00016	0.00165	-0.00013	0.00060	0	-0.00043	0.04517	0.06609
Northern Bering - Chukchi Seas	-0.09041	-0.00774	-0.00275	0.00012	-0.00010	0.00001	0.00020	0	0.00002	0	-0.00002	-0.17110	0.05170
Insular Pacific-Hawaiian	-0.17504	-0.00053	-0.00038	-0.00064	-0.00003	-0.00002	0.00024	0	0.00006	-0.00002	-0.00025	-0.21238	0.03877
East Siberian Sea	-0.22535	-0.00002	0.00000	0	-0.00011	0.00000	0.00001	0	0.00000	0	0	-0.30759	0.05703
California Current	-0.25496	-0.00118	-0.00086	-0.00210	-0.00001	-0.00002	-0.00006	0	0.00001	-0.00016	-0.00132	-0.26849	0.01876
Aleutian Islands	-0.48007	-0.02560	-0.00421	-0.00720	0.00014	0.00001	0.00006	0	0.00001	0	-0.00021	-0.41229	-0.03405
East Bering Sea	-0.74419	-0.04420	-0.01342	-0.01080	0.00007	0.00001	-0.00016	0	0.00000	0	-0.00067	-0.66481	-0.01251
Gulf of Alaska	-0.94104	-0.01482	-0.00280	-0.00530	-0.00012	0.00005	-0.00025	0.00000	-0.00001	0	-0.00022	-0.96149	0.03128

3.4 California Current System

In such a large-scale global analysis, a number of pressures in coastal regions, which could have important impacts to local areas, were omitted (Halpern *et al*., 2008). In order to include these, and also to examine whether the results at regional coastal scales were consistent with the results from the global-scale analysis, Halpern *et al*. (2009) repeated their analysis for the California Current System. For this region they identified 24 anthropogenic pressures, including local sources such as fish farms and power plants (Table 3.4), which were spatially, but not temporally, resolved. They also applied a more rigorous process to define the pressure by habitat impact weightings using a social science approach involving 107 experts to assess the relative vulnerability of 20 habitat types to 53 pressures (Teck *et al*., 2010). Experts were asked to consider each habitat's potential resistance to each pressure, and the number of species or trophic levels affected. Teck *et al*. (2010) found that four intertidal habitats (mud flats, beach, salt marsh,

Table 3.4 Pressures and habitat types defined by Halpern *et al*. (2009) for assessment of cumulative impacts on the California Current System.

Pressure	**Habitat type**
Nutrient input	Beach sandy
Organic pollution	Rocky intertidal
Inorganic pollution	Mud flats
Coastal engineering	Salt marsh
Human trampling	Intertidal
Coastal power plants	Suspension-feeding reefs
Sediment increase	Seagrass Shallow, subtidal
Sediment decrease	Kelp forest
Noise/light pollution	Rocky reef Hard substrate <30 m depth
Atmospheric deposition of pollutants	Shallow soft-bottom Soft sediment <30 m depth
Commercial shipping	Hard shelf Hard substrate 30–200 m depth
Invasive species	Soft shelf Soft sediment 30–200 m depth
Ocean-based pollution	Hard slope Hard substrate 200–2,000 m depth
Marine debris (trash)	Soft slope Soft sediment 200–2,000 m depth
Aquaculture	Hard deep benthic Hard substrate >2,000 m depth
Pelagic low bycatch	Soft deep benthic Soft sediment >2,000 m depth
Pelagic high bycatch	Canyons Hard and Soft substrate
Demersal destructive	Seamounts
Demersal nondestructive low bycatch	Surface pelagic
Demersal nondestructive high bycatch	Deep pelagic
Oil rigs	
SST	
UV	
Ocean acidification	

and rocky intertidal) were judged to be the most vulnerable to the anthropogenic pressures that were considered. Coastal ecosystems were judged to have high vulnerability to invasive species, ocean acidification, sea surface temperature change, sea level rise, and habitat alterations. Offshore ecosystems were judged to be most vulnerable to ocean acidification and demersal destructive fishing practices. Halpern *et al*. (2009) found their results for the California Current System were largely consistent with those from their global analysis (Halpern *et al*., 2008). The results also indicated more multiple impacts in the northern California Current System off Oregon and Washington States, compared with southern and Baja California (Fig. 3.5).

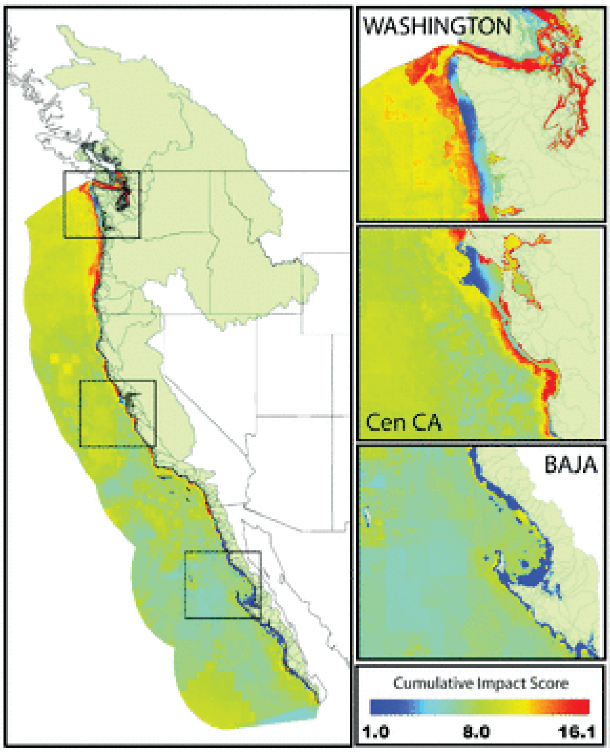


Fig. 3.5 Cumulative impact map of 25 different human activities on 20 different marine habitats within the California Current System. From Halpern *et al*. (2009). Reproduced with permission of Wiley.

A different approach to identifying key anthropogenic pressures in the California Current System, using time series but not spatially resolved data, is provided by Andrews *et al*. (2015). They used a set of 22 pressures similar to Halpern *et al*. (2009), with data intermittently available over the period 1970 to 2012 (Table 3.5). They used multivariate statistical methods to summarize and reduce the large number of pressures to a smaller number of representative trends. Figure 3.6 shows two indices of cumulative pressures for 15 anthropogenic pressures that had data for the period 1994 to 2008. These analyses indicated that, for these 15 pressures, the period 2004 to 2008 experienced both peaks and strong declines of cumulative pressures. Andrews *et al*. (2015) suggested that relative changes among pressures may be due to changes in management actions, business practices, economic activity, technological advances, and/or social norms. The California Current System Integrated Ecosystem Assessment (*e.g*., sub-section 2.2.7) includes these anthropogenic pressures (Table 3.5) and adds 20 physical, chemical, biological, and climate pressures (Table 3.6; Harvey *et al*., 2014).

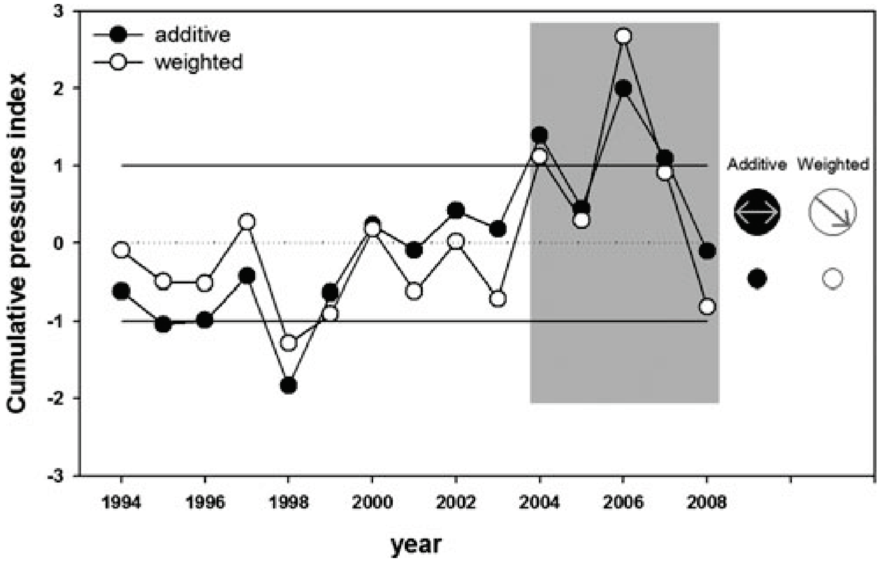


Fig. 3.6 Two indices of cumulative pressures derived from 15 anthropogenic pressures for the California Current System. 'Additive' is the sum of all pressures; 'Weighted' is the sum multiplied by their weighting value. From Teck *et al*. (2010). Shaded area represents the most recent five-year period; symbols to the right indicate trends over this five-year period: decreasing for the Weighted index, neutral for the Additive index. From Andrews *et al*. (2015). Reproduced with permission of Cambridge Univsersity Press.

Table 3.5 Top pressures and associated indicators for anthropogenic pressures in the California Current System. From Andrews *et al*. (2015). Reproduced with permission of Cambridge Univsersity Press.

Category	Pressure	Indicator
Terrestrial pollutants	Atmospheric pollution	Sulphate deposition
	Inorganic pollution	Chemical releases
	Organic pollution	Toxicity concentrations
	Nutrient inputs	Nitrogen and phosphorus inputs
Transportation	Dredging	Dredge volumes
	Commercial shipping	Volume of water disturbed
	Ocean-based pollution	Commercial shipping and tons of cargo
	Invasive species	Tons of cargo
Coastal disturbance	Marine debris	Predicted counts of debris
	Recreational use	Beach attendance
	Light pollution	Average night visible light
	Habitat modification	Distance trawled
Food	Fisheries removals	Total landings
	Shellfish aquaculture	Shellfish production
	Finfish aquaculture	Finfish production
	Seafood demand	Total consumption

Table 3.5 Continued.

Category	Pressure	Indicator
Construction	Coastal engineering	Human coastal population
	Freshwater retention	Impoundment storage
	Sediment retention	Impoundment storage
	Benthic structures	Number of offshore wells
Energy	Oil and gas activities	Offshore oil and gas production
	Power plant activities	Saline water withdrawal volume

Table 3.6 Climate, physical, chemical and biological oceanographic pressures considered in California Current Integrated Ecosystem Assessments, in addition to the anthropogenic pressures of Table 3.5. After Harvey *et al*. (2014).

Pressure category	Indicator
Climate	Multivariate El Niño Index
	Northern Oscillation Index
	North Pacific Gyre Index
	Pacific Decadal Oscillation Index
	Date of Spring transition in circulation patterns
	Duration of upwelling season
Physical	Eddy kinetic energy
	Upwelling index
	Total upwelling magnitude
	Sea level height
	Sea surface temperature
	Meridional winds
	Pycnocline depth
	Pycnocline strength
Chemical	$NO_2 + NO_3$ (at 150 m)
	Dissolved oxygen (at 150 m)
Biological oceanographic	Monthly copepod biomass
	Monthly copepod community composition
	Monthly northern copepod biomass anomaly
	Monthly southern copepod biomass anomaly

3.5 Puget Sound, Washington State, USA

The Puget Sound Partnership, a government agency of Washington State, USA, has developed an approach to identifying valued ecosystem components (‘endpoints’) and key pressures on these components for the Puget Sound marine and terrestrial ecosystems. In its framework (Labiosa *et al*., 2014; see also sub-section 2.2.2), an expert elicitation approach was used to identify which pressures are likely to impact which endpoints, the intrinsic vulnerability of each endpoint to each pressure, and the intensity of the pressure and whether the pressure and endpoint overlap in time and space (‘exposure’), to derive the potential impact of that pressure on that endpoint at that location. The Puget Sound Partnership considered the impacts of 34 pressures on valued ecosystem components (endpoints) in two ecosystem realms (terrestrial watersheds, marine basins; McManus *et al*., 2014). For marine basins in Puget Sound, conversion of land cover for transportation, utilities, and natural resource production (including farmland) was ranked as having a very high impact (Fig. 3.7). High impacts were assigned to non-point source persistent toxic chemicals, shading of shallow water habitats, shoreline hardening, spread of disease and parasites to native species, introduction of human pathogens, species disturbances, and non-point source water pollutants. Changing ocean conditions (including sea surface temperatures and acidification) and bycatch were ranked as having moderate impacts, and sea level rise and harmful algal blooms as having low impacts. These rankings reflect the large coastal perimeter to water surface area ratio of Puget Sound and the importance of specific terrestrial and coastal pressures. A number of pressures were identified as having high impacts in both watershed and marine basin systems of Puget Sound (Fig. 3.8).

3.6 British Columbia, Canada

Ban and Alder (2008) and Ban *et al*. (2010) followed a similar approach to Halpern *et al*. (2008) to identify multiple pressures and their potential impacts to marine ecosystems of British Columbia, Canada. They examined the impacts of 36 pressures on 14 habitat types (Table 3.7). Commercial fishing was found to have the highest impact on most of the benthic habitat types (Fig. 3.9). When additional pressures were included, rocky reef and seagrass habitats had the highest mean impact scores, followed closely by kelp beds (Fig. 3.9). Spatially, the Strait of Georgia had the highest impact scores (and the greatest number of pressures), followed by the straits and passages in northern Vancouver Island and near the border with Alaska, also representing areas of greater human population and activities. This analysis was repeated by Clarke Murray *et al*. (2015), using updated and expanded data available over the five years subsequent to previous study by Ban *et al*. (2010). They found a spatial pattern of impacts similar to Ban *et al*. (2010), although with increased cumulative impacts off the west coast of Vancouver Island and in Dixon Entrance south of the border with Alaska (Fig. 3.10). Clarke Murray *et al*. (2015) concluded that commercial fishing remained the largest overall impact among marine activities in British Columbia. Intertidal habitats were the most impacted habitats per unit area, whereas pelagic habitats had the highest total cumulative impact scores.

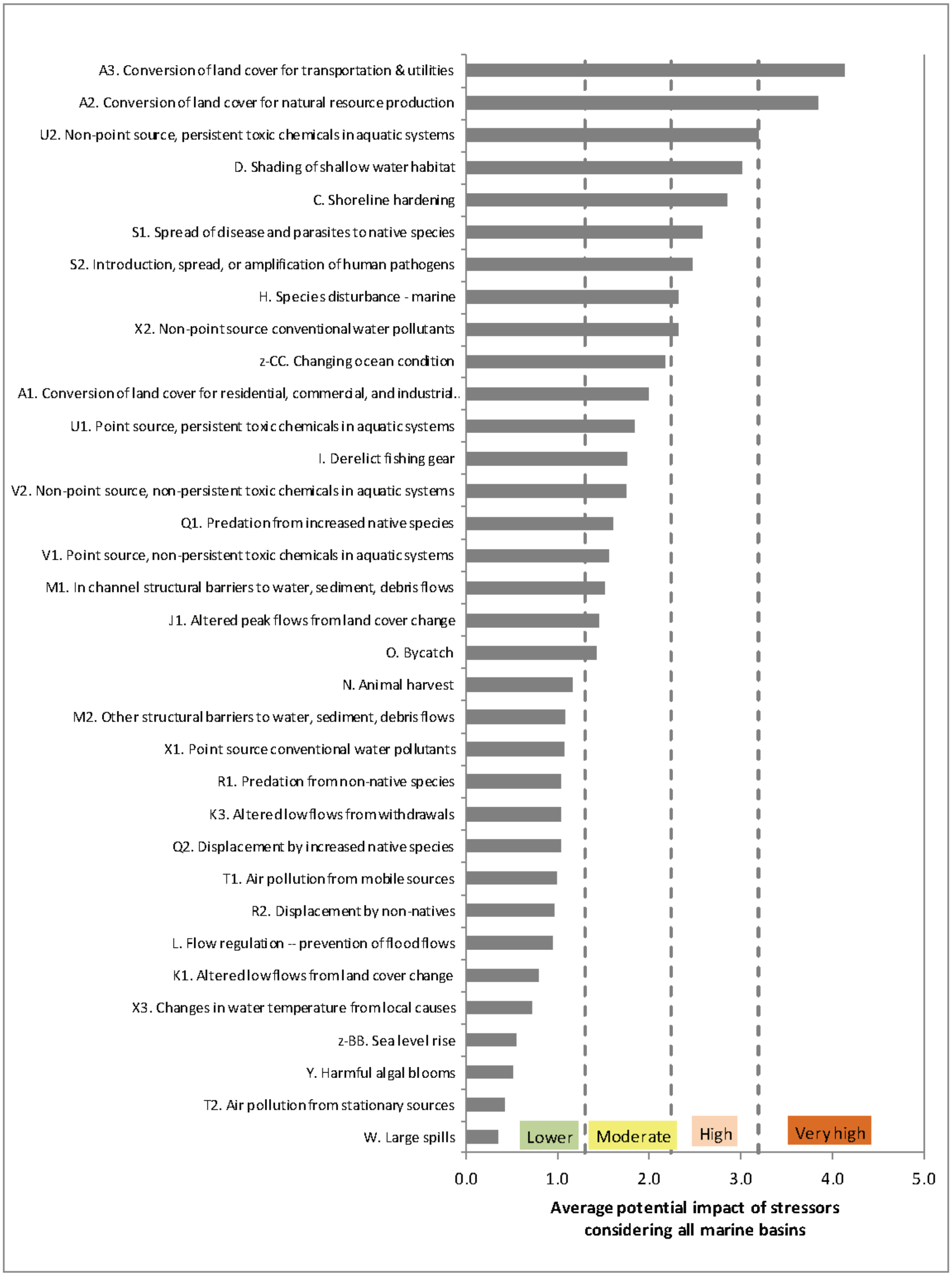


Fig. 3.7 Stressors with the most potential impacts in marine basins of Puget Sound. From McManus *et al.* (2014).

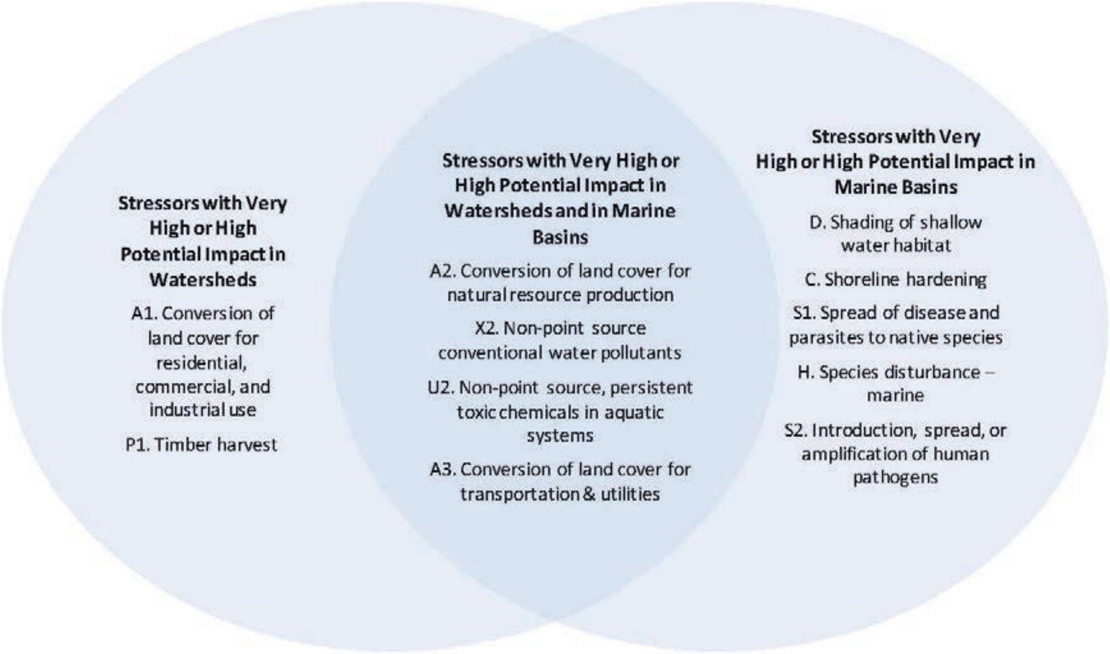


Fig. 3.8 Puget Sound stressors with Very High or High Potential Impact in marine basins, terrestrial watersheds, and those that may affect both. From McManus *et al*. (2014).

Table 3.7 Pressures and habitats defined by Ban *et al*. (2010) for identification of cumulative impacts along the British Columbia coast.

Category	Pressure	Habitat
Coastal marine-based/commercial activities	Finfish aquaculture	Kelp
	Shellfish aquaculture	Rocky reef
	Transportation: large vessels	Sea grass
	Transportation: ports, marinas, harbors	Suspension-feeding reef
	Ocean dumping (non-toxic)	Shelf: soft-bottom
Land-based activities	Industry	Shelf: hard bottom
	Forestry (sedimentation)	Slope: soft-bottom
	Forestry: log-dumping	Slope: hard-bottom
	Forestry: pulp and paper	Deep: soft-bottom
	Onshore mining	Deep: hard-bottom
	Agriculture	Canyon
	Human settlements	Seamount
Fishing	Recreational fishing	Shallow pelagic waters
	Commercial fishing (21 different types)	Deep pelagic waters

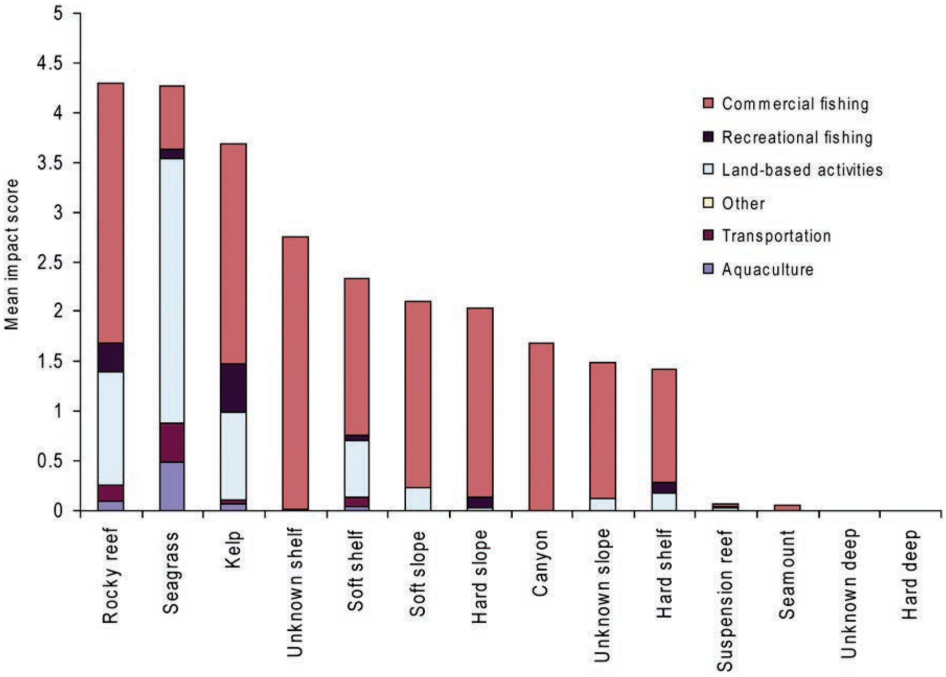


Fig. 3.9 Mean impact score (per 200 m pixel) on benthic habitats in Canada's Pacific marine region, by activity category. From Ban *et al*. (2010). Reproduced with permission of Elsevier.

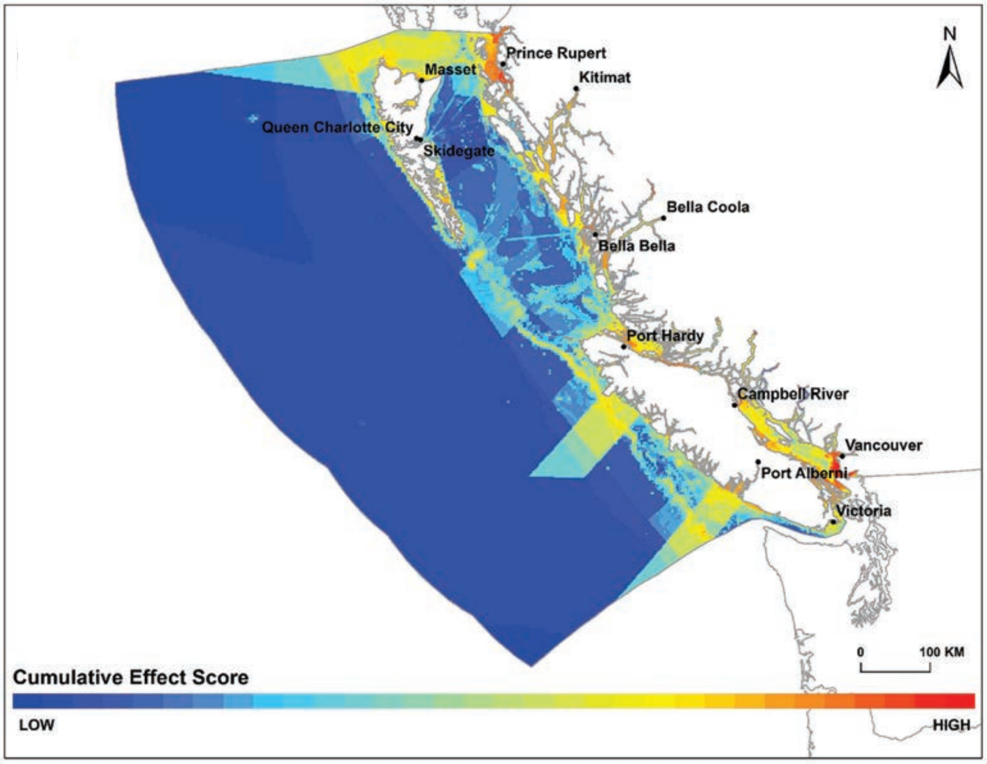


Fig. 3.10 Cumulative effects scores for the marine waters of Pacific Canada, updated from Ban *et al*. (2010). From Clarke Murray *et al*. (2015). Reproduced with permission of Elsevier.

3.7 Alaska, USA

Alaska, with its smaller human population but very large area, has fewer anthropogenic pressures than other regions of the Northeast Pacific. The main human pressure is commercial fishing. In 2016, Alaska produced 57% of the total U.S. fisheries landings, with Alaska pollock the largest U.S. commercial fishery (Klouda, 2017). Fishing impacts include targeted removals, unintentional removals (bycatch), and gear impacts on benthic habitats. Oil and gas development, and related shipping and transport activities, are the next most important human pressures (with much of the extraction taking place in Alaska's Arctic waters). Additional pressures include chemical pollution, for example, acid rain drainage into the western Bering Sea from coal mines in Russia (Francis *et al*., 1996). Environmental and climate-related pressures, such as increasing sea surface temperatures and decreasing sea ice extents and durations, have important impacts on Alaska's marine ecosystems. Detailed ecosystem assessments for three of Alaska's marine systems are produced annually, presenting time series and annual updates to many climate, oceanographic, fisheries, and human pressures and indicators (Eastern Bering Sea: Siddon and Zador, 2017; Aleutian Islands: Zador, 2016; Gulf of Alaska: Zador and Yasumiishi, 2017).

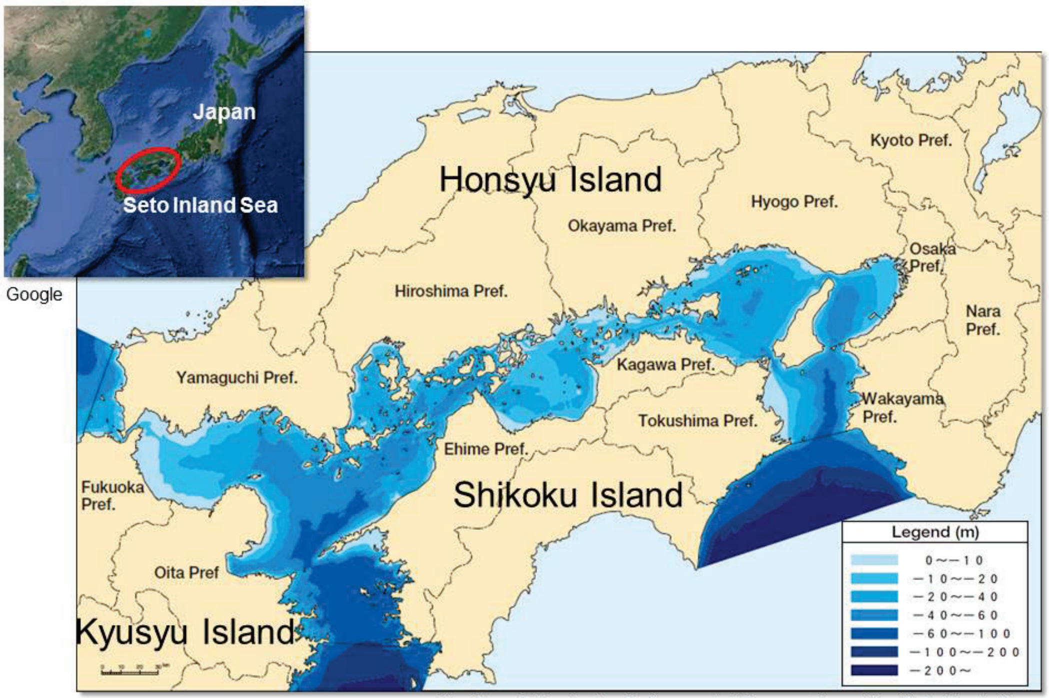
3.8 Seto Inland Sea and coastal waters, Japan

Motomitsu Takahashi, Naoki Yoshie and Kazuhiko Mochida

Various marine environmental problems have been studied in both the coastal and oceanic regions around Japan. This section describes Japanese studies of multiple stressors using two examples: environmental issues (in particular, relating to coastal engineering, coastal development, nutrient inputs, and harmful algal blooms) of the Seto Inland Sea, and the present status of marine pollution in the sea around Japan.

The Seto Inland Sea is the largest semi-enclosed coastal sea in Japan; it is surrounded by three large islands, Honshu (the main island of Japan), Kyushu and Shikoku (Fig. 3.11), and has more than 700 small islands within its area. Its total shoreline is 7,000 km long. The Seto Inland Sea is about 500 km from east to west and varies from 15 to 55 km north to south with an average depth of 40 m. It has many large and small straits, bays and shore reefs. This complicated geometry results in wide variations in the marine environment (Yanagi *et al*., 2008). The Seto Inland Sea region is also one of the most industrialized areas in Japan. After the New Industrial City Law was enacted in 1963, many facilities for heavy industry were built in the coastal areas surrounding the Seto Inland Sea. Urbanization around the coast also increased. At present, approximately 35 million people live within the Seto Inland Sea watershed. This industrialization and urbanization required substantial reclamation of land. The marine environment of the Seto Inland Sea has been significantly affected by these impacts over the last five decades (Takeoka, 2002). In order to tackle the environmental problems and keep the natural environment beautiful for future generations, various entities such as local governments, companies, non-governmental organizations, and citizens are working hard to protect it.

Since ancient times, the coastline of the Seto Inland Sea, because of its shallow depth, has been changed by land reclamation for agriculture and salt farmland. The rapid industrialization from the 1960s required a great deal of reclamation and, as a result, the natural coastline is only 37% of the total coastline of the Seto Inland Sea at present, which is less than the value for Japan as a whole (55%). Artificial beaches have been created to restore lost natural beaches. The state of the coastline of the Seto Inland Sea is shown in Figure 3.12A (Yanagi *et al*., 2008).

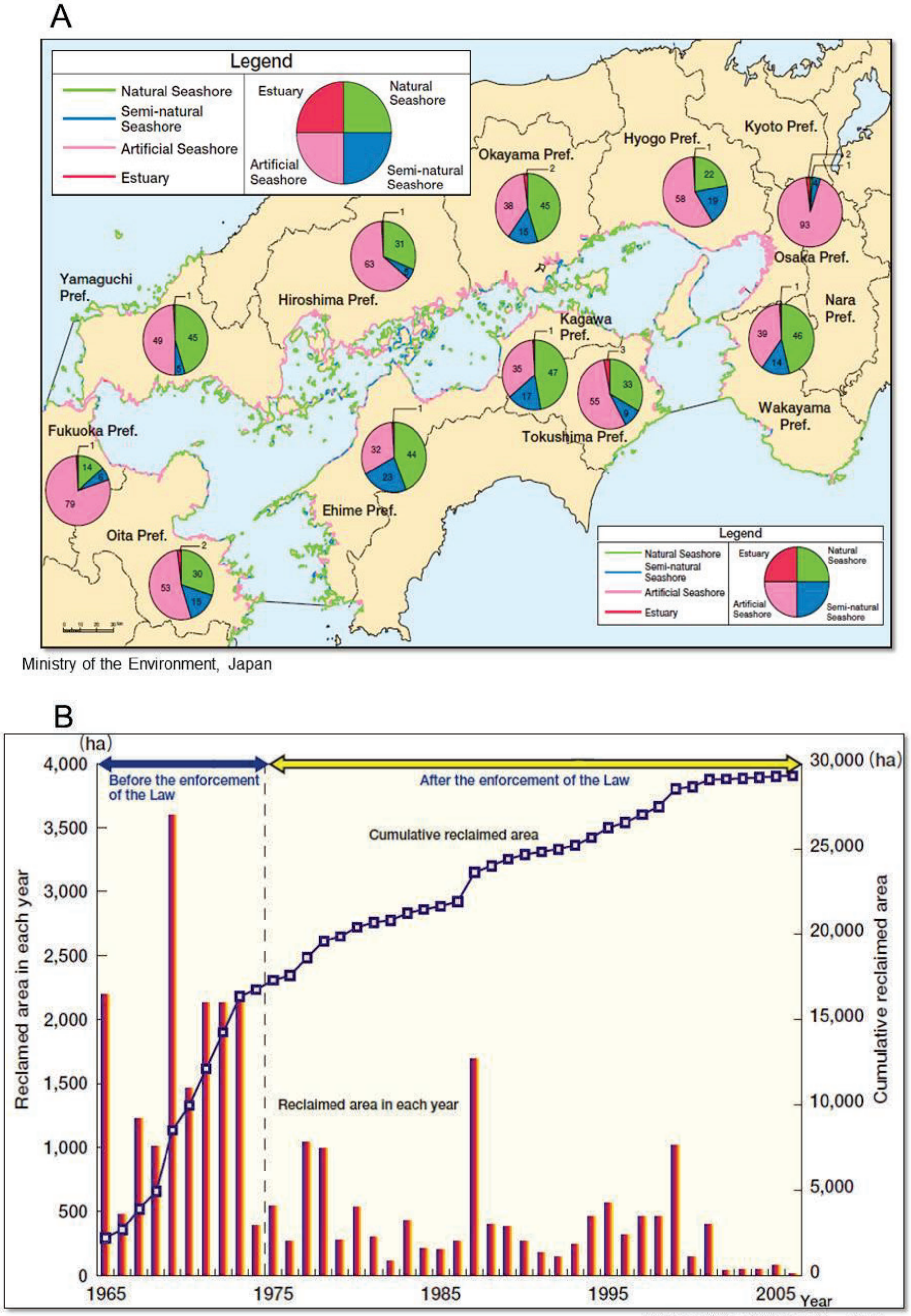


The Association for the Environmental Conservation of the Seto Inland Sea

Fig. 3.11 Location and water depth of the Seto Inland Sea, Japan. From International EMECS Center (2008).

Figure 3.12B shows transitions in reclaimed land. The total area of permitted reclamation is clearly distinct from 1965 to 1973, but decreased drastically thereafter. It was in 1973 that the “Law Concerning Special Measures for Conservation of the Environment of the Seto Inland Sea (Setouchi Law)” was established. The total area of land reclaimed since 1965 is approximately 250 km^2, which is approximately 12% of the Seto Inland Sea area with a depth of less than 10 m. More than half of the marine forest that existed in the early 1960s has been lost by reclamation. In particular, not only the seagrass beds but also the tidal flats have decreased. The former is considered to be important as a zone for nursery grounds of shellfish and finfish. The latter plays an important role in the ecosystem and in self-purification. Total areas of seagrass beds and tidal flats in the Seto Inland Sea are shown in Figure 3.13. Coastal development caused a decrease in seagrass beds and tidal flats until the early 1980s.

Sea sand is an important raw material for building construction. The amount of sea sand extracted from the bottom of the Seto Inland Sea represents 8% of Japanese consumption. Interannual changes in sea sand extraction and the catch of sand eel in Okayama prefecture are shown in Figure 3.14. The sand eel is a commercially low-value small fish; however, it is good prey for high-value large fishes such as sea bream and Japanese seaperch in the Seto Inland Sea. The sand eel needs the sand bank on the sea bottom to hibernate during the summer. When the catch of sand eel clearly decreased with the extraction of sand, the large fishes also decreased with the decrease of their prey. Since 2006, sea sand extraction has been prohibited in the Seto Inland Sea. The artificial regeneration of the sand bank was also undertaken to aid recovery of the marine ecosystem on the bottom of the Seto Inland Sea.



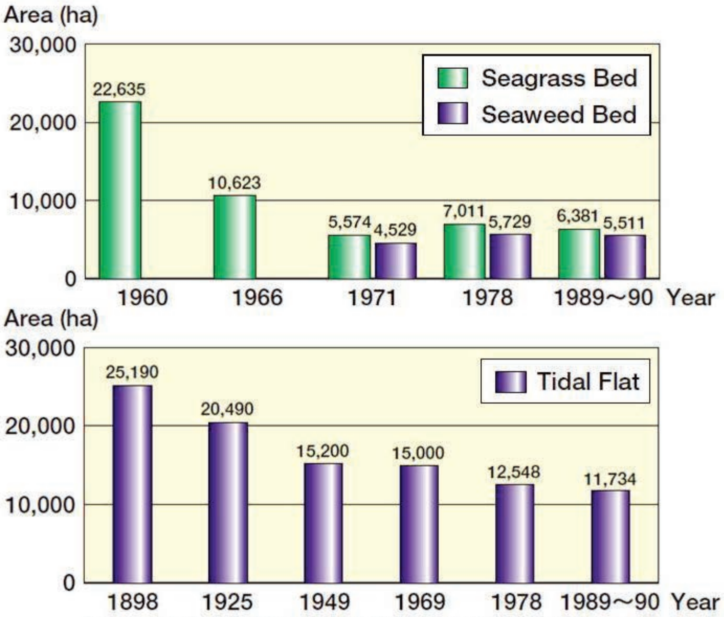
Ministry of the Environment, Japan

Ministry of the Environment, Japan

Fig. 3.12 A) The state of the shoreline along the Seto Inland Sea; B) Trends in reclaimed areas in the Seto Inland Sea from 1965 to 2006. From International EMECS Center (2008).

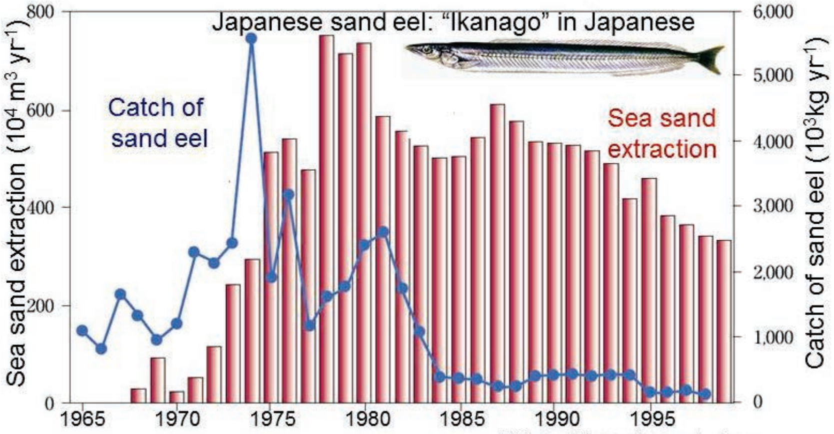
The Seto Inland Sea is greatly influenced by river drainage due to its relatively shallow depth. Fluctuations in water temperature, salinity and nutrient concentration sometimes make the area susceptible to unusual events, such as harmful algal blooms (HABs, *e.g.*, red tides). During the period of high economic growth after World War II, large parts of the shallow coastal areas were reclaimed in order to construct industrial and residential zones. Large quantities of industrial effluent, as well as domestic sewage, were released into the sea. Water quality rapidly degraded and triggered frequent red tides, resulting in extensive damage to fisheries. In Japan, total nitrogen (TN) and total phosphorous (TP) concentrations have been used as indicators of water quality. The horizontal distribution of TN and TP in the surface water during the summer of 2003 are shown in Figure 3.15A (Yanagi *et al.*, 2008), where high TN and TP occurred in the eastern part of the Seto Inland Sea and the enclosed bays.

Dissolved inorganic nitrogen (DIN) and phosphorous (DIP) have also been used as indicators for eutrophication. Both DIN and DIP in the eastern part of the Seto Inland Sea (Figure 3.15B) have clearly decreased by control of the total volume of emissions from the industrial companies (Fisheries Research Agency, Japan, 2015).



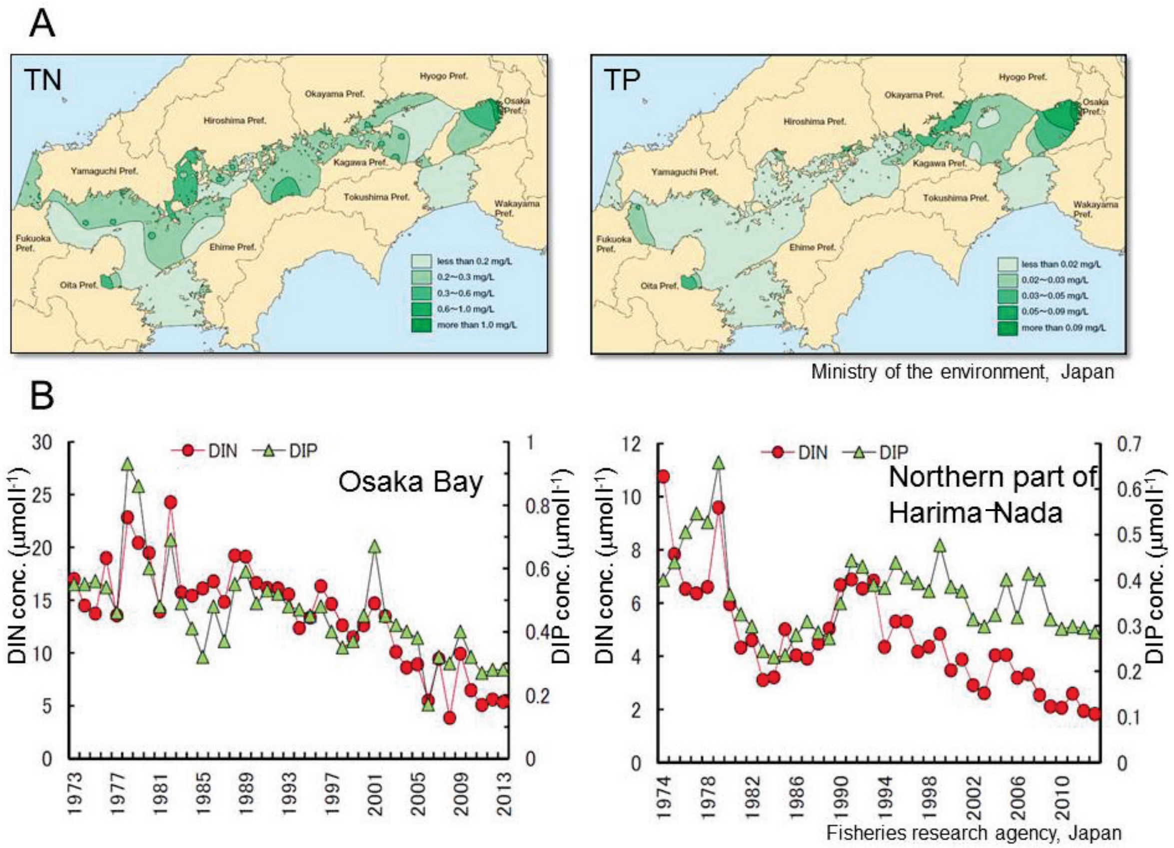
The Association for the Environmental Conservation of the Seto Inland Sea

Fig. 3.13 Trends in areas of seagrass and seaweed beds, and tidal flats, in the Seto Inland Sea. From International EMECS Center (2008).



Ministry of the environment, Japan

Fig. 3.14 Interannual changes in sea sand extraction and catch of sand eel in Okayama prefecture. From Ministry of the Environment, Japan (2009a).



Ministry of the environment, Japan

Fisheries research agency, Japan

Fig. 3.15 A) Horizontal distribution of TN and TP in the surface layer of the Seto Inland Sea during summer, 2003. From International EMECS Center, 2008; B) Interannual variations of DIN and DIP in Osaka Bay and northern part of Harima-Nada. From Fisheries Research Agency, Japan (2015).

During the 1960s and 1970s, the Japanese economy grew rapidly. In 1960 and 1965, the beginning of the high-growth period of the Japanese economy, the total number of occurrences of HABs was less than 50 per year in the Seto Inland Sea (Okaichi, 1997). Figure 3.16A represents the occurrences of HABs (incidents per year) in the Seto Inland Sea from 1970 to 2005 (Fisheries Research Agency, Japan, 2000, 2006). The total number of occurrences was 79 in 1970, but a marked increase occurred to a maximum of 299 per year in 1976 because of eutrophication. After the peak in 1976, the number of such incidents decreased substantially per year (accompanied by low occurrences in fishery damage), and this level has been maintained to the present.

The distribution of HABs in the Seto Inland Sea from 1960 to 2000 is depicted in Figure 3.16B. In 1960, there were few occurrences of HABs (18 cases), and the area involved was small. In the 1970s and 1980s, large-scale HABs occurred frequently, especially during the summer season. In extreme cases, some HABs covered almost the whole area of Nada Bay, such as Osaka Bay, Harima-Nada, Hiuchi-Nada, and Suo-Nada. In the 1990s and thereafter, the scale and frequency of HABs appears to have become smaller and shorter (Yanagi *et al*., 2008).

The Japanese Ministry of the Environment carried out a monitoring survey for hazardous chemical substances, such as polychlorinated biphenyls (PCBs), dioxins (polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs)), and butyltins (BTs) in both seawater and sediment from 1998 to 2007 (Ministry of the Environment, 2009b) in seven different regions around Japan (Fig. 3.17). PCBs had been used mainly as an insulating oil in electronic devices. The dioxins are classified as persistent organic pollutants and are unintentionally generated by combustion. Both compounds have caused concern for human and ecological health. Import and production of PCBs in Japan has been prohibited since 1975. BTs are antifouling booster biocides and were mainly used on ship hulls and fishing nets to prevent or reduce biofouling by colonizing marine organisms. In the 1970s, most of the ships in the world bore BTs, such as tributyltin (TBT). However, due to the severity of TBT-induced impacts on marine ecosystem health, Japan banned all TBT usage in Japanese shipyards in 1991. Thus, officially they are out of use in Japan.

In coastal areas, PCBs and dioxins originating from metropolitan areas were still detectable at concentrations up to 30 pg-TEQ/g-dry weight in the sediment over the course of the survey. In addition, low concentration levels remain in the sediments in offshore areas. Dioxins, but not PCBs, tended to decrease in some marine areas and in some marine organisms over this decade, but not in general. No marked downward trend in PCB concentration levels were observed in the bodies of marine organisms over the duration of the survey (Ministry of the Environment, 2009a).

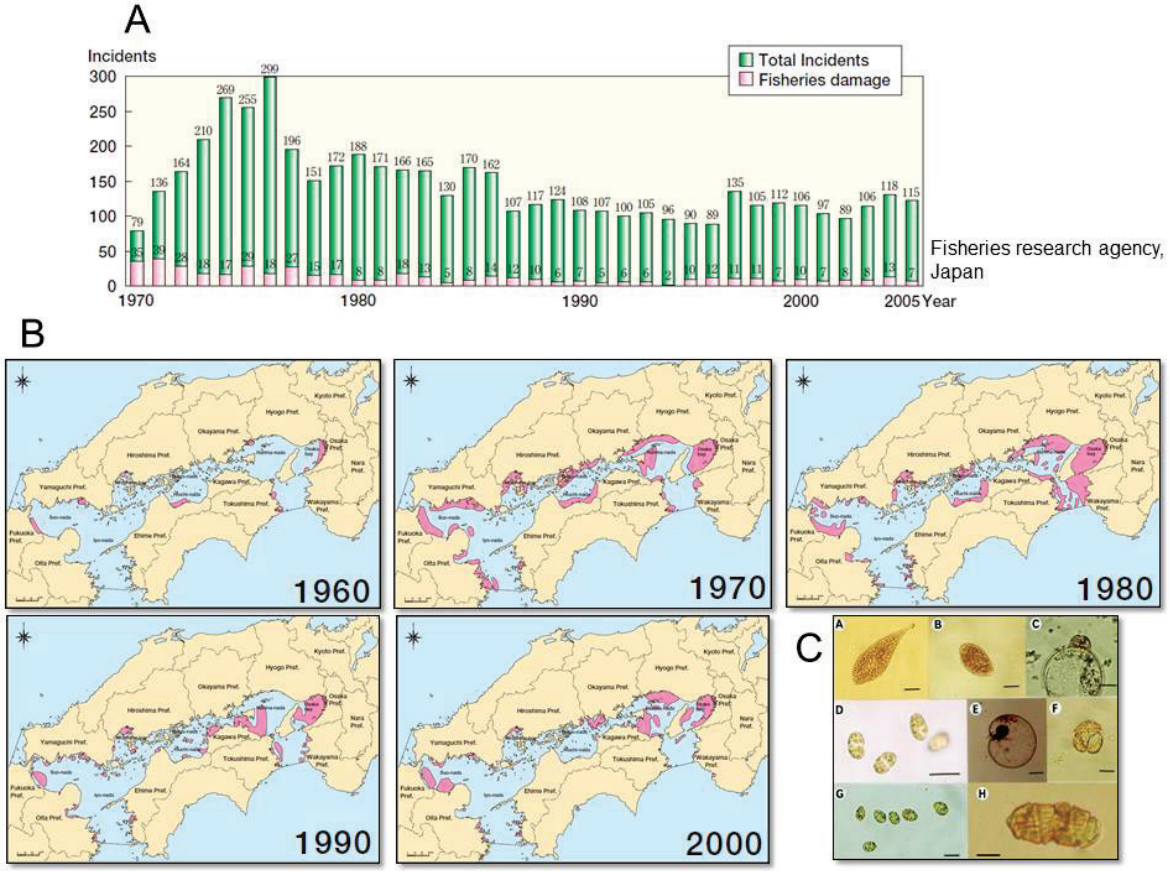


Fig. 3.16 A) Occurrence of harmful algal blooms (HABs) in the Seto Inland Sea from 1970 to 2005. The short (pink) columns indicate incidents of fishery damage such as fish-kills; B) Decadal changes in the distribution of HABs and noxious microalgae in the Seto Inland Sea; C) Fish-killing raphidophyte taxa (A–D), and red tide-forming dinoflagellates (E–H). From International EMECS Center (2008).

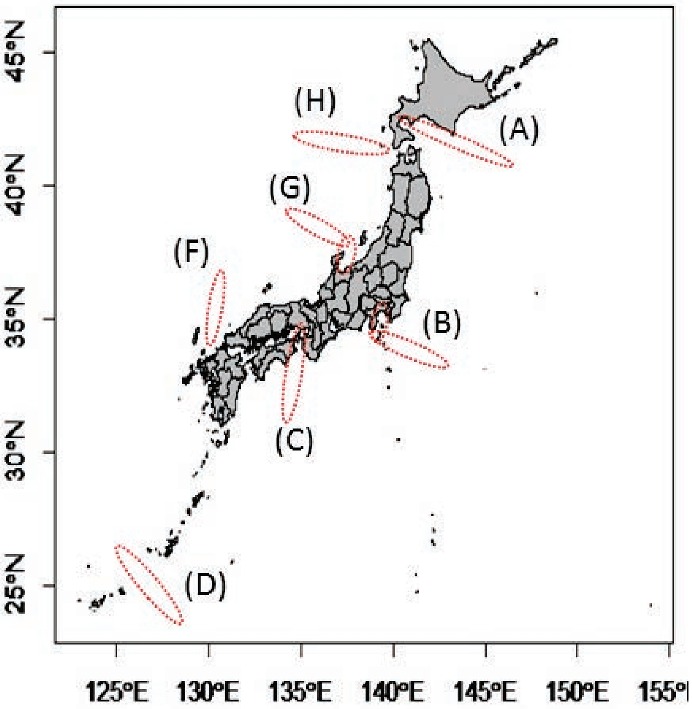


Fig. 3.17 Geographical distribution of the sampling regions around Japan for the Marine Environmental Monitoring Survey carried out by the Ministry of the Environment from 1998 to 2007. A) Coastal to offshore of Funka Bay in Hokkaido; B) Tokyo Bay; C) Osaka Bay; D) region between the main island of Okinawa and Miyakojima Island; F) eastern part of Tsushima Straits; G) Toyama Bay; H) western part of Tsugaru Strait.

With respect to BTs, mono- and di-butyltin were the primary forms detected. TBT was detected only in sediment samples of inner bays and coastal areas located in metropolitan areas, and the highest concentrations were about 30 ng/g-dry weight. Because the use of antifouling paints containing BTs has already been prohibited in Japan, a main source is likely to be from the heavy traffic of foreign vessels. Like PCBs, BTs have also tended to decrease in other areas and in some marine organisms over this decade, but not in general (Ministry of the Environment, 2009a). As for other antifouling biocides as alternatives to BTs, sporadic surveys were carried out from 1997 to 2013 for a couple of herbicides, Irgarol 1051 (2-methylthio-4-tertiary-butylamino-6-cyclopropylamino-s-triazine) and Diuron (3-(3,4-dichlorophenyl)-1,1-dimethylurea) in the Seto Inland Sea. They have been detected in seawater samples at levels averaging 30 ng/L (Okamura *et al*., 2003; Balakrishnan *et al*., 2012; Kaonga *et al*., 2015). Although Irgarol 1051 was occasionally detected in some harbors and marinas in the Seto Inland Sea at concentration levels that have the potential to affect marine algal species, the concentration level in general has not been a concern for ecological risk to marine organisms (Mochida and Fujii, 2008).

The Japanese Ministry of the Environment also carried out monitoring surveys for benzo [a] pyrene (BaP) from 2008 to 2013 (Ministry of the Environment, Marine Environment Monitoring Survey results, https://www.env.go.jp/water/kaiyo/monitoring/status_report.html). BaP is one of the polycyclic aromatic hydrocarbons and is a typical anthropogenic chemical compound which is carcinogenic. Concentrations of BaP tend to decrease from coastal to offshore, suggesting that the source is derived from anthropogenic activities on land. The highest concentration in coastal areas around metropolitan areas is about 40 ng/g-dry weight.

3.9 Korea

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Korea identifies multiple pressures and their potential impacts to marine ecosystems of the East Sea, East China Sea, and Yellow Sea in adjacent Korean waters according to a Marine Ecology Map (http://coast.mof.go.kr/coastAdmin/research/ecology.do). The impacts of 4 pressures (general habitats of marine biology, health and productivity of the marine ecosystem, biodiversity, and marine protected areas) on 189 unit lattices (10′ × 10′, about 278.2 km^2) have been evaluated since 2006. Based on variables such as eutrophication, benthic dissolved oxygen, heavy metal concentrations of Cd, Cu, Pb, Zn, *etc*., biomass of large benthos, the occurrence of harmful algal blooms (HABs), appearance of habitat and spawning areas, species diversity index, and number of species, Korean waters were categorized into three tiers (Fig. 3.18).

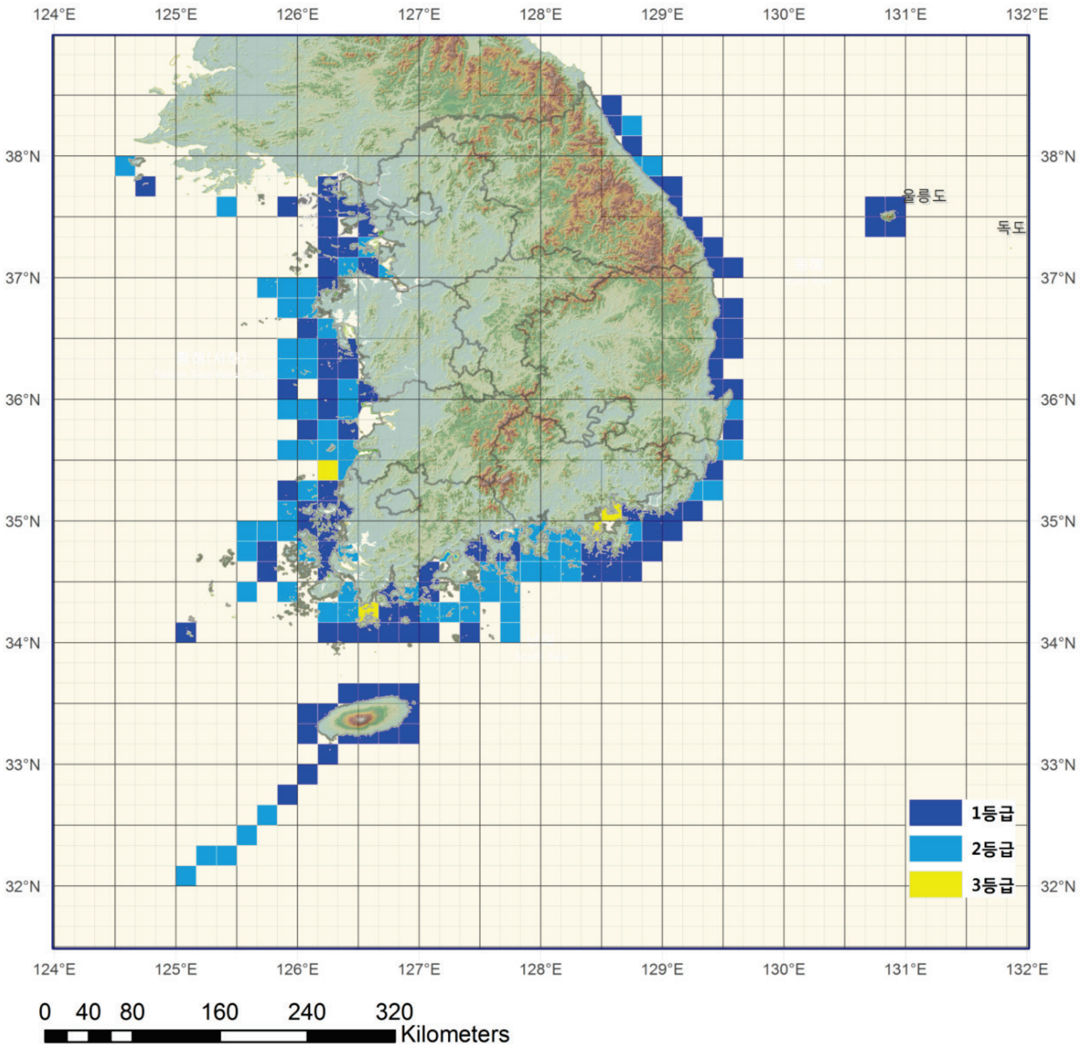

Fig. 3.18 Marine Ecology Map for waters around Korea. Colors were categorized from tier 1 (high) to tier 3 (low) biodiversity and health of marine ecosystems, based on the impacts of 4 pressures on 189 unit lattices (10′ × 10′). From Ministry of Oceans and Fisheries, Republic of Korea (2015).

The assessment, forecasting and management system for fisheries called "Integrated Fisheries Risk Analysis Method for Ecosystems" (IFRAME) (see sub-section 2.2.6), was developed using an ecosystem-based fisheries assessment (EBFA; Zhang *et al*., 2011). Its usefulness for assessing the impacts of climate change on fisheries has been evaluated by a comparative analysis of a suite of ecosystem models (Hollowed *et al*., 2013). For applying the EBFA approach in Korea, fourteen indicators of multiple pressures were selected, including four indicators for sustainability, four indicators for biodiversity, three indicators for habitat quality and three indicators for socio-economic benefit. Based on this approach, ecosystem risk indices (ERIs) for the Yellow Sea, East China Sea and East Sea were estimated as 2.17, 1.87 and 1.95,[1] respectively (Zhang *et al*., 2019). The ERI was highest for the Yellow Sea ecosystem. Fisheries risk indices (FRIs) of two fisheries in the Yellow Sea ecosystem were higher than their ERI, while those of eight fisheries in the East China Sea ecosystem and four fisheries in the East Sea ecosystem were higher than their ERI, respectively (Fig. 3.19).

Recently, IFRAME was extended to assess and forecast ecosystem dynamics and risk indices in a spatio-temporal context. The extended IFRAME has two more components than the original approach. First, a spatial component was added to explain the risk indices by the unit sea block in EBFA. Second, Ecospace, a spatial and temporal dynamic module in the EwE model (see sub-section 2.2.3) was added to the forecasting process of IFRAME. This extended approach was demonstrated with a preliminary application to the East Sea ecosystem, based on four scenarios, considering changes in fishing mortality and habitat preference, which were chosen in the forecasting process.

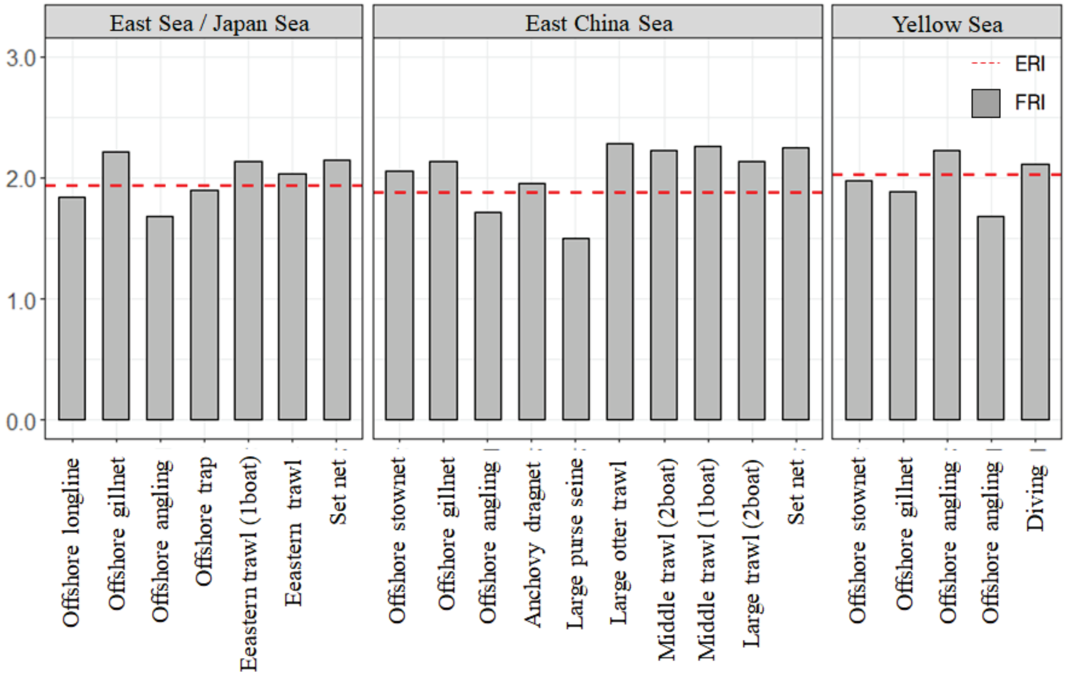

Fig. 3.19 Ecosystem risk index (ERI) and fisheries risk index (FRI) of multiple pressures for three ecosystems in Korean waters. From Zhang *et al*. (2019). Reproduced with permission of Elsevier.

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[1] Values confirmed by C.I. Zhang, personal communication.

3.10 China

China's economy has grown exponentially over the past few decades. This rapid economic growth has resulted in accelerated rates of degradation of China's coastal ecosystems, after relatively little change from 1950 to 1978 (He *et al*., 2014). Significant anthropogenic pressures on these ecosystems include excess nutrient inputs, chemical pollution, changes in runoff due to the building of dams and changes in land use, reduced sediment delivery to the ocean, and intense land reclamation (Jiao *et al*., 2015). The increase in nutrient inputs has altered the ratios of nitrogen, phosphorous, and silicate which, among other consequences, has contributed to an increased occurrence of harmful algal blooms (HABs); in the 2000s there were more than four times the number of HABs in China's coastal waters than in the 1990s (Jiao *et al*., 2015). The increased frequency of HABs in turn has contributed to increased occurrences of hypoxia, being most severe in the northern and nearshore areas and weakest along the outer continental shelf (Jiao *et al*., 2015). Chemical pollution from agricultural and industrial activities, waste water discharges, and aquaculture has also increased, along with occurrences of emerging contaminants such as polybrominated diphenyl ethers (PBDEs) and antibiotics (Jiao *et al*., 2015). Small oil spills, especially at port facilities, have also increased but major incidents involving large spills are also becoming more common (Jiao *et al*., 2015).

To these anthropogenic pressures must be added natural pressures such as changes in the Asian monsoon cycle, changes in the flows from very large rivers, and variability in the Kuroshio Current system (Zhang *et al*., 2016). Sea temperatures have increased at rates over 1°C since the 1950s in the Bohai, Yellow and East China seas, leading to increasing sea level rise and changes in the distributions of several zooplankton and fish species. Ocean acidification has also increased, with aragonite saturation levels lower than 2 in the bottom waters of most coastal seas (Jiao *et al*., 2015).

A site-specific example of the impacts of multiple pressures is provided by Yu *et al*. (2015) for Xiamen Bay in Fujian Province, southeastern China. They found that coastal engineering activities were the biggest sources of routine risks, followed by typhoons and storm surges. Oil spills were the biggest accidents contributing to risks, followed by routine discharges of oil. The ecosystems most likely to be impacted were, first, the shallow water swamp systems followed by inter-tidal mudflat ecosystems. They also found that species diversity was most affected in these ecosystems, followed by species population abundances.

3.11 Synthesis of multiple pressures on North Pacific marine ecosystems

PICES member countries around the North Pacific encompass large differences in human population size, urbanization, and industrialization of their coastlines. Despite these differences, the types of pressures on the marine ecosystems of the North Pacific are broadly similar (*e.g*., Table 3.1), with differences relating to the relative intensities of pressures among areas. Climate-related changes (*e.g*., temperature, oxygen concentration, and acidification) and fishing are often seen as the main large-scale pressures, having impacts across of the North Pacific. Halpern *et al*. (2015) concluded that climate change-related processes were the primary drivers of the changes they observed between 2008 and 2013. Specific pressures become apparent in coastal and continental shelf areas in which chemical pollutants and habitat changes can have strong local effects. Clarke Murray *et al*. (2015) identified commercial fishing as having the largest impact to the marine ecosystems of British Columbia, but in Puget Sound McManus *et al*. (2014) identified the strongest pressures as those deriving from terrestrial use and land cover change.

It is clear, therefore, that the perception of the most important pressures on marine ecosystems of the North Pacific will depend on the location being examined (*e.g.*, whether the California Current System or the Seto Inland Sea) and the spatial scale of the analysis. At small (*e.g.*, local) scales many pressures can be expected to be potentially more important than at large (*e.g.*, open ocean or basin) spatial scales. Of course, the extent (and difficulty) of multiple interacting pressures also increases with the number of pressures, so developing indicators for multiple pressures will be more difficult in coastal areas. The degree of impact of any pressure will also depend on the habitat type being considered (*e.g.*, from nearshore rocky reefs to deep ocean environments, and pelagic to benthic realms). Analyses of the impacts of multiple pressures in the North Pacific, and developing indicators thereof, need to consider spatial scale and habitat type. Temporal scale (*e.g.*, of the frequency of exposure of a particular habitat type to a particular pressure) also needs to be considered in the analysis. This is discussed in more detail in the next section of case studies.

3.12 Summary and recommendations

North Pacific marine ecosystems are exposed to many and varied pressures, including from natural and anthropogenic sources. Studies have found there are more pressures in coastal than in oceanic regions, including point source and local pressures closer to shore (often from anthropogenic sources) compared with large-scale regional pressures away from the shore (often from large-scale climate-related sources). All marine ecosystems in the North Pacific appear to experience more than one pressure, which means that multiple pressures are to be expected. Pressures identified for North Pacific marine systems tend to be similar throughout the region, with the differences in the types of pressures relating more to the type of ecosystem being examined. For example, coastal systems which are close to human populations have similar pressures around the North Pacific, but these are different from the pressures experienced by open ocean systems which are far from major population centers. Many studies have examined the impacts of a set of about 15 pressures on 20 habitat types (*e.g.*, Table 3.2), often using an expert elicitation method. Experimental evidence for the impacts of multiple pressures on multiple habitat types is rare because of the logistical difficulties of controlling and evaluating many interacting factors.

Recommendations

The list of pressures and habitats proposed by Halpern *et al*. (2008, and later publications; Table 3.2) should be used as a starting point for analyses and comparisons of multiple pressures on North Pacific marine ecosystems. Such analyses should also consider explicitly the spatial and temporal scales of pressures and the habitats they are impacting.

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4 Case Studies of Multiple Pressures on North Pacific Marine Ecosystems

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4.1 Introduction

This section provides two case studies which apply the expert elicitation (*e.g*., sub-sections 2.2.5 and 3.3) method of identifying multiple pressures and their impacts on marine habitats in the North Pacific. The pressures and sub-habitats that were considered were the same as described in Section 3, specifically those defined by Halpern *et al*. (2008). Each case study is described separately, and then comparisons are made between the results of the two case studies. Three marine ecosystems were examined and compared in Japan (the Seto Inland Sea, the East China Sea and Yellow Sea, and the Kuroshio and Oyashio regions). In Canada, one ecosystem was considered: the Strait of Georgia. An on-line questionnaire used for the studies can be found in Appendix 3.

4.2 Ecosystem responses to anthropogenic and natural pressures in inland, shelf and oceanic waters around Japan, based on the expert elicitation approach

Motomitsu Takahashi, Sachihiko Itoh, Naoki Yoshie and Kazuhiko Mochida

4.2.1 Introduction

Understanding the cumulative impacts of multiple pressures on marine ecosystems is an urgent issue for ecosystem-based management of human activities. Interactions among multiple pressures in an ecosystem are classified into additive, synergistic, and antagonistic, and most of the cases have been identified as non-additive systems (Darling and Côté, 2008). Habitat-specific impacts of multiple pressures on an ecosystem have been evaluated based on an expert elicitation approach and literature surveys (Halpern *et al*., 2007; Teck *et al*., 2010). Mapping cumulative impacts has been reported locally and globally (Halpern *et al*., 2008; Ban *et al*., 2010). Thus, tools for evaluating the cumulative impacts of multiple pressures on marine ecosystems have been developed since the 2000s (see, for example, Section 5 of this report and Boldt *et al*., 2014).

Evaluation of ecosystem states in Japan has also been conducted in coastal waters and semi-enclosed bays since the 2000s, and the reports have been published in domestic and international literature (Ocean Policy Research Foundation, 2005, 2009; International EMECS Center, 2008). Inter-decadal changes in pollutant loads, occurrence of harmful algal blooms (HABs) and degradation of natural shorelines have been focused on the Seto Inland Sea (International EMECS Center, 2008). The Ocean Policy Research Foundation (formerly called the Ship and Ocean Foundation, 2005, 2009) developed its own framework to monitor ecosystem stability and smoothness of material cycles in semi-enclosed bays around Japan and evaluated ocean health using a diagnostic approach consisting of seven indices: species composition, habitat areas, habitat qualities, primary productivity, effective nutrient loading, sedimentation/ decomposition, and carbon/nutrient removal (see sub-section 2.2.4).

Comparing the cumulative impacts of multiple pressures on marine ecosystems among PICES member countries in the North Pacific is valuable. Previous evaluations of environmental states around Japanese waters are limited to coastal and semi-enclosed bays in which anthropogenic pressures obviously occur. The Seto Inland Sea has been monitored rigorously since the 1970s. However, the cumulative impacts of multiple pressures have not been addressed in the assessments. In contrast to the coastal and semi-enclosed bays, environmental conditions in the shelf waters and open oceans have scarcely been assessed because of limited information on their long-term changes and vulnerability.

In this case study we applied the existing framework for evaluating the cumulative impacts of multiple pressures (Halpern *et al.*, 2007) to the Seto Inland Sea (SIS) as an example of inland waters, the East China and Yellow seas (ECYS) as examples of shelf waters, and the Kuroshio and Oyashio regions (KOR) as examples of oceanic waters in the western North Pacific (Fig. 4.1). We examined the pressures having the most impact in each of the three different ecosystems using the discussions of ecosystem monitoring provided in the previous sections of this report.

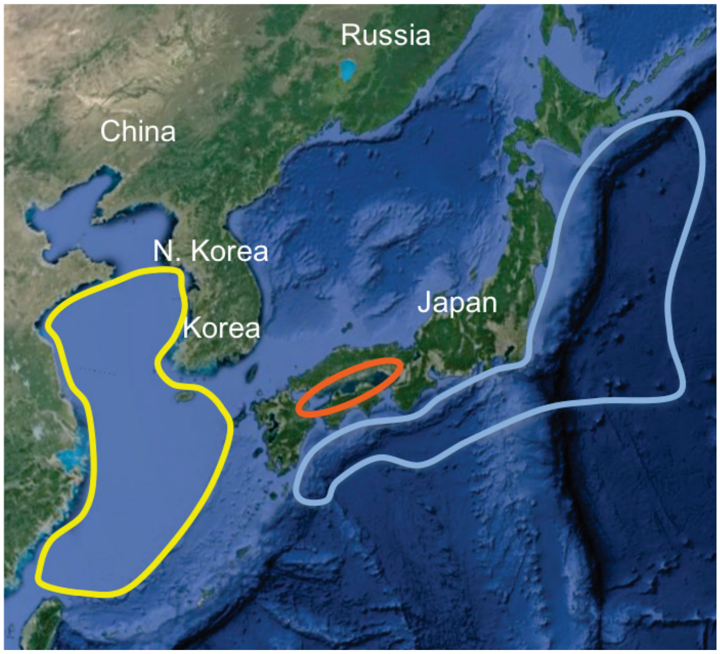


Fig. 4.1 Study area: the Seto Inland Sea (SIS, orange), the East China and Yellow seas (ECYS, yellow), and the Kuroshio and Oyashio regions (KOR, blue).

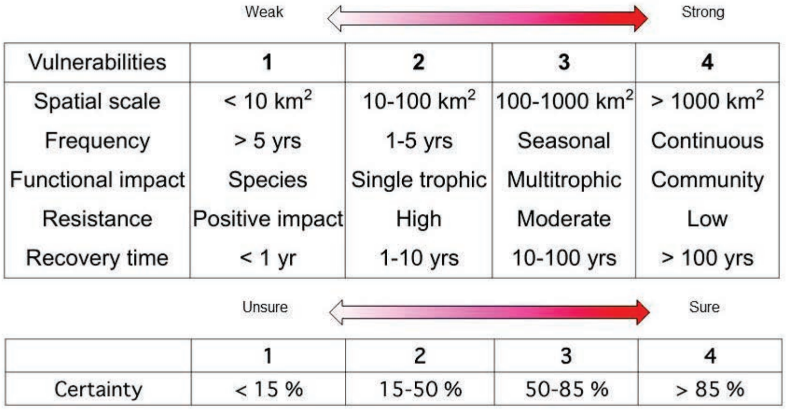
4.2.2 Materials and methods

The impacts of anthropogenic and natural pressures on marine ecosystems were evaluated based on an expert elicitation approach using a habitat–pressure matrix (Table 4.1, Halpern *et al.*, 2007; see also Appendix 3). An ecosystem was assigned into four habitats including intertidal, coastal, shelf, and oceanic waters, and each habitat was further divided into four to nine sub-habitats. For each sub-habitat, responses to 20 pressures were evaluated with regard to their vulnerability to each pressure and the certainty of the estimate. Vulnerabilities of specific sub-habitats to each pressure were defined based on spatial scale, frequency, functional impact, resistance, and recovery time with scores from 1 to 4 (Table 4.2). Higher vulnerability received higher scores. Certainty, as an index of data quality, was also evaluated from 1 to 4 in which greater confidence in the knowledge of the process was assigned a higher score (Table 4.2).

Table 4.1 Habitat–pressure matrix, modified from Halpern *et al.* (2007), for evaluating vulnerabilities and certainty in marine ecosystems. Reproduced with permission of Wiley.

Pressure	Intertidal	Coastal	Shelf	Oceanic
1. Pollition from land	1. Rocky	1. Seagrass	1. Soft bottom	1. Soft bottom slope
2. Coastal engineering	2. Beach	2. Kelp forest	2. Hard bottom	2. Hard bottom slope
3. Coastal development	3. Mud	3. Rocky reef	3. Ice	3. Soft bottom benthic
4. Direct human impact	4. Salt marsh	4. Suspension feeder reef	4. Pelagic water column	4. Seamount
5. Ecotourism		5. Sub-tidal soft bottom		5. Vents
6. Commerical activity				6. Soft bottom canyon
7. Aquaculture				7. Hard bottom canyon
8. Fishing – demerasal				8. Deep pelagic water column
9. Fishing – pelagic				9. Upper pelagic water column
10. Fishing – illegal				
11. Offshore development				
12. Pollution from ocean				
13. Freshwater input				
14. Sediment input				
15. Nutrient input				
16. Harmful algal blooms				
17. Hypoxia				
18. Species invasion				
19. Sea level change				
20. Sea temperature				

Table 4.2 Scoring vulnerability and certainty in each pressure–habitat cell.



Weak Strong

Vulnerabilities	1	2	3	4
Spatial scale	< 10 km^2	10-100 km^2	100-1000 km^2	> 1000 km^2
Frequency	> 5 yrs	1-5 yrs	Seasonal	Continuous
Functional impact	Species	Single trophic	Multitrophic	Community
Resistance	Positive impact	High	Moderate	Low
Recovery time	< 1 yr	1-10 yrs	10-100 yrs	> 100 yrs

Unsure Sure

	1	2	3	4
Certainty	< 15 %	15-50 %	50-85 %	> 85 %

The relative risk (*R*) of pressures in each sub-habitat was estimated, based on Samhouri and Levin (2012), as the Euclidean distance of the pressure from the origin in a sub-habitat defined by indices of exposure (*E*) and sensitivity (*S*) as follows:

$$E = \frac{\sum_{i=1}^{N} \frac{e_i}{c_i}}{\sum_{i=1}^{N} \frac{1}{c_i}}, \tag{4.1}$$

$$S = \frac{\sum_{i=1}^{N} \frac{s_i}{c_i}}{\sum_{i=1}^{N} \frac{1}{c_i}}, \tag{4.2}$$

$$R = \sqrt{(E-1)^2 + (S-1)^2}, \tag{4.3}$$

where e_i is the vulnerability score of spatial scale, frequency, and functional impact, s_i is the score for resistance and recovery time (Table 4.2), and c_i is the certainty of each score as provided by the expert.

To evaluate the spatial occurrence of multiple pressures in the SIS, the relative risk of each pressure was averaged in each sub-habitat which was assessed by more than three experts. Compared to the case of the SIS, fewer experts were available to assess the relative risk of each pressure at each sub-habitat for the other two case studies. Therefore, for the ECYS and KOR, we present the occurrence of pressures in each sub-habitat including cases where the number of respondents was less than three. To compare the most impactful risks in each of the three different ecosystems, the relative risks were averaged only for the cases in which more than three experts provided assessments for all habitats.

4.2.3 Results

The habitat–pressure matrix was sent to 30 experts, and a total of 848 scores of vulnerability and certainty were evaluated for the SIS. The most frequent (top 5, upper 25%) pressures were nutrient input, coastal development, coastal engineering, direct human impact, and HABs (Fig. 4.2). Sea temperature, illegal fishing, pelagic fishing, offshore development, and sediment input were ranked as less frequent pressures (bottom 5, lower 25%). The SIS consists of intertidal and coastal habitats. More than 100 vulnerabilities were evaluated for suspension-feeder reef, sub-tidal soft bottom, kelp forest, rocky reef, and salt marsh sub-habitats, whereas less than 50 were evaluated for beach and rocky intertidal sub-habitats (Fig. 4.2). Mean relative risks of coastal engineering and coastal development were ≥ 3.1 in rocky and mud sub-habitats in intertidal waters, and 3.1 in seagrass, kelp forest and rocky reef sub-habitats in coastal waters (Table 4.3). Demersal fishing scored 3.1 on suspension feeder reef and sub-tidal soft bottom sub-habitats, and nutrient input scored ≥ 3.2 on rocky and beach sub-habitats in intertidal waters. Ecotourism and freshwater input scored ≤ 2.5, and sediment input and pollution from the ocean also scored ≤ 2.5 in coastal waters, excluding sediment input in kelp forests and pollution from the ocean in seagrass and kelp forest sub-habitats.

The habitat–pressure matrix was sent to 5 experts, and a total of 79 scores were returned for the ECYS. The most frequent (top 5, upper 36%) pressures were nutrient input, freshwater input, pollution from the ocean, species invasion, and coastal engineering (Fig. 4.3). The ECYS consists of intertidal, coastal, and shelf habitats. The mean relative risks of coastal engineering and coastal development were > 3.7 and were the highest among the pressures identified (Table 4.4). Freshwater input and nutrient input scored between 3.0 and 3.5, excluding 2.4 for the sub-tidal soft bottom sub-habitat, and higher than pollution from the ocean (2.6–3.0). Species invasion (2.0–2.4) scored lower than the other pressures, although it was included in the top five frequent pressures.

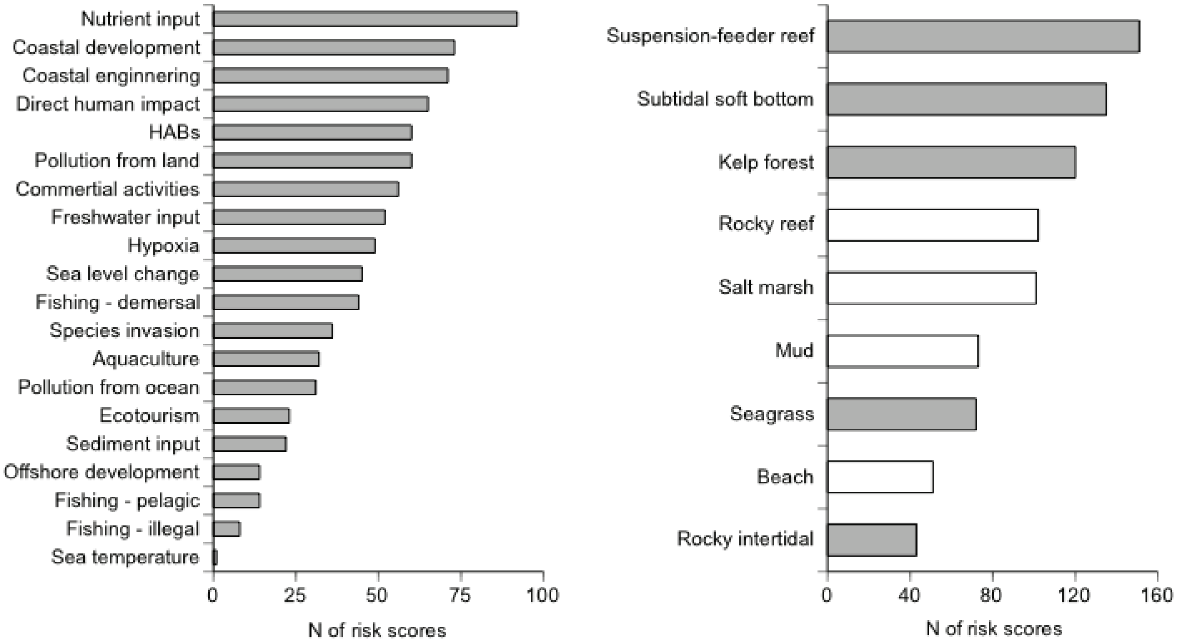


Fig. 4.2 Number of risk scores evaluated for each pressure (left) and for each sub-habitat (right) in the Seto Inland Sea (SIS). Open and shaded bars in the right panel indicate intertidal and coastal waters, respectively.

Table 4.3 Mean relative risk to each pressure for each habitat in the Seto Inland Sea.

Pressures	Intertidal				Coastal				
	Rocky	Mud	Salt marsh	Beach	Seagrass	Kelp forest	Rocky reef	Suspention feeder reef	Sub-tidal soft bottom
1. Pollution from land	2.8	2.9	2.8	2.7	2.8	2.9	2.9	2.8	3.0
2. Coastal enginnering	3.1	3.3	2.9	3.0	3.1	3.1	3.1	2.9	3.0
3. Coastal development	3.1	3.3	3.0	3.0	3.1	3.1	3.1	3.0	2.9
4. Direct human impact	3.0	3.2	2.8	2.9	2.8	2.8	2.8	2.9	2.9
5. Ecotourism	2.3	2.5	2.2	2.6	2.1	2.1	2.1		2.3
6. Commertial activity	2.9	3.0	2.8	2.7	2.6	2.7	2.7	2.9	2.9
7. Aquaculture		3.1	2.8		2.8	3.1	2.7	2.9	2.9
8. Fishing - demersal		2.9	2.9		2.7	2.7	2.8	3.1	3.1
9. Fishing - pelagic		2.8	2.8					2.9	2.8
10. Fishing - illecal		2.8	2.8					2.9	
11. Offshore development		2.8	2.8	2.8	2.7	2.7	2.8	2.8	2.3
12. Pollution from ocean	3.1	2.8	2.6	2.6	2.8	2.6	2.5	2.3	2.5
13. Freshwater input	2.5	2.5	2.4	2.6	2.3	2.2	2.2	2.5	2.2
14. Sediment input	2.8	2.7	2.7	2.8	2.5	2.9		2.4	2.5
15. Nutrient input	3.3	3.0	2.9	3.2	2.7	2.7	2.8	2.7	2.7
16. HABs	2.5	2.8	2.6	2.5	2.6	2.8	2.9	2.8	2.9
17. Hypoxia	3.0	2.8	2.7	2.7	2.7	2.8	2.7	2.9	2.9
18. Species invasion	2.8	2.8	2.7	2.7	2.9	3.0	2.9	2.6	2.6
19. Sea level change		2.9	2.7	2.8	3.2	2.9	3.0	3.0	2.5
20. Sea temperature					3.4				

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Cells with no values indicate missing data.

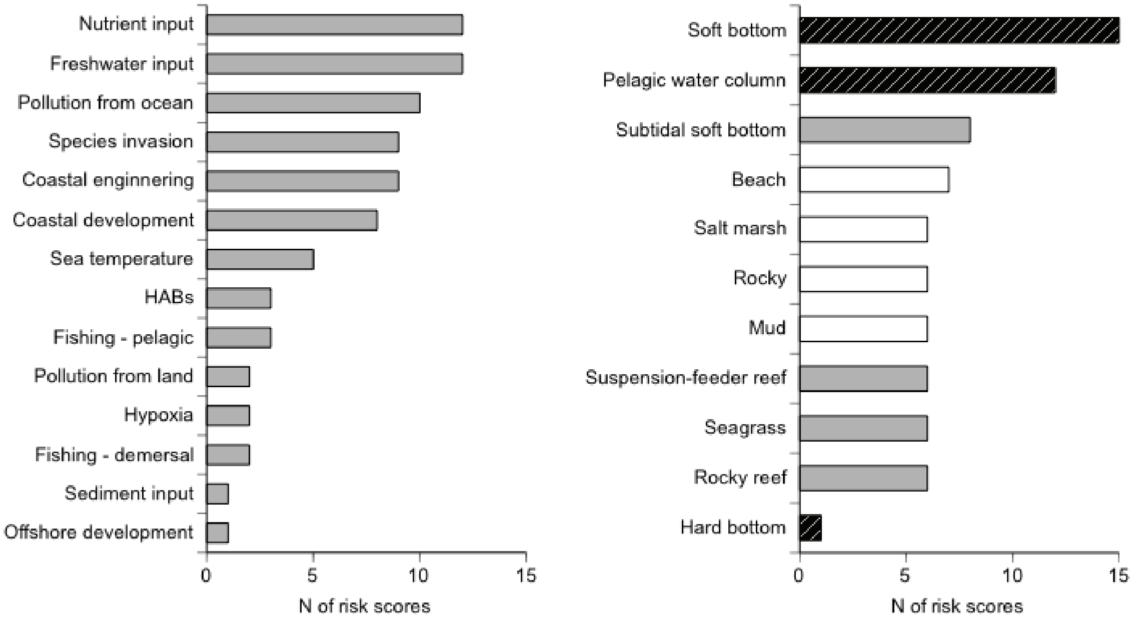
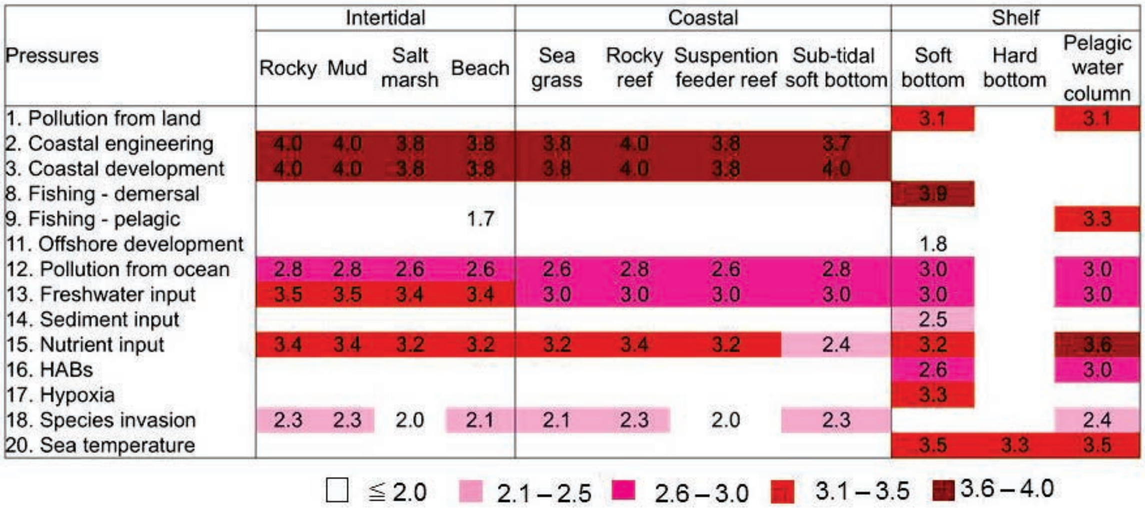


Fig. 4.3 Number of risk scores evaluated for each pressure (left) and for each sub-habitat (right) in the East China and Yellow seas (ECYS) ecosystems. Open, shaded and striated black bars in the right panel indicate the intertidal, coastal, and shelf waters, respectively.

Table 4.4 Mean relative risk to each pressure for each habitat in ECYS.



Pressures	Intertidal				Coastal				Shelf		
	Rocky	Mud	Salt marsh	Beach	Sea grass	Rocky reef	Suspention feeder reef	Sub-tidal soft bottom	Soft bottom	Hard bottom	Pelagic water column
1. Pollution from land									3.1		3.1
2. Coastal engineering	4.0	4.0	3.8	3.8	3.8	4.0	3.8	3.7			
3. Coastal development	4.0	4.0	3.8	3.8	3.8	4.0	3.8	4.0			
8. Fishing - demersal									3.9		
9. Fishing - pelagic				1.7							3.3
11. Offshore development									1.8		
12. Pollution from ocean	2.8	2.8	2.6	2.6	2.6	2.8	2.6	2.8	3.0		3.0
13. Freshwater input	3.5	3.5	3.4	3.4	3.0	3.0	3.0	3.0	3.0		3.0
14. Sediment input									2.5		
15. Nutrient input	3.4	3.4	3.2	3.2	3.2	3.4	3.2	2.4	3.2		3.6
16. HABs									2.6		3.0
17. Hypoxia									3.3		
18. Species invasion	2.3	2.3	2.0	2.1	2.1	2.3	2.0	2.3			2.4
20. Sea temperature									3.5	3.3	3.5

□ ≦ 2.0 ■ 2.1 – 2.5 ■ 2.6 – 3.0 ■ 3.1 – 3.5 ■ 3.6 – 4.0

Cells with no values indicate missing data.

The habitat–pressure matrix was sent to 8 experts, and a total of 32 scores of vulnerability and certainty were evaluated for the KOR. The most frequent pressure was sea temperature (Fig. 4.4). Mean relative risk of sea temperature ranged from 3.3 to 3.6 and was evaluated at all habitats identified (Table 4.5). Nutrient input scored 3.4 for the pelagic water column sub-habitat in shelf waters. For the anthropogenic pressures, demersal fishing scored 3.5 for the soft bottom sub-habitat in shelf waters and pelagic fishing scored 3.2 for the pelagic water column and 3.4 for the upper pelagic water column sub-habitats in shelf and oceanic waters, respectively.

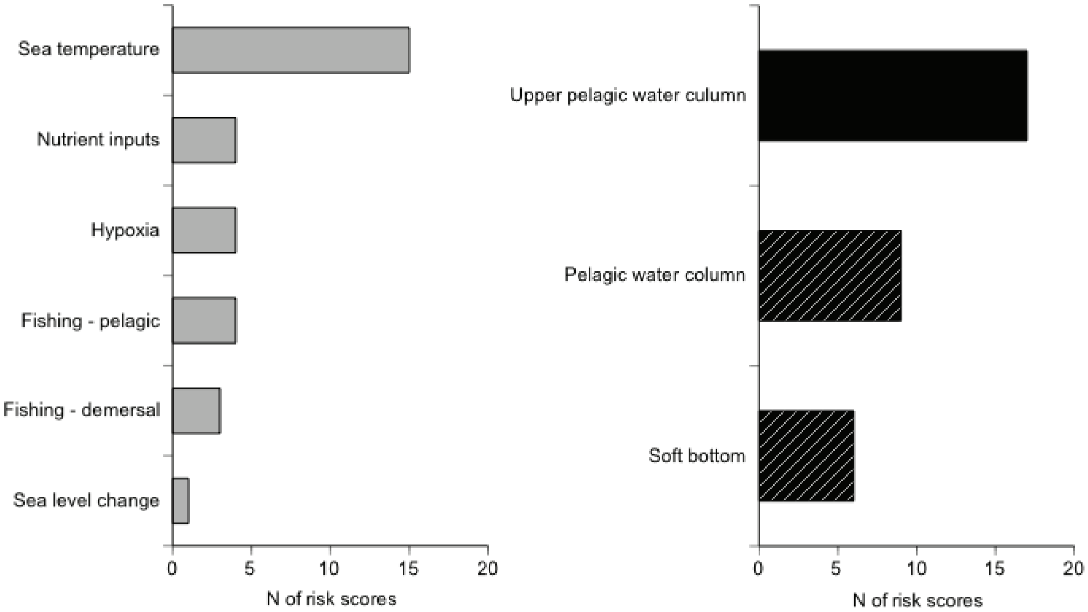


Fig. 4.4 Number of risk scores evaluated for each pressure (left) and for each sub-habitat (right) in the Kuroshio and Oyashio regions (KOR). Striated black and solid black bars in the right panel indicate the shelf and oceanic waters, respectively. Note: the KOR consists of pelagic water column and soft bottom sub-habitats in shelf waters, and upper pelagic water column sub-habitats in oceanic waters.

Table 4.5 Mean relative risk to each pressure for each habitat in the KOR.

Pressures	Shelf		Oceanic
	Pelagic water column	Soft bottom	Upper pelagic water column
8. Fishing - demersal		3.5	2.7
9. Fishing - pelagic	3.2		3.4
15. Nutrient input	3.4		3.0
17. Hypoxia	2.9	3.1	
19. Sea level change			3.4
20. Sea temperature	3.4	3.6	3.3

☐ ≦ 2.0 ▧ 2.1–2.5 🟪 2.6–3.0 🟥 3.1–3.5 🟫 3.6–4.0

Cells with no values indicate missing data.

Table 4.6 Mean relative risk to each pressure among the Seto Inland Sea (SIS), the East China and Yellow seas (ECYS) and the Kuroshio and Oyashio regions (KOR).

Pressures	SIS	ECYS	KOR
1. Pollution from land	2.9		
2. Coastal enginnering	3.1	3.9	
3. Coastal development	3.1	3.9	
4. Direct human impact	2.9		
5. Ecotourism	2.3		
6. Commertial activity	2.8		
7. Aquaculture	2.9		
8. Fishing - demersal	2.9		3.2
9. Fishing - pelagic	2.8	2.8	3.3
10. Fishing - illegal	2.8		
11. Offshore development	2.7		
12. Pollution from ocean	2.5	2.8	
13. Freshwater input	2.3	3.2	
14. Sediment input	2.6		
15. Nutrient input	2.9	3.1	3.2
16. HABs	2.8	2.9	
17. Hypoxia	2.8		3.0
18. Species invasion	2.8	2.2	
19. Sea level change	2.9		
20. Sea temperature		3.4	3.4

☐ ≦ 2.0 ▧ 2.1–2.5 🟪 2.6–3.0 🟥 3.1–3.5 🟫 3.6–4.0

Cells with no values indicate missing data.

Mean relative risk of each pressure in the three ecosystems is shown in Table 4.6. A value of 3.1 for coastal engineering and coastal development was the highest among the pressures identified for the SIS. Other pressures scored 2.8 or 2.9, excluding ecotourism (2.3), offshore development (2.7), pollution from the ocean (2.5), freshwater input (2.3), and sediment input (2.6). In the ECYS, the highest risks (3.9) were coastal engineering and coastal development, similar to the SIS. Sea temperature, freshwater input, and nutrient input scored 3.4, 3.2 and 3.1, respectively, and higher than the other pressures. In the KOR, mean relative risk of sea temperature was 3.4, ranked high in its range (3.1–3.5), followed by and pelagic (3.3) and demersal (3.2) fishing, and nutrient input (3.2). Mean relative risk of demersal fishing was evaluated in the SIS and the KOR but only two risks were identified for the soft bottom in the shelf waters in the ECYS, so it was deleted from the table.

4.2.4 Discussion

The expert elicitation approach to evaluate ecosystem responses to multiple pressures is effective in coastal waters where environmental conditions are rigorously monitored, because much more information is available on ecosystem responses to environmental conditions than for the oceanic waters. Although relative risks tended to be concentrated in the 2.6–3.0 range (Table 4.6), the values are indicative of the vulnerability and certainty of the defined pressures. The method may not work as well for oceanic waters, however, for which less information on ecosystem responses is available. Relative risk is considered to be comparable within an ecosystem because the values are standardized information on ecosystem responses from experts in the same field.

Coastal engineering and development scored highest among the pressures identified for the SIS and the ECYS. Land reclamation increased dramatically during the third quarter of the 20th century for these two areas, but decreased slightly in the most recent quarter in the SIS (International EMECS Center, 2008). Tidal flats, measured by remote sensing, gradually decreased due to land reclamation during the last 40 years in Jiangsu Province, China, whereas tidal flats in Dongtai and Rudong cities sharply decreased after the 1990s (Zhao *et al*., 2015). These trends suggest that coastal engineering and development reduce natural shorelines and hence affect various animal habitats in coastal waters. Higher risk scores shown in this study may represent the strong impact of coastal engineering and development on these coastal ecosystems.

Nutrient input scored higher among the pressures identified for the ECYS and the KOR. However, the source of nutrients may be different between the two ecosystems. Concentrations of nitrate and phosphate off the Changjang River mouth, which is the most developed agricultural area in China, have increased since the 1960s and these elevated concentrations of nutrients enhanced the frequency and spatial scales of HABs after the 1980s (Zhou *et al*., 2008). In contrast, in the Oyashio and the Kuroshio–Oyashio Transitional Waters, bi-decadal changes in phosphate are synchronous with the index of diurnal tidal strength and the biomass of a northern copepod *Neocalanus plumchrus* (Tadokoro *et al*., 2009). Thus, these studies indicate that nutrient inputs derived from anthropogenic activities strongly affect the intertidal and coastal waters of the ECYS, whereas nutrients derived from natural oscillations in the nutrient-rich Oyashio region affect the KOR.

Sea temperature scored higher in the ECYS and the KOR, but was not identified (only 1 risk) as a major risk for the SIS. Sea temperature at the surface and at the bottom continuously increased during 1975–1995 in the waters off Changjiang River mouth (Ning *et al*., 2011). Low (< 2 mg l^{-1}) dissolved oxygen, hypoxic, water masses form at 10–30 m depth during summer, and the volume increased from 1975 to 1995 with increasing temperatures. Three potential mechanisms for the formation of hypoxic water proposed by Ning *et al*. (2011) are special hydrographic topography, intensified stratification of the water column, and increased occurrences of phytoplankton blooms. Sea temperature and eutrophication act synergistically with hypoxia and acidification to impact the coastal ecosystems of the ECYS (Cai *et al*., 2011).

In the KOR, sea temperature has been associated with the population dynamics of small pelagic fishes, such as Japanese sardine, anchovy, and chub mackerel (Kawasaki, 1983; Yatsu *et al*., 2005). Sardine populations increase during cool periods, whereas anchovy populations increase during warm periods in the western North Pacific. Potential mechanisms proposed for these population dynamics include trophodynamic changes in response to temperature regime shifts (Takasuka *et al*., 2008; Takahashi *et al*., 2009). Sea temperature could directly affect all trophic communities in oceanic waters.

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4.3 Ecosystem responses to anthropogenic and natural pressures in the Strait of Georgia, Canada, based on an expert elicitation approach

R. Ian Perry

4.3.1 Introduction

The Strait of Georgia is arguably the most human-dominated marine ecosystem in Canada. It is located in southwestern British Columbia (BC), and is surrounded by the two largest population centers in British Columbia, including the third largest city (Vancouver) in Canada. Puget Sound, in Washington State, connects with the Strait of Georgia to the south, and both then connect with the outer ocean *via* Juan de Fuca Strait (Fig. 4.5). Collectively these three bodies of water and their various adjoining passages are called the Salish Sea. With the populations of greater Vancouver, Victoria, and Nanaimo in BC, and Seattle, Everett, and Bellingham in Washington State, over 6.7 million people live on the shores of the Salish Sea, an area of about 18,000 km^2. This comprises a surrounding population density of about 372 people per km^2, and significant anthropogenic pressures (Johannessen and MacDonald, 2009; Perry and Masson, 2013).

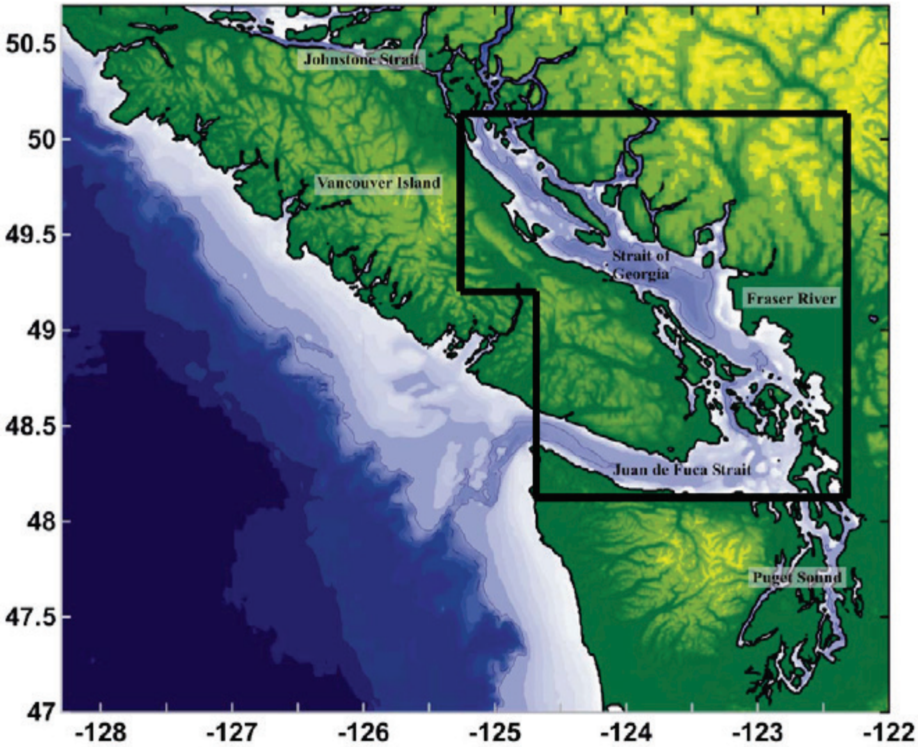

Fig. 4.5 Location of the Strait of Georgia (within the black box, including the Juan de Fuca Strait) in southwestern British Columbia, Canada. Puget Sound in Washington State, USA, is located to the south of the Strait of Georgia. Together these three inland water bodies and their adjacent passages comprise the Salish Sea.

The Strait of Georgia is also a semi-enclosed estuary, which receives considerable freshwater input mainly from the Fraser River but also from surrounding local rivers. It has a surface area of about 6,800 km^2 and a maximum depth of 420 m located in its central basin (Thomson, 1981). Its physical dynamics are driven by both local and remote forcing (Johannessen and MacDonald, 2009; Perry and Masson, 2013) including local changes in temperature and winds, remote forcing of freshwater fluxes from processes occurring in central BC (such as cycles and amounts of snow and rain as transmitted through the Fraser River), and basin-scale processes such as El Niño, Pacific Decadal Oscillation, and the North Pacific Gyre Oscillation.

Masson and Perry (2013) describe six key processes framing how the Strait of Georgia ecosystem works. These are 1) enrichment, which is the addition of nutrients to the system from natural (*e.g.*, offshore) and anthropogenic processes; 2) initiation (*e.g.*, the processes that initiate phytoplankton blooms at the base of the food web); 3) retention of water masses and their constituents within the Strait of Georgia for long enough to become incorporated into the food web and to contribute to the productivity; 4) concentration (*i.e.*, the processes which aggregate organisms into concentrations greater than the background average); 5) trophic (or food-web) dynamics which include the various processes involved in the production of organic material and its transfer among trophic levels; and 6) nearshore and benthic dynamics, which recognizes the interactions between nearshore and benthic zones with the pelagic realm. In addition to these natural processes, human pressures include fishing, shipping, shoreline recreation and commerce, *etc*., all of which have their own specific intensities and footprints.

In this case study, we follow a similar approach to that used in Section 4.2 (by Takahashi *et al*.) to identify key natural and anthropogenic pressures on this system, and which habitats may be more vulnerable (or at greater risk) to which pressures.

4.3.2 Methods

The British Columbia Marine Conservation Analysis (BCMCA: https://bcmca.ca/) conducted a spatially explicit analysis of pressures imposed on the entire coast of British Columbia. Ban *et al*. (2010) provide a high-level overview of some of the main results. A more detailed analysis was provided by the BCMCA itself (British Columbia Marine Conservation Analysis, 2011, plus see their web site). They used a combination of expert knowledge (in particular, derived from workshops with groups of experts on related topics such as seabirds, marine plants, marine mammals, marine and anadromous fish, and marine invertebrates) and available literature data sources. Once data for all features were compiled, the data were mapped to a planning unit (or 'pixel') size of 4 km^2 (2 km × 2 km) and again, reviewed by experts (British Columbia Marine Conservation Analysis, 2011). The active phase of this project ran from 2006 to 2013. For this case study, data from the BCMCA data base were extracted, with a spatial focus on the Strait of Georgia area.

We also conducted our own web-based survey of experts on various features and habitats in the Strait of Georgia ecosystem to request their assessments of the potential multiple pressures and their impacts on each sub-habitat, as was done for the Seto Inland Sea case study (Section 4.2; see also Appendix 3). Following that approach, we used the same pressure–habitat (and sub-habitat) matrix, modified from Halpern *et al*. (2007), with the exclusion of the 'Oceanic' habitat since this does not occur in the Strait of Georgia. We considered the 'Shelf' habitat to apply to the deeper waters of the Strait of Georgia (*e.g.*, greater than 50 m; note there are several deep basins in the Strait of Georgia with bottom depths over 200 m). In addition, we included sub-tidal soft bottom sub-habitats as part of the Shelf habitat, rather than as part of the Coastal habitat as in Table 4.1. We used a similar set of pressures as Table 4.1

(Section 4.2; Takahashi *et al.*) for the Seto Inland Sea, with the deletion of ecotourism, offshore development, commercial activity, and illegal fishing. In addition, we combined pollution from land with pollution from the ocean into a 'pollution/contaminants' pressure.

Experts were asked to assess as many sub-habitats against as many pressures as they felt competent, and to rate them on the same five features and scales of ecosystem risk (or vulnerability) as in Section 4.2. These were:

- Spatial extent: the spatial scale of a single event of the activity or pressure,
- Frequency: the average annual frequency at which an activity or pressure stressor occurs,
- Trophic impact: the primary trophic level affected by the activity or pressure,
- Resistance to change: the degree to which the habitat's 'natural' state is impacted,
- Recovery time: the time required for the sub-habitat to return to its 'natural' state.

In addition, each expert was asked to assign a score to each risk (or vulnerability) estimate reflecting how 'certain' they were of their assessment. Scores for the different ranges of vulnerability features and certainty estimates were the same as for the Seto Inland Sea case study (Table 4.2).

We followed Section 4.2 by defining exposure (E) as the weighted mean of the scores (e_i) for spatial scale, frequency, and trophic impacts:

$$E = \frac{\sum_{i=1}^{N} \frac{e_i}{c_i}}{\sum_{i=1}^{N} \frac{1}{c_i}}. \tag{4.1}$$

Similarly, we defined sensitivity (S) as the weighted mean of the score (s_i) for resistance and recovery time:

$$S = \frac{\sum_{i=1}^{N} \frac{s_i}{c_i}}{\sum_{i=1}^{N} \frac{1}{c_i}}. \tag{4.2}$$

For both features, the uncertainties in the scores of each expert (c_i) were used as the weights (Table 4.2).

The relative risk (or vulnerability, R) was then defined as the Euclidean distance of the pressure from the origin in a sub-habitat defined by the indices of exposure (E) and sensitivity (S) (Samhouri and Levin, 2012) as

$$R = \sqrt{(E-1)^2 + (S-1)^2}. \tag{4.3}$$

For those cases in which more than one expert provided an assessment of a pressure on a sub-habitat, the individual scores for E and S were averaged before calculation of R.

Note that this approach to estimating the relative risks (or vulnerability) of all defined pressures on each sub-habitat assumes that the effects of multiple pressures are additive.

4.3.3 Results

The BCMCA data for the Strait of Georgia identifies two classes of features: ‘ecological’ and ‘human’. Each class is then composed of many different features. For example, the feature type ‘birds’ within the ecological class includes 72 different features, such as bird colonies, staging areas, and at-sea survey sightings, often for particular taxonomic groupings (Table 4.7). The data indicate that 62% of the area of the Strait of Georgia includes one or more of these bird features. Other examples for plants, marine mammals, and herring spawning within the ecological class, and commercial and recreational fishing, shipping, aquaculture tenures, and tourism within the human class, are presented in Table 4.7. This table also indicates that only 1.3% of the total area of the Strait of Georgia had no human pressure among those pressures investigated by the BCMCA. Examples of the spatial distributions within the Strait of Georgia for two features, marine mammals (ecological class) and commercial fishing (human class) are presented in Figure 4.6.

Table 4.7 Examples of selected classes and features for the Strait of Georgia defined by the British Columbia Marine Conservation Analysis (bcmac.org).

Class	Feature type	Number of features	% of total SofG area with 1 or more features	Feature examples
Ecological	Birds	72	62	Bird colonies, staging areas, at-sea surveys, *etc*.
	Plants	40	57	Algae, *etc*.
	Mammals	5	12	California sea lion haulouts, harbour seal haulouts, Steller sea lion haulouts and rookeries
	Herring spawning	1	12	–
Human	Commerical fishing	35	96	Salmon, groundfish, intertebrate fishing locations
	Recreational fishing	4	72	Salmon, groundfish, crab, shrimp
	Shipping	17	76	Ferry routes, terminals, fishing vessels, bulk carriers, cruise ship routes, *etc*.
	Tenures	17	42	Aquaculture, powerlines, industrial uses, *etc*.
	Tourism	45	63	Anchorages, marinas, boating routes, *etc*.
	No human stressors	0	1.3	–

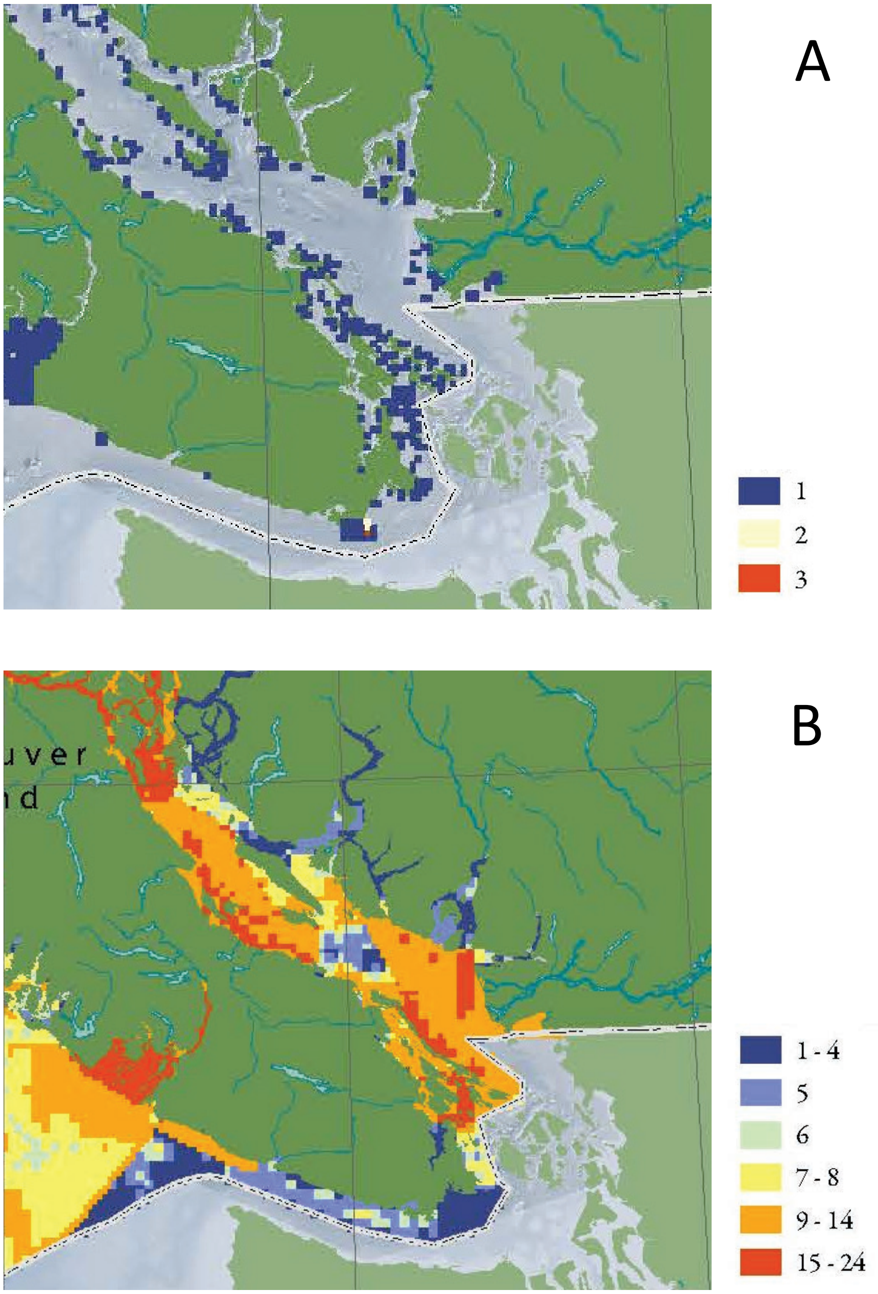

Fig. 4.6 Examples of spatial distributions in the Strait of Georgia for two features examined by the BC Marine Conservation Analysis (bcmca.org). (A) Feature counts, *i.e.*, the number of planning units for one or more features, for marine mammals; (B) Feature counts for commercial fishing activities. Colour bars indicate colours used for various numbers of features in any planning unit. Planning unit (‘pixel’) size is 4 km^2 (2 km × 2 km).

On a per-planning unit (pixel) basis, 90% of the area of the Strait of Georgia experiences 30 or fewer human pressures. The ‘most common’ number of pressures in any single 4 km^2 planning unit is 20 to 25. Relatively few planning units had more than 30 human pressures (Fig. 4.7).

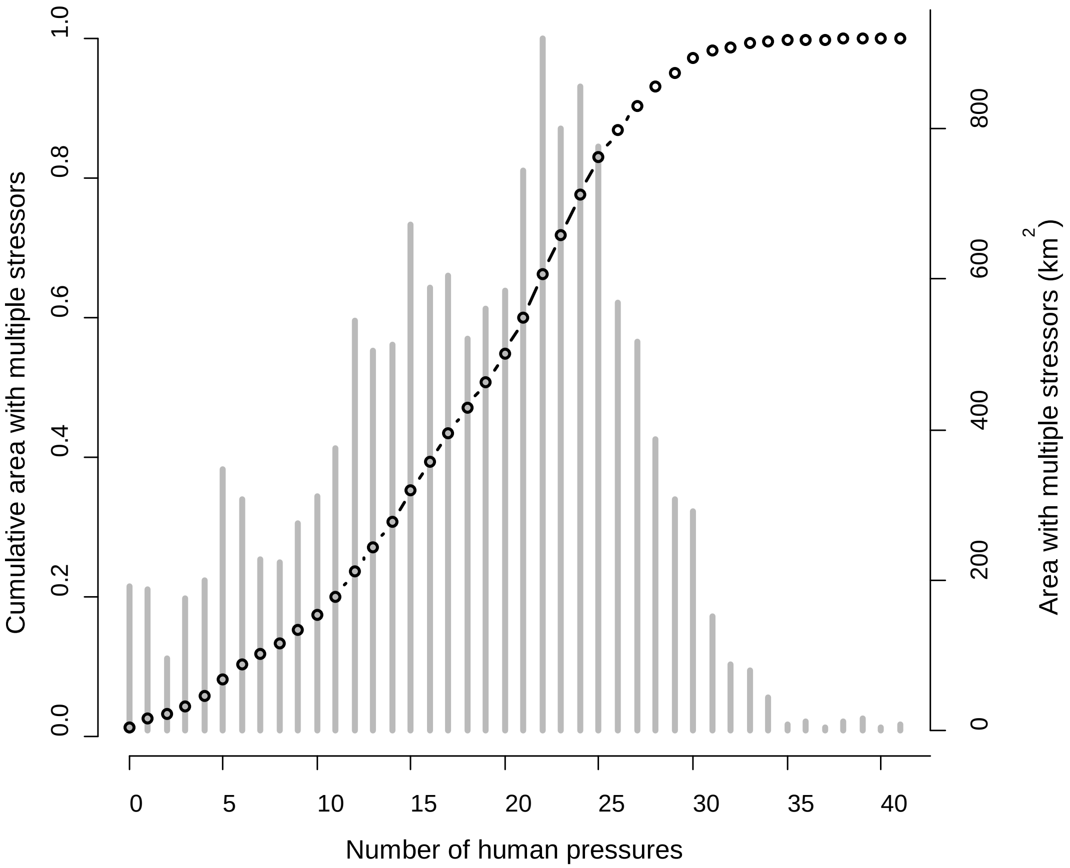

Fig. 4.7 Frequency histogram of the number of human pressures on each 4 km^2 planning unit ('pixel') in the Strait of Georgia, as assessed by the BC Marine Conservation Analysis (bcmca.org). Shaded bars (and right axis) represent the area of the Strait with each number of human pressures (with area calculated as the number of planning units multiplied by 4 km^2 per planning unit). The left axis represents the cumulative proportion of the area of the Strait with human pressures. Note the area of the Strait of Georgia is approximately 6,800 km^2.

The number of pressures on areas of ecological importance differs with the particular ecological feature, and is not randomly distributed over the entire Strait of Georgia (Fig. 4.8). Taxa-specific cumulative pressure curves are significantly different from the cumulative pressure curve for the Strait of Georgia as a whole (Kolomogorov–Sminov test, $P < 0.05$), likely because of the high number (3,652) of planning units in the analysis. This result indicates that the number of human pressures in the Strait of Georgia differs among locations that are important to marine plants, birds, and marine mammals. In the analysis presented in Figure 4.8, the number of human pressures on locations of importance to marine mammals in the Strait of Georgia is significantly greater (marine mammal cumulative curve is situated to the right of the "all Strait of Georgia" curve) than for the Strait of Georgia as a whole.

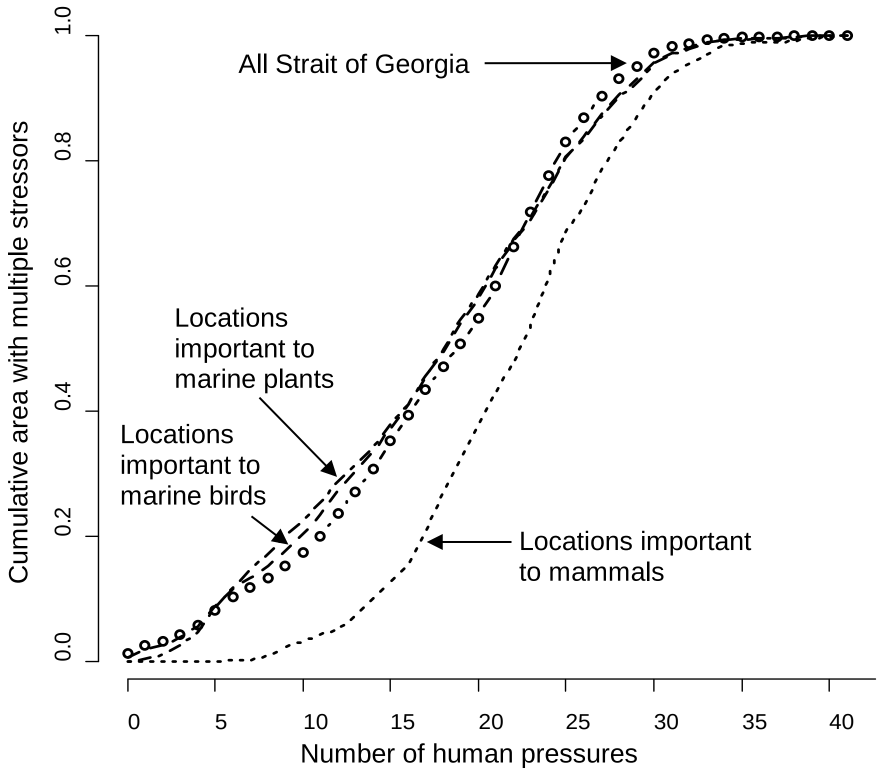

Fig. 4.8 Comparison of cumulative curves for the area of the entire Strait of Georgia with the number of human pressures defined along the *x*-axis (dashed line with circles; same as in Fig. 4.7) and the cumulative curves for the number of human pressures on areas (4 km^2 planning units) of importance to marine plants, marine birds, and marine mammals. Number of human pressures on each of these features is significantly different from the number of human pressures on the Strait of Georgia as a whole (K-S test, $P < 0.05$).

The expert elicitation survey to assess multiple pressures on the Strait of Georgia was distributed to 56 participants (Table 4.8). The response rate was relatively low (32%) and consisted entirely of regional government and academic experts. Most respondents were comfortable assessing the spatial scale, frequency, and trophic level impacts of pressures on sub-habitats (*i.e.*, certainly scores mostly of 3 and above), but less comfortable assessing the resistance to change or the recovery time of those sub-habitats to pressures (uncertainty scores in the mid-range of 2 or 3; Fig. 4.9).

Table 4.8 Distribution and returns of the web survey to assess 15 multiple pressures on 11 sub-habitats in the Strait of Georgia, British Columbia.

	Sent	Returned
Government	34	12
Academic	14	6
Non-Governmental Organization	8	0

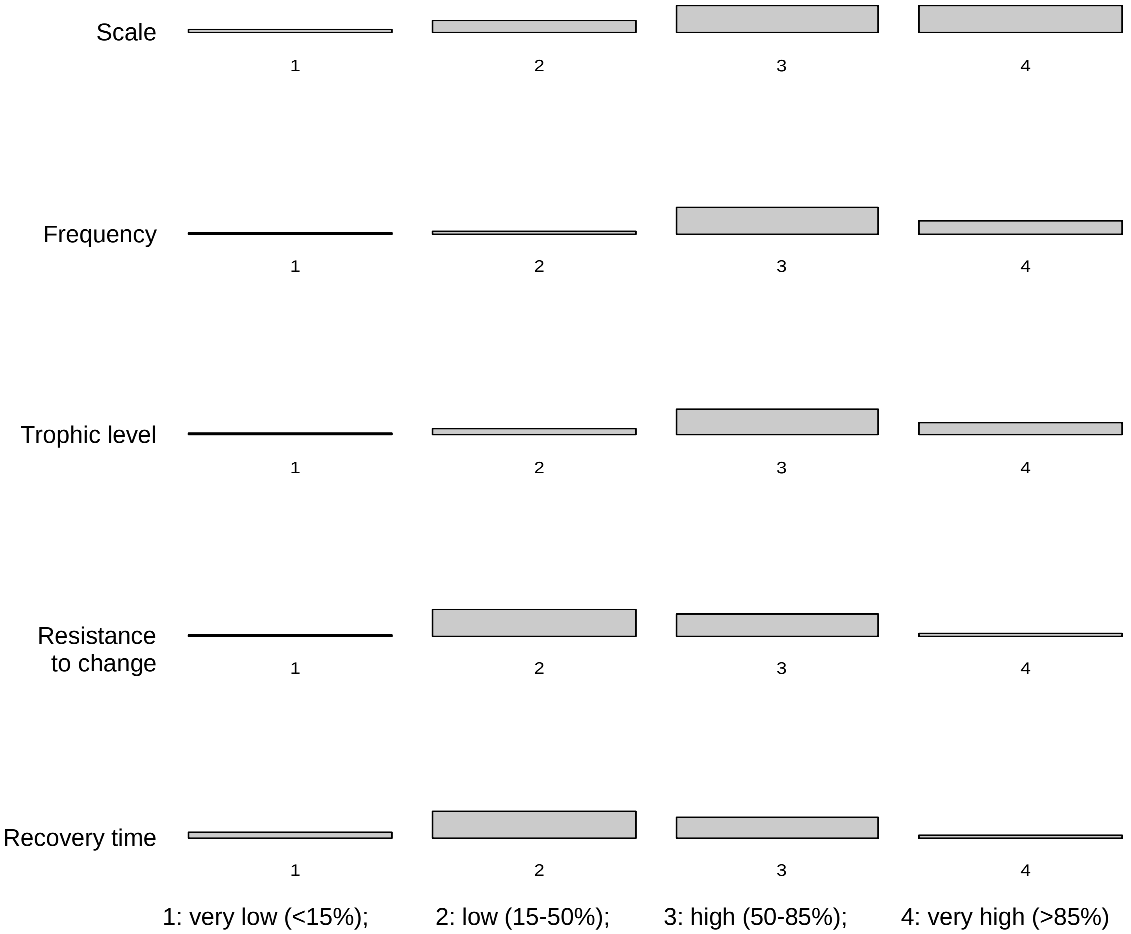

Fig. 4.9 Comparison of the self-determined 'certainty' of experts on the five features of pressures on sub-habitats examined for the Strait of Georgia.

Collectively, the experts identified pelagic shelf and rocky intertidal sub-habitats as having the greatest number of pressures (more than 8; Fig. 4.10), whereas the salt marsh sub-habitat was identified as having the least number of multiple pressures (1). In terms of the number of sub-habitats impacted by each pressure, sea temperature change due to climate change, pollution/contaminants, demersal fishing, sediment and freshwater inputs, and coastal engineering and development were assessed as affecting the broadest number of sub-habitats, with pressures from aquaculture and HABs being confined to specific sub-habitats (Fig. 4.11).

More details on the relative risks of pressures on each sub-habitat, assessed using the features of exposure (spatial scale, frequency, trophic level) and sensitivity (resistance and recovery time), are available from the results of the expert elicitation method (Table 4.9). Changes in temperature as a result of climate change were assessed to be the most wide-spread pressure likely to impact these sub-habitats. The most intense impact was by pollution and contaminants on soft bottom shelf habitats (risk score of 3.9). Although sub-habitats such as intertidal salt marsh and coastal suspension-feeding reefs have few pressures (among the list examined here, *e.g.*, Fig. 4.10), the potential impacts of these pressures was assessed to be relatively high (risk scores of 2.6 to 3.0).

There was not a huge range of relative risks of pressures when summed across all sub-habitats (risk scores ranged from 1.7 to 3.0), which may in part be due to high uncertainties (*e.g.*, Fig. 4.9). The pressures with the lowest assessed relative risks across all sub-habitats were pelagic fishing and HABs (risk scores over all sub-habitats of 1.7, Table 4.9). The pressures with the highest assessed relative risks across all sub-habitats were (in rank order) sea level rise (3.0) and temperature change (2.9) due to climate change, coastal development (2.9), changes in nutrient supply and pollution/contaminants (both 2.7), and coastal engineering (2.6). Sea level change was assessed as being an important pressure on only two intertidal habitats (rocky shores and beaches); however, they were assessed with a high risk score for both.

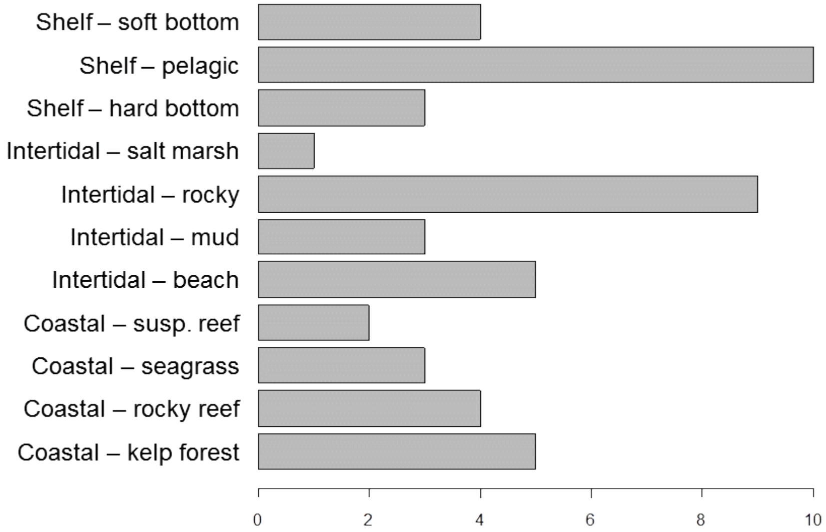

Fig. 4.10 Number of pressures identified per sub-habitat type in the expert elicitation survey for the Strait of Georgia. The *x*-axis represents the number of pressures.

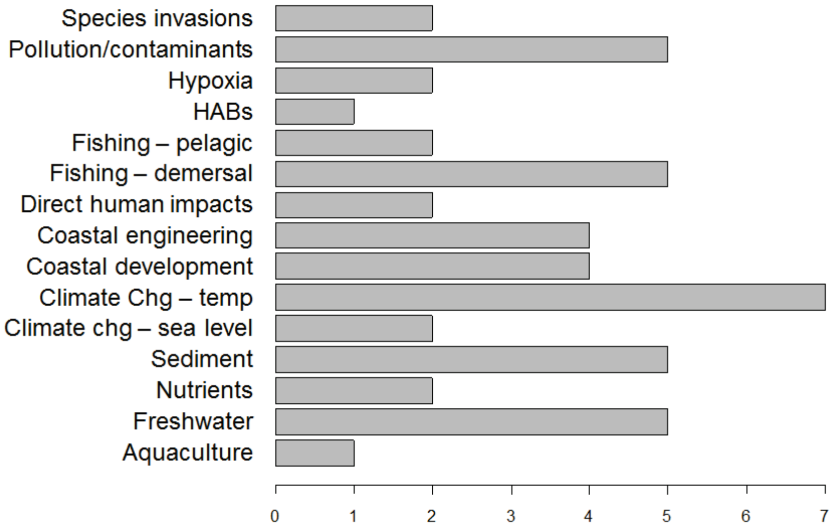

Fig. 4.11 Number of sub-habitats identified per pressure in the expert elicitation survey for the Strait of Georgia. The *x*-axis represents the number of sub-habitats. HABs = harmful algal blooms.

Table 4.9 Relative risk scores as assessed by expert elicitation for pressures on sub-habitats in the Strait of Georgia.

Pressure	INTERTIDAL				COASTAL				SHELF			All Habitats
	Rocky	Mud	Salt marsh	Beach	Seagrass	Kelp forest	Rocky reef	Suspension-feeder reef	Soft bottom	Hard bottom	Pelagic water column	
Pollution and Contaminants	2.1	1.4							3.9		3.0	2.7
Coastal engineering	2.5	2.7		2.1							2.9	2.6
Coastal development	3.2				3.1	2.5					2.8	2.9
Direct human impacts	2.2			2.1								2.1
Aquaculture	2.0											2.0
Fishing - demersal						2.4	2.3		2.5	2.5	3.1	2.5
Fishing - pelagic						1.3					1.9	1.7
Changes in Freshwater	2.3					2.4	2.2		1.9		2.3	2.2
Changes in Sediment		2.2		2.6	2.8		2.3	2.9				2.5
Changes in Nutrients									2.4		3.1	2.7
HABs											1.7	1.7
Hypoxia										2.4	2.1	2.3
Species invasion	2.7			2.3								2.5
Climate change - sea level	3.0			3.1								3.0
Climate change - Temperature	2.8		3.0			2.6	2.6	2.6		3.0	3.0	2.9

☐ ≦ 2.0 ■ 2.1–2.5 ■ 2.6–3.0 ■ 3.1–3.5 ■ 3.6–4.0

HABs = harmful algal blooms

4.3.4 Discussion

A response rate of 32% (18 experts) is not a large number to make definite conclusions about multiple pressures on sub-habitats in a region such as the Strait of Georgia. The overall results, however, are consistent with other studies of pressures on this marine ecosystem (*e.g.*, Johannessen and McCarter, 2010; Masson and Perry, 2013). Johannessen and McCarter (2010) noted that “The ecosystem [of the Strait of Georgia] has shown resilience in the past, having recovered from numerous stressors and climatic variations. However, the combination of accelerating climate change with urbanization and fishing pressure is new”. In the present analysis, similar relative risks were assessed for natural processes such as nutrient supply and climate change-driven sea level and temperature increases as for human pressures of pollution/contaminants and coastal engineering and development. DFO (2012) provides a discussion of drivers of change on the Strait of Georgia marine ecosystem, including identification of specific drivers of change in the Strait of Georgia at different spatial scales. Not surprisingly, large-scale pressures tend to result from natural processes (such as climate and atmospheric processes) whereas impacts to local features in the Strait of Georgia result from a combination of large-scale, regional, and local pressures (DFO, 2012, p. 6). That study also concluded that fishing was an important pressure throughout the Strait and that coastal habitat modifications have altered nearshore biological communities. In particular, contaminants can have a long residence time in the Strait because of burial in the sediments (Johannessen and Macdonald, 2009).

The finding of the present case study that pelagic fishing pressure had the lowest relative risk is consistent with its current low intensity in the Strait of Georgia (*e.g.*, Perry and Masson, 2013) and that it is non-destructive of fixed habitats. Aquaculture occurs in few locations in the Strait of Georgia and its impacts to sub-habitats throughout the Strait are likely limited. Similarly, although HABs occur frequently in the Strait of Georgia, any single bloom usually occupies a relatively small area and occurs for a relatively short duration such that their impacts to the sub-habitats defined in this case study are likely limited. The data from the BC Marine Conservation Analysis project for the Strait of Georgia demonstrate that almost every 4 km^2 planning unit is impacted by multiple pressures, and that the most common number of pressures in each unit is 20 to 25. It is clear that analyzing so many multiple pressures in a control experimental-type approach is impossible. The conclusion, therefore, is that assessing the impacts of so many multiple pressures, and developing ecosystem indicators, is mostly likely done by expert elicitation and ecosystem modelling approaches.

4.3.5 References

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4.4 Comparison between analyses of ecosystem responses to anthropogenic and natural pressures in the Seto Inland Sea, Japan, and the Strait of Georgia, Canada

The Seto Inland Sea, Japan, and the Strait of Georgia, Canada, are both enclosed inland seas, with the Seto Inland Sea about three times the surface area of the Strait of Georgia (23,203 km^2 *vs.* 6,800 km^2, respectively). Both are dominated by regional- and local-scale human impacts, but also experience significant large-scale natural pressures. The use of a similar method for the expert elicitation approach facilitates comparisons of multiple pressures impacting similar habitat types as described by these two case studies.

In the Seto Inland Sea, the 9 sub-habitats examined in that case study (Section 4.2) have similar numbers of pressures (using the list of pressures as defined here), ranging between 14 to 16 pressures (Fig. 4.12). This suggests a broad spatial distribution of pressures, compared with the Strait of Georgia which has a greater range of pressures (from 1 to 11 per sub-habitat) on a similar list of sub-habitats (Fig. 4.10). In terms of multiple pressures on sub-habitats in the Seto Inland Sea, experts assessed that 13 pressures impacted more than 7 sub-habitats each, that 5 pressures impacted between 2 and 6 sub-habitats, and that 2 pressures impacted only 1 sub-habitat each (Fig. 4.12). This compares with the Strait of Georgia for which experts assessed 7 pressures impacted 4 or more sub-habitats, and that 8 pressures impacted 1 or 2 sub-habitats (Fig. 4.11).

The exposure and sensitivity estimates of habitats to multiple pressures in the Seto Inland Sea and the Strait of Georgia share some similarities, but also clear differences emerge (Fig. 4.13). Both ecosystems are similar in having exposure and sensitivity of habitats to pressures grouped in the middle of the risk diagram, *i.e.*, with generally intermediate exposure and sensitivity scores. The ecosystems differ, however, because the Seto Inland Sea has a greater spread to higher sensitivity and lower exposure scores. This puts ecotourism at the level of low concern but three human pressures (ocean-derived pollution, species invasions, and illegal fishing) are of moderate to high concern because of greater sensitivity, and nutrient inputs and climate change-derived ocean warming are at high concern due to high exposure of habitats to these pressures (Fig. 4.13A).

Habitats in the Strait of Georgia had moderate levels of exposure and sensitivity to HABs and moderate exposure and lower sensitivity to aquaculture (Fig. 4.13B). In the Seto Inland Sea, habitats were assessed as having similar exposure (moderate) to aquaculture as in the Strait of Georgia, but greater sensitivity (Fig. 4.13A). In the Strait of Georgia, habitats had the highest exposure and sensitivity to coastal development and climate change-induced increases in ocean temperature. The locations of these two pressures in the risk diagram of the Seto Inland Sea (Fig. 4.13A) and the Strait of Georgia (Fig. 4.13B) were similar, even though they were assessed by completely different experts.

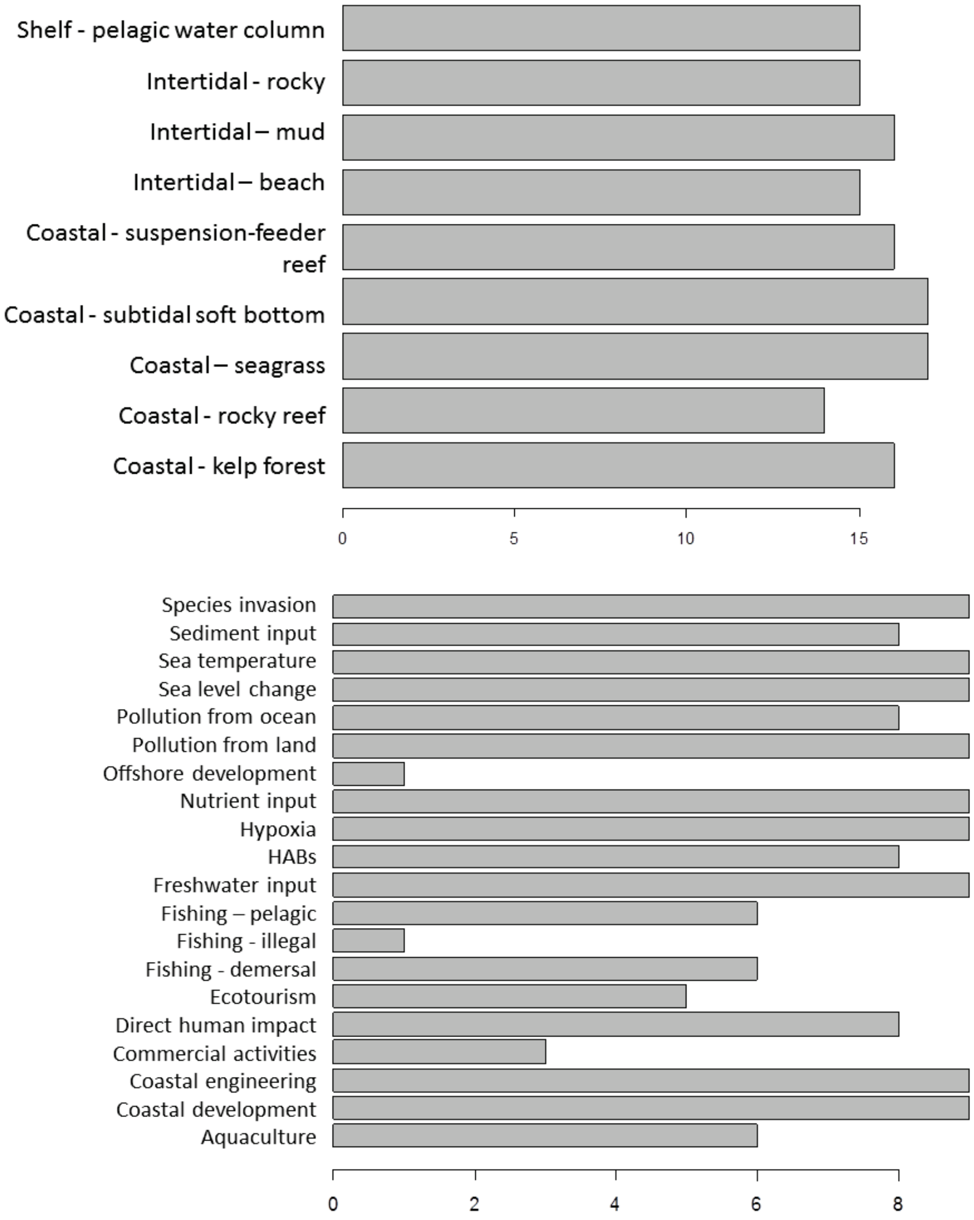

Fig. 4.12 Seto Inland Sea. Top: Number of pressures per sub-habitat (*x*-axis) as assessed by expert elicitation. Pressures are as defined in Table 4.1. Bottom: Number of sub-habitats (*x*-axis) impacted by each pressure, as assessed by expert elicitation. Sub-habitats are defined as in Table 4.1. HABs = harmful algal blooms.

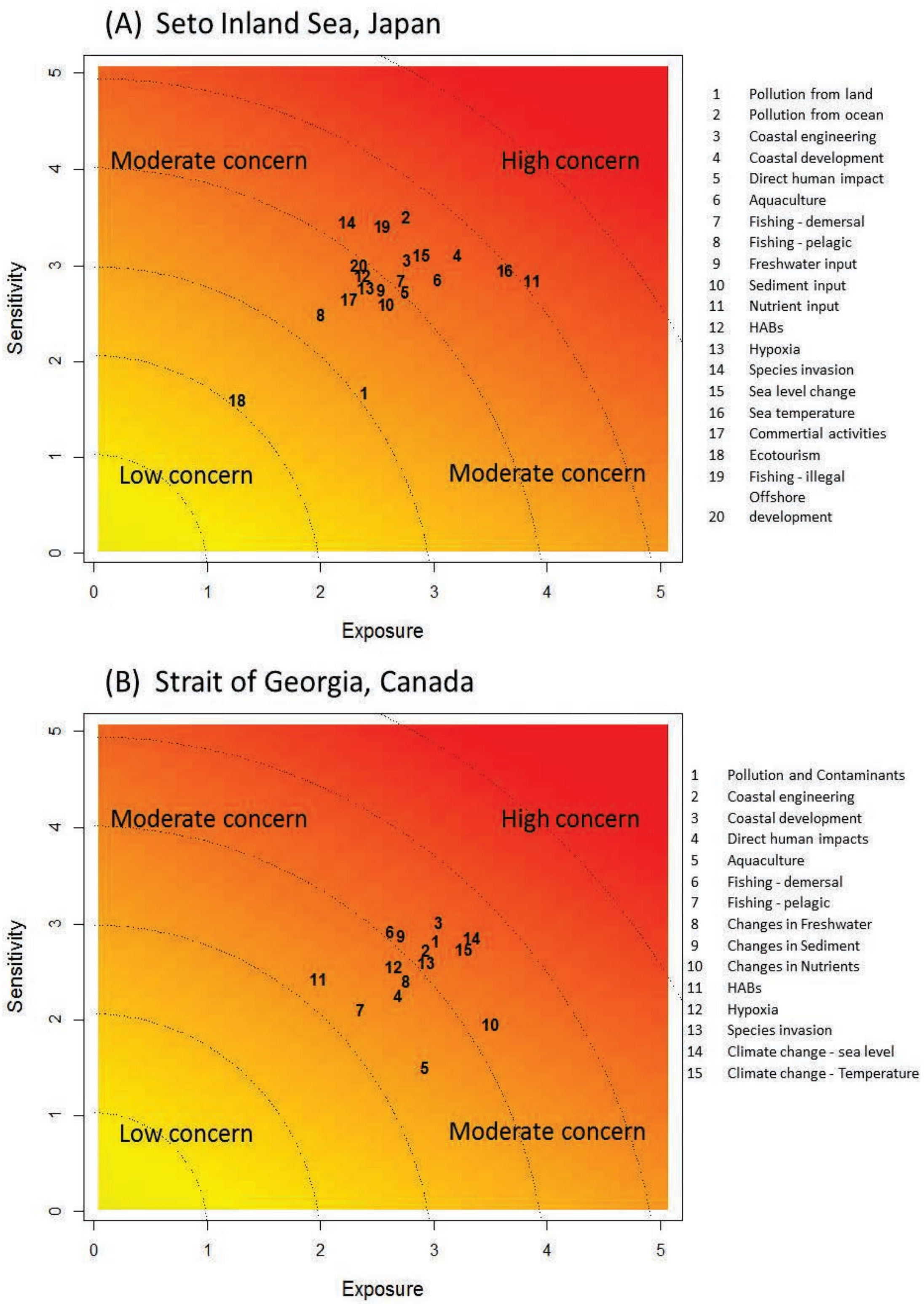

Fig. 4.13 Relative risk diagram for estimated exposure and sensitivity of sub-habitats to multiple pressures, for (A) the Seto Inland Sea, and (B) the Strait of Georgia. The numbered list to the right of each diagram identifies the pressures that are coded onto the risk diagram. Note the code numbers are not the same between panels A and B. Pressures and sub-habitats for both ecosystems are as defined in Table 4.1.

In conclusion, marine habitats in both the Seto Inland Sea and the Strait of Georgia experience multiple pressures, with perhaps more pressures per habitat in the Seto Inland Sea than the Strait of Georgia. Assessments of the relative risks of these multiple pressures are similar in general (*e.g*., strong impacts of coastal development and ocean warming, and of lower concern for pelagic fishing in both ecosystems) but differ in details (*e.g*., the similar exposure but increased sensitivity of habitats to aquaculture in the Seto Inland Sea compared with the Strait of Georgia).

4.5 Summary and recommendations

This section used the expert elicitation method and the list of main pressures and habitats described in Section 3.3 (see also sub-section 2.2.5) to examine two similar coastal marine ecosystems in the North Pacific: the Seto inland Sea, Japan, and the Strait of Georgia, Canada. Analyses of the experts' assessments revealed similar intense pressures on each ecosystem, such as coastal development (a local pressure) and ocean warming (a large-scale pressure). Most sub-habitats were assessed with many more than two or three pressures; for the Strait of Georgia the most common number of pressures per 4 km^2 planning unit was 20 to 25. This makes assessment of the impacts of multiple pressures impossible using standard experiment-type approaches.

Recommendation

The expert elicitation method is appropriate for marine ecosystems of the North Pacific, and may be the only way to adequately assess more than three simultaneous pressures, in particular, when sufficient data are not available to develop ecosystem simulation models. Since many effects of anthropogenic pressures are focused in coastal areas, further studies such as those presented here but done at coastal embayment scales, and compared among regions, may provide further understanding of local responses to both large-scale and local pressures.

5 Developing Ecosystem Indicators for Responses to Multiple Pressures[1]

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5.1 Introduction

Globally, research organizations are focusing on providing science advice to marine management clients on a broad range of issues under changing environmental conditions (*e.g.*, NOAA, 2006; DFO, 2007; ICES, 2013). Scientific support is required for ecosystem-based management of the diverse range of human activities and ocean use sectors. To address this need, various approaches and frameworks, such as Integrated Ecosystem Assessments (IEAs) and risk-based assessments, have been developed to evaluate ecosystems and potential risks to valued ecosystem components (*e.g.*, Levin *et al*., 2009; DFO, 2012; Dickey-Collas, 2014; Levin *et al*., 2014; Link and Browman, 2014; Samhouri *et al*., 2014). A goal of these approaches is to integrate scientific understanding into management measures and into the development of conservation objectives (Levin *et al*., 2009; DFO, 2012; Borja *et al*., 2013). In addition, IEAs and other frameworks should facilitate exploration of decision-making and policy options that can contribute to weighing tradeoffs among various environmental, social, and economic objectives (Dickey-Collas, 2014).

A broad range of human activities across a wide array of sectors occurs in coastal and marine systems, providing a suite of benefits for people. Much valuable research has focused on understanding the effects of single pressures, such as fishing or climate, on fisheries resources (*e.g.*, Megrey *et al*., 2007; King *et al*., 2011). Activities, however, can produce a number of pressures from both land and sea that can impact the surrounding environment simultaneously (*e.g.*, sedimentation, nutrient input, contaminants, shading, noise, and others). Multiple pressures can act additively, synergistically, or

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antagonistically to change ecosystem structure, function, and dynamics in unexpected ways that differ from single pressure responses (Adams, 2005; Crain *et al*., 2008; Darling and Côté, 2008; Halpern *et al*., 2008; Ban *et al*., 2010; Micheli *et al*., 2013; Ban *et al*., 2014). Cumulative effects can result from the incremental, accumulating, and/or interacting impacts of an activity and its pressures on habitats and species (Hegmann *et al*., 1999). In order to fully account for the cumulative effects on coastal and marine ecosystems that arise from multiple human activities and their associated pressures, scientists and managers must be able to understand: 1) the pressures caused by activities, 2) the magnitude, frequency, and spatial scale at which the activities occur, 3) the resulting direct and indirect cumulative effects, and 4) the responses of multiple interacting ecosystem components.

To address all changes in an ecosystem is complex. Establishing causal relationships between pressures and observed effects in natural systems is difficult due to: 1) biotic and abiotic factors that can modify responses of biota to pressures (McCarty and Munkittrick, 1996), 2) compensatory mechanisms that operate in populations (Power, 1997), 3) time lags between cause and effect (Vallentyne, 1999), 4) multiple pathways by which pressures can disrupt ecosystem functions, and 5) potentially spurious correlations between pressures and observed effects. The complexity of marine ecosystems, their inherent high variability and non-stationarity, and the broad array of activities that may impact aspects of these ecosystems suggest that no single measure is adequate for assessing the effects of multiple pressures. As such, there is a need to identify suites of ecosystem indicators that can be used to provide an understanding of how coastal and marine ecosystems respond to multiple pressures.

Various tools and approaches have been and are currently being developed to characterize ecosystem responses to multiple pressures and cumulative impacts (*e.g*., Levin *et al*., 2009; Ban *et al*., 2010; Halpern *et al*., 2012). The focus of this paper is to review indicator selection methods and review general approaches that have been used to assess indicator responses to multiple pressures. We compare and contrast example ecosystem assessments to identify similarities and differences in the pressures and indicators selected and how responses to multiple pressures were addressed. Finally, we conclude with recommendations for identifying suites of indicators and approaches for assessing indicator responses to multiple pressures.

5.2 What are indicators?

Ecosystems are complex and dynamic. Indicators, therefore, are useful tools because it is not possible to measure everything in an ecosystem. In the scientific literature, indicators have been defined in several ways (OECD, 1999, 2003; Jackson *et al*., 2000; Dale and Beyeler, 2001; Kurtz *et al*., 2001; Carignan and Villard, 2002). Hayes *et al*. (2012) succinctly summarized the definitions and identified two key properties of indicators: 1) “components or processes of the ecosystem that can be measured in order to tell us something about the impacts of anthropogenic activities on the health or sustainability of the system”, and 2) “reduce the complexity of real-world systems to a small set of key characteristics that are useful for management and communication purposes”. Additionally, indicators reflect changes taking place at various levels: from genes to species to regional levels (Dale and Beyeler, 2001). This is captured in Niemi and McDonald’s (2004) definition of indicators as “measurable characteristics of the structure (*e.g*., genetic, population, habitat, and landscape pattern), composition (*e.g*., genes, species, populations, communities, and landscape types), or function (*e.g*., genetic, demographic/life history, ecosystem, and landscape disturbance processes) of ecological systems.” The function of indicators is to quantify, simplify, and communicate (Elliot, 2011) as well as synthesize information and facilitate interpretation (Doren *et al*., 2009). Science has developed indicators and suites of indicators to communicate responses to individual pressures, such as fishing (*e.g*., Blanchard *et al*., 2010; Coll *et al*., 2010). More recently, various tools and approaches have been and are currently being developed to characterize ecosystem responses to multiple pressures and cumulative impacts (*e.g*., Levin *et al*., 2009; Ban *et al*., 2010; HELCOM, 2010; Borja *et al*., 2011; Halpern *et al*., 2012; Korpinen *et al*., 2012).

5.3 Identifying indicators

Explicit objectives for management should be the basis for developing and selecting indicators within an ecosystem-based approach to marine management (Levin *et al*., 2009; Perry *et al*., 2010a). There is a vast quantity of literature identifying ecosystem indicators and a general agreement that utilizing a suite of indicators is the best approach to understanding ecosystem responses to drivers and pressures (Link, 2002, 2005; Fulton *et al*., 2005; Greenstreet *et al*., 2012). Which indicators are included in that suite is determined by using a framework and selection criteria (*e.g*., Rice and Rochet, 2005; Borja and Dauer, 2008). Common indicator selection criteria used in the literature were summarized by Niemeijer and de Groot (2008; Table 5.1), with some additions, such as "non-destructive" (Elliot, 2011), or with different phrasing to address data accuracy and precision (Rice and Rochet, 2005; Painting *et al*., 2013), and indicator independence of sample size (Noss, 1990). Most criteria apply to single indicators. However, one key criterion is that suites of indicators should be integrative, covering key components and gradients in the ecosystem.

Table 5.1 Common indicator selection criteria as summarized from the literature by Niemeijer and de Groot (2008) and adapted here. Reproduced with permission of Elsevier.

theoretically sound	time bound	understandable by the public
credible	measurable	compatible at different scales
integrative	repeatable	links to socio-economic indicators
important	specific	links to management
historical data available	good statistical properties	links to policy targets
reliable	applicable to other areas	apparent significance
anticipatory	applicable to other situations	relevant
predictably responds to changes	applicable to other scales	appropriate spatial and temporal scales
insensitive to interference	cost-effective	thresholds to determine action
sensitive to stresses	operationally simple	user-driven
space-bound	achievable and timely	

Choosing a suitable suite of indictors that is complementary, non-redundant, and that integrate responses to multiple pressures and reflect the status of the ecosystem is a difficult process (Painting *et al*., 2013). Considerations for selecting a suite of indicators include ensuring they cover key eco-regions and the appropriate boundary settings to achieve adequate spatial and temporal coverage (Doren *et al*., 2009; Birk *et al*., 2012), consider different levels of biological organization, from cellular to ecosystem levels (Adams and Greeley, 2000; Elliot, 2011) and key functional groups (Rombouts *et al*., 2013), and cover the essential ecosystem characteristics or attributes (Harwell *et al*., 1999; Fulton *et al*., 2005) and processes (Rapport *et al*., 1985) with fast and slow dynamics (Fulton *et al*., 2005). To incorporate these and other considerations in the selection of a suite of indicators, frameworks and procedures for selecting indicators are used. Examples of frameworks that can inform the selection of a suite of indicators include an Ecosystem Risk Assessment Framework (DFO, 2012), environmental assessments (United States Environmental Protection Agency, EPA), hierarchical frameworks (Dale and Beyeler, 2001; Kershner *et al*., 2011), an eight-step process defined by Rice and Rochet (2005), and causal chain frameworks such as Driver-Pressure-State-Impact-Response (DPSIR; Elliot, 2002).

To assess ecosystem integrity, indicators must account for ecosystem "structure, composition, and natural processes, including function and dynamics of its biotic communities and physical environment" (Borja *et al*., 2008). Because it is not possible to study all components of a marine or coastal system, a set of species, habitats, or community properties may be selected to serve as sentinel indicators of the overall health or integrity of the ecosystem (Rapport *et al*., 1985), or that reflect a particular management goal. Identifying appropriate indicators for ecosystem responses to multiple pressures requires an understanding of: 1) how ecological components are connected in the ecosystem, and the roles they play in energy flow in the system, 2) the hierarchical pathways through which sector activities affect ecosystem components, and 3) how changes manifest in species or habitats (Canter and Atkinson, 2011). These can be measured in a number of different ways but are generally captured using metrics of, respectively, (a) connectivity or importance of the ecosystem component in the food web (*e.g*., important trophic positions or niches, keystone species that contribute significantly to the biomass or energy flow of a system, or species or habitats that are particularly sensitive or vulnerable to pressures in the system, or are particularly good for monitoring biomarkers of exposure), (b) exposure of the ecosystem component to the pressure, and (c) vulnerability or sensitivity of the ecosystem component to the pressure(s) (Borja *et al*., 2008; Samhouri and Levin, 2012).

The exposure attribute describes how much activities or pressures interact with the ecosystem component in space and time. Depicting exposure can be done using metrics that capture the level of activities or pressures in ecosystems (*e.g*., levels of nutrient loads, urbanization, ocean noise) or by using abiotic and biotic markers of exposure, such as physiochemical measurements, DNA damage, or expression of stress proteins in organisms (Adams and Wendel, 2005). Vulnerability or consequence describes the potential for long-term harm to an ecosystem component as a result of interactions with one or more pressures. This represents the capacity of the ecosystem component to resist and/or recover from exposure to pressures. Indicators of vulnerability or consequence can be identified at varying levels of organization, such as: individual-organism condition, population-level demographic rates or abundance, species-level distribution, interactions, or diversity, community-level functional diversity, and ecosystem-level states and functions (Rombouts *et al*., 2013).

The combination of multiple pressures in marine systems can affect the resilience of systems and push them towards thresholds, ultimately leading to regime shifts (Hughes *et al*., 2013) beyond which ecosystems may fail to recover to their previous state (Duarte *et al*., 2009). To develop management strategies that identify impending ecological thresholds or tipping points before they occur, researchers are developing early warning indicators, by combining methodologies from economics, climatology, and ecological modelling and testing them primarily in model systems that have already crossed a threshold (Scheffer *et al*., 2009, 2012; Dakos *et al*., 2012). One of the most robust early warning indicators of impending ecological thresholds is a "critical slowing down" (Drake and Griffen, 2010; Dakos *et al*., 2012), resulting in longer recovery times from a disturbance due to the loss of resilience

(Scheffer *et al*., 2009). Ecosystems have also been shown to exhibit rising system memory (*i.e*., correlation; Biggs *et al*., 2009; Dakos *et al*., 2010, 2012), increased variability (Carpenter and Brock, 2006; Daskalov *et al*., 2007), and "flickering" between alternate ecosystem states (Dakos *et al*., 2012) as they approach thresholds. Recovery from a degraded ecosystem structure and function can take many years and ecosystems may never recover to a previous state due to shifting baseline environmental conditions (Duarte *et al*., 2009, 2013; Borja *et al*., 2010).

5.4 Approaches to assess indicator responses to multiple pressures

A broad group of approaches has been used to assess indicators of multiple pressures, including data-based, expert-opinion and judgment, combined observation and expert judgment, and model-based. Some of the strengths and challenges of each approach were identified by examining several examples in the literature. The goal of comparing approaches was to recommend a strategy for assessing indicators of responses to multiple pressures.

5.4.1 Data-based approaches

Data-based approaches for evaluating indicator responses to multiple pressures include, for example, empirical observations (*e.g*., Peterson *et al*., 2013), biomarkers of exposure (*e.g*., Mussali-Galante *et al*., 2013), bioindicators of effects (*e.g*., Adams, 2005), meta-analysis (*e.g*., Crain *et al*., 2008), and multiple regression interaction terms (Thrush *et al*., 2008). For example, the Northwest Fisheries Science Center (NWFSC, Seattle, USA) used empirical observations of a suite of indicators to provide qualitative forecasts of Coho salmon (*Oncorhynchus kisutch*) and Chinook salmon (*O. tshawytscha*) survival (Peterson *et al*., 2010, 2013). As noted by the authors, this approach did not work in all years, and there is a need to consider the strength and co-linearity of multiple pressures at different life history stages (Peterson *et al*., 2013). Burke *et al*. (2013) used a multivariate approach to forecast salmon returns using 31 indicators of large- and local-scale environmental conditions, growth, feeding, predation, disease, and cohort abundance. This type of analysis has the benefit of identifying the relative importance of indicators and can include co-varying indicators.

Rohr *et al*. (2006) used a laboratory experimental approach to examine the effects of multiple pressures on salamander survival. Their results indicate contaminants not only directly affect mortality of amphibians during exposure but also months after the exposure occurred, and can be mediated by animal density (Rohr *et al*., 2006). Laboratory experiments such as these are valuable for clearly identifying the effects of a small number of pressures; however, it is difficult to replicate multiple pressures experienced by animals in the natural habitat. There may be annual variation in the number, type, or strength of pressures animals encounter, susceptibility to pressures may vary among species, and effects of pressures may depend on the community structure (Rohr *et al*., 2006).

An integrated bioindicators approach has been used to understand mechanisms of ecosystem responses to pressures in field situations. Adams and Greeley (2000) demonstrated the use of an integrated bioindicators approach in which indicator responses were measured at different levels of biological organization and at appropriate time scales to link pressures with indicator responses. They noted several advantages of this approach, including "(1) early warning signals of environmental damage and (2) assessment of the integrated effects of a variety of environmental pressures on the health of organisms, populations, and communities" (Adams and Greeley, 2000).

Meta-analyses have been used to explore potential patterns in indicator responses to multiple pressures (*e.g.*, Crain *et al*., 2008; Darling and Côté, 2008). This approach entails searching published studies for impacts of multiple pressures, and results show that responses can be additive, synergistic, or antagonistic (Crain *et al*., 2008; Darling and Côté, 2008; Ban *et al*., 2014). Furthermore, Crain *et al*. (2008) noted the importance of understanding mechanisms by which single pressures affect indicator responses, as a step towards improved understanding of responses to multiple pressures. Meta-analyses are limited by the studies available in the published literature and, to date, most studies are on species-level responses conducted in laboratory settings, and there are few replicate studies on many potentially important pressures (Crain *et al*., 2008; Darling and Côté, 2008).

Some advantages of data-based approaches to evaluating indicator responses to multiple pressures are: 1) causal relationships between pressures and indicator responses can be established, 2) emerging pressures can be tracked in cases where expert input is untested or models are unavailable, 3) indicators can be tailored to the physical and biological nature of the ecosystem, and 4) remotely sensed data are available for many physical environmental variables (Table 5.2). It is, however, sometimes difficult to find data at the appropriate scales that link multiple pressures to ecosystem indicators and this may limit analyses to the shortest available time series and/or the smallest common spatial domain (Table 5.2). Multivariate statistical analyses can address correlations among indicators, but may eliminate critical information. It is also difficult to replicate multiple pressures in a laboratory setting and document the number, type, or strength of pressures animals encounter or are susceptible to in the natural environment.

5.4.2 Expert-judgment tools

Researchers and managers across the globe have turned to risk assessment frameworks based on expert judgment to prioritize and identify indicators of potential impacts from multiple pressures by integrating across multiple activities and ecological components (*e.g.*, Halpern *et al*., 2007; Weisberg *et al*., 2008; Teck *et al*., 2010; Teixeira *et al*., 2010; Hobday *et al*., 2011; DFO, 2012; Samhouri and Levin, 2012). Some risk assessment frameworks have been modified for specific ecosystem components, such as seagrass or marine mammals (Grech *et al*., 2011; Lawson *et al*., 2013) or activities (DFO, 2013), while others are generalized to include multiple pressures and multiple ecological components (Suter, 1999; Hayes and Landis, 2004; Hobday *et al*., 2011; DFO, 2012; Samhouri and Levin, 2012). Based on qualitative and/or quantitative data, indicators of exposure include the spatial and temporal extent of the pressure and intensity of the pressure in terms of concentration or effort. The consequence scoring can be based on expert judgment of population or habitat responses to pressures, life history attributes of species, habitat attributes, or community attributes that indicate vulnerability of a particular ecosystem component to pressures (*e.g.*, Fig. 5.1).

A framework for integrated system-level assessments that rely on expert judgment was developed for Australia's marine environment (Ward, 2014). This framework was applied in Australia and the South China Sea marine ecosystems where indicators were populated using a rapid expert elicitation process to provide a synthesis of the pressures on and condition of components of the ecosystems (Feary *et al*., 2014; Ward *et al*., 2014). Knights *et al*. (2013) used a combination of expert knowledge and published literature to identify linkages between activities, pressures, and ecological characteristics. Rather than a linear DPSIR or PSR approach, Knights *et al*. (2013) developed a network of linkages between multiple activities, pressures, and responses. Network topology metrics, such as linkage density and number of links per ecological characteristic, along with cluster analyses, permitted the grouping of similar impact chains (Knights *et al*., 2013).

Some advantages of expert-based judgment tools are that they provide some insight in cases where data are unavailable, they are useful for prioritization of ecological components or pressures, the methods are transparent and repeatable, and they can be appropriate for global and regional visualization (Table 5.2). In the case of network and network analyses, management measures may become more efficient by addressing groups of pressures (Knights *et al*., 2013). There is, however, often not enough information for specific response variables and these approaches generally do not provide a mechanistic understanding of pressure–response interactions (Table 5.2).

Table 5.2 Some strengths and challenges of general alternative approaches for evaluating ecosystem responses to multiple pressures: Data-based, expert judgment, combined data-based and expert judgment (only additional strengths and challenges of combining the two approaches are listed), and model-based approaches.

	Strengths	**Challenges**
Data-based	Causal relationships established	Difficult to replicate multiple pressures in laboratory setting
	Track emerging pressures where expert input is untested or models are unavailable	Difficult to find data at appropriate scales
	Appropriate indicators tailored to physical and biological nature of ecosystem	Analyses limited to least common denominator (shortest time series, smallest common spatial domain)
	Remotely sensed data available for many physical variables	Multivariate analyses may eliminate critical information
Expert judgment	Provide insight where there are no data	Often not enough information for specific response variables
	Prioritization of ecological components or pressures	Do not provide mechanistic understanding of pressure-response interactions
	Appropriate for global and regional visualization	–
	Network approach may be more efficient by addressing groups of pressures	–
Combination data-based and expert judgment	Incorporates data into the expert judgment approach	Assumptions (for example, additivity of responses) on outputs have not been fully explored
Model-based	Can generate as much data as needed	Must have a model (data and time intense)
	Can create an ensemble of models using different frameworks	Outputs are only as good as the data that go into the model

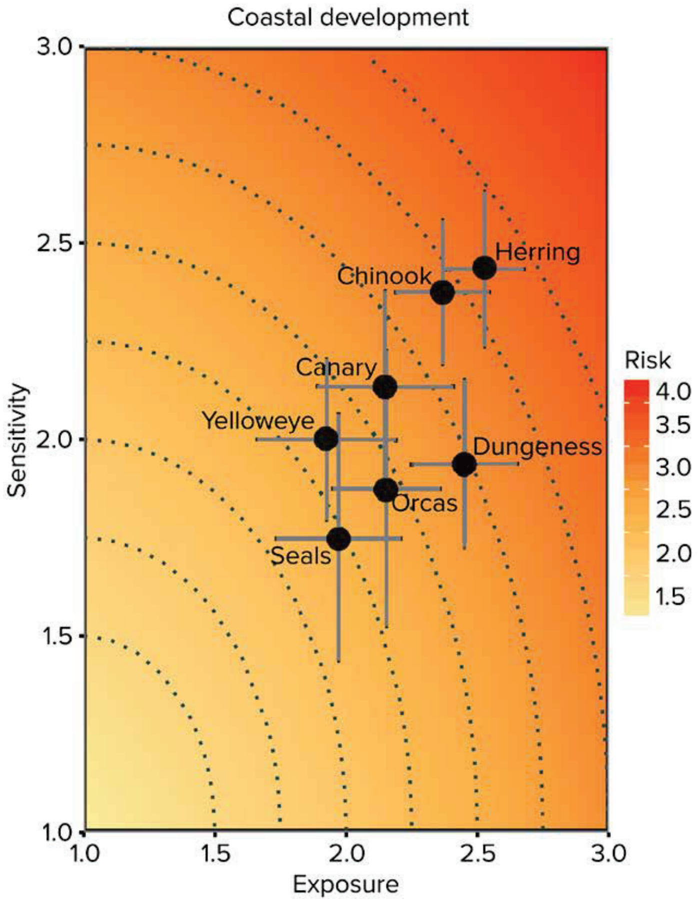

Fig. 5.1 Risk to indicator species in Puget Sound, Washington State, USA, due to coastal development. From Samhouri and Levin (2012). The relative risk is expressed as the Euclidean distance of the species from the origin in the exposure–sensitivity space. Image courtesy of Elsevier.

5.4.3 Combined observation/expert judgment–mapping and GIS approaches

There are recent examples of combined data-based and expert opinion methods that have been applied with mapping approaches to address ecosystem responses to multiple pressures. The Cumulative Impacts tool, developed by the National Center for Ecological Analysis and Synthesis (NCEAS), University of California Santa Barbara and Stanford University, is a spatial analysis tool that maps human activities and their ecological impacts (www.nceas.ucsb.edu/globalmarine). The Cumulative Impacts tool has been used mainly by the scientific community to understand broad-scale patterns in pressure interactions and ecosystem health. This approach models and maps the intensity of each pressure in the ocean, maps the location of each habitat type or species in the ocean, and applies a vulnerability weight derived from expert judgment that translates the intensity of a pressure into its predicted impact on the habitat or species; this creates a metric of impact that can be compared across pressures or ecological components (Halpern *et al.*, 2007, 2008; HELCOM, 2010; Teck *et al.*, 2010; Kappel *et al.*, 2012). These individual impact scores for each pressure in each habitat can then be summed to obtain a total cumulative impact score. The summed impact scores or the individual scores for each habitat can be used to identify which habitats are vulnerable to specific pressures or to the cumulative effects of multiple pressures, or to identify those pressures that in combination are widespread and may have major consequences for ecosystems.

There have been recent advances in the quality and quantity of data available for this type of cumulative impact mapping (*e.g.*, Maxwell *et al.*, 2013); however, opportunities remain to improve these models for identifying indicators (Halpern and Fujita, 2013). For example, groundtruthing the scores using field-collected data on ecosystem condition may improve indicator selection. Finally, most management focuses on the delivery of benefits from nature to people (Millennium Ecosystem Assessment, 2005). Understanding impacts to ecosystem service provision would improve the linkage between cumulative impact mapping and decision making (Halpern and Fujita, 2013). There are some examples of this type of analysis (Altman *et al.*, 2011; Allan *et al.*, 2013), but there is a need for additional research on this topic.

The combination of approaches (data-based and expert judgment) addresses one of the challenges of expert-opinion methods by incorporating data of exposure to human activities and pressures, and is appropriate for global, regional, and local-scale visualization of impacts to the ocean (Table 5.2). The challenges of this approach are that the models of activities and pressures are built on a suite of assumptions (*e.g.*, additivity of responses to multiple pressures) and the effects of these assumptions on model outputs have not been fully explored. In addition, these approaches still use vulnerability rather than measures of consequence and do not include a mechanistic understanding of the impacts of human activities on ecosystems and ecosystem services, in part due to limitations in empirical research on such relationships (Table 5.2).

5.4.4 Model-based approaches

A variety of modelling approaches have been developed to assess ecosystem responses to multiple pressures. Effective approaches and analyses have been developed or applied that use qualitative models, a combination of data and models, multivariate analyses, and quantitative models, including ecosystem models. For example, in Australia, the Commonwelath Scientific and Industrial Research Organisation (CSIRO; Hayes *et al.*, 2012) used qualitative models of feature–pressure interactions to identify ecological indicators. Qualitative models were used because there was not enough quantitative data available. Key ecological features and the drivers and pressures that affect them were mapped. Using the qualitative model, various 'pressure scenarios' were examined to assist in the identification of indicators robust to uncertainty about ecosystem structure and selection criteria were used to refine the indicator list. Notwithstanding the shortage of empirical data, this unique approach resulted in one to four ecological indicators and one to three pressure indicators identified for some of southwestern Australia's key ecological features (Hayes *et al.*, 2012).

Painting *et al.* (2013) developed a valuable approach to testing indicators that, with a well-developed model including all potential pressures combined with field-collected data, enabled the identification of indicators that met several selection criteria (*e.g.*, sensitive and specific). They examined two pressures, climate and trawling, and found three potential indicators sensitive and specific to climate effects (primary production, phytoplankton productivity, and near-bed oxygen concentrations) and one indicator sensitive to demersal trawling (oxygen penetration depth).

There are several efforts to understand the multiple factors that affect salmon throughout their complex life history, as previously mentioned (Burke *et al.*, 2013; Peterson *et al.*, 2013). Mantua *et al.* (2007) used a policy gaming model (MALBEC) for assessing links between ecosystems to integrate spatially explicit impacts of multiple pressures on all life stages of salmon. This type of modelling strategy required data for several ocean and freshwater regions of the North Pacific, such as salmon abundance, oceanographic data, and zooplankton biomass from field or model-derived time series, and these data are not always available. Due to a lack of data, Araujo *et al*. (2013) built a probabilistic network that utilized available data and observations, expert opinion, and model output to examine factors (physical, biological, and hatchery production) affecting the early marine survival of Coho salmon in the Strait of Georgia.

At the global scale, comparative modelling efforts have been utilized to draw generalities about ecosystem responses to multiple pressures. Programs such as Global Ocean Ecosystem Dynamics (GLOBEC; Megrey *et al*., 2007), Comparative Analysis of Marine Ecosystem Organization (CAMEO; Link *et al*., 2012), and Indicators for the Seas (IndiSeas; Bundy *et al*., 2012) have used a combination of data and modelling approaches to compare ecosystems. As part of CAMEO, Fu *et al*. (2012) used partial least squares (PLS) regression to infer pressure–response interactions for nine ecosystems. The advantages of this type of statistical analysis are that predictor variables (pressures) can be correlated and multiple response variables can be included, unlike in regression analyses (Fu *et al*., 2012). Also, PLS regression may be better for predicting indicator responses than, for example, principal components from multivariate analyses (Fu *et al*., 2012). The authors noted that trophodynamic data time series were unavailable for some ecosystems, again, highlighting one challenge in large-scale, multi-national ecosystem comparisons.

In addition to the previously mentioned multinational programs, Barange *et al*. (2014) explored the effects of climate change on fish production and economies of 67 ecosystems/nations. A climate model was used to drive a dynamic size-based food web model; the nutritional and economic consequences to nations were examined using an index of fisheries dependency based on measures of vulnerability. The authors pointed out that model results may be sensitive to assumptions that are necessary in the modelling process. Other data intensive ecosystem models, such as Object-oriented Simulator of Marine Ecosystems (OSMOSE) have been used to simulate indicator responses to pressures, such as fishing, climate change, and their interactions (Fu *et al*., 2013). One advantage of this approach is that model results can be additive, synergistic, or antagonistic (Fu *et al*., 2013).

Many early warning indicators of ecological thresholds, such as increased variance, critical slowing down, and flickering, have been identified using modelling simulations and long-term datasets (Daskalov *et al*., 2007; Dakos *et al*., 2012). Identifying reliable indicators and quantifying thresholds in ecological systems can be challenging due to the lack of appropriate data (deYoung *et al*., 2004; Håkanson and Duarte, 2008; Goberville *et al*., 2010). Many early warning indicators require long-term, high-resolution data with relatively little noise, which are uncommon in ecological systems (Dakos *et al*., 2008, 2012; Scheffer *et al*., 2009). Furthermore, recent studies have shown that threshold detection *via* a single early warning indicator is insufficient and that using multiple indicators could strengthen predictions of impending thresholds (Dakos *et al*., 2012), and some indicators may be correlated (Contamin and Ellison, 2009; Ditlevsen and Johnsen, 2010). Boettiger and Hastings (2012) suggest it is unlikely there are early warning indicators common across ecosystems and recommend that data-driven exploration within ecosystems be utilized to identify system-specific characteristics of ecological thresholds. Experimental approaches may help to address this issue by capturing the context-dependent nature of thresholds (Thrush *et al*., 2009; Hewitt and Thrush, 2010), particularly when conducted across environmental and/or disturbance gradients.

Model-based approaches are perhaps one of the best tools to understand ecosystem responses to multiple pressures but also require the most data- and time-investment. A variety of frameworks can be used to create an ensemble of models and models can generate data as needed; however, the outputs are only as good as the data that go into the model (Table 5.2). Also, setting up models and supplying data to those models may not be feasible due to lack of resources and/or data availability.

The various approaches to assessing responses to multiple pressures (data-, expert judgment, combinations of data and expert judgment, and model-based approaches) have several strengths and challenges. As noted above, data-based approaches enable the establishment of causal relationships between pressures and indicator response. Three of the approaches, data-based, combined observation and expert judgment, and model-based, share a common challenge in that they all depend on data availability. Expert-opinion approaches avoid this problem, but may not provide a mechanistic understanding of pressure–response interactions. Modelling approaches are recommended as the best approach to assessing indicator responses to multiple pressures; however, they require significant investment in data and resources, which are often not available. The strengths and challenges of the three approaches also depend on the objectives. For example, is the objective to determine the state of ecosystems or identify management interventions? Although providing a general understanding of the state of ecosystems and ecosystem responses is a key scientific goal for ecosystem-based management, identifying clear management objectives is a key aspect of choosing appropriate indicators. As such, linking scientific pursuits directly to specific decision contexts is a next step. In light of the strengths and challenges of the described approaches and that data availability will continue to be lacking for some pressures and ecosystems, we recommend using multiple approaches to identify indicators and evaluate multiple pressures on marine ecosystems.

5.5 Comparison of programs that have identified suites of indicators

There are many programs that have identified suites of indicators for monitoring and assessing the status and trends in ecosystem composition, structure, and function. Below are several examples of programs that have taken various approaches to assessing the state and trends of marine ecosystems. The U.S. National Marine Fisheries Service, Alaska Fisheries Science Center's (AFSC) Ecosystem Considerations report (Zador, 2013) uses the DPSIR approach to assess several ecosystems, thereby providing an opportunity to compare suites of indicators arising from the same process and institution across multiple ecosystems. The United States Environmental Protection Agency (EPA) and Environment Canada jointly assembled a report on the Salish Sea (Georgia Basin–Puget Sound ecosystem; http://www2.epa.gov/salish-sea) and the Puget Sound Partnership assembled a Puget Sound Vital Signs (PSVS) report (Puget Sound Partnership, 2013; Fig. 5.2). The Salish Sea and PSVS reports cover overlapping ecosystems and thereby provide an opportunity to compare indicators and approaches used by different organizations for an overlapping geographic area. The Helsinki Commission (HELCOM, 2013) assembled a core set of indicators for the Baltic Sea using a PSR approach. The U.S. National Oceanic and Atmospheric Administration (NOAA) used a hierarchical selection process to choose indicators that represent a broad set of ecosystem management goals ranging from sustaining fisheries to ecological integrity and protected species. Finally, Europe's Marine Strategy Framework Directive (MSFD) identified 11 descriptors of ecosystems in good environmental status. In this report we compared indicators used in these different ecosystem assessments and identified sources of differences.

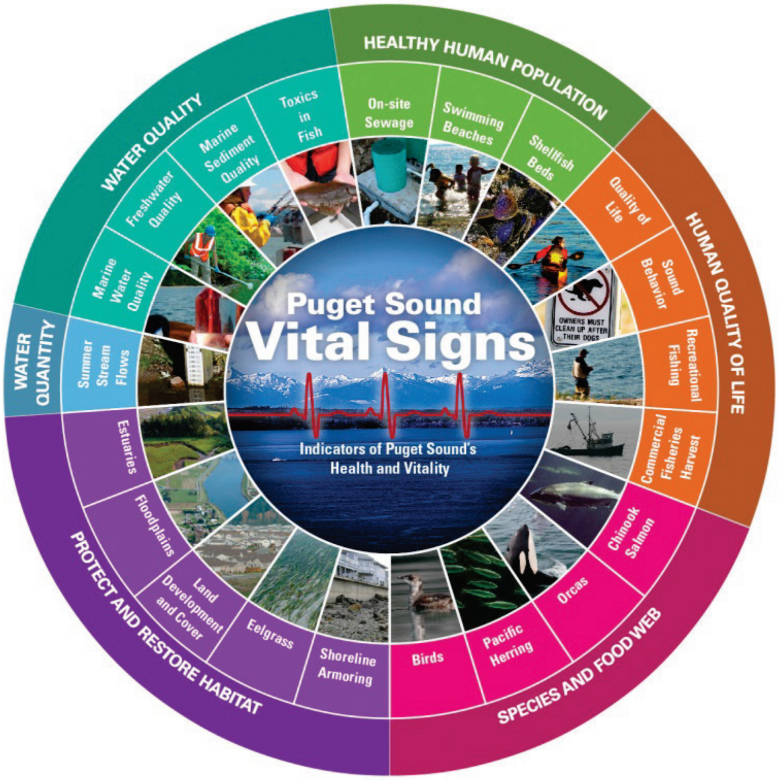

Fig. 5.2 The Puget Sound Vital Signs Wheel or Dashboard is a part of Puget Sound Partnership's Puget Sound Vital Signs (PSVS) report. The Dashboard identifies the key ecosystem indicators and pressures, incorporates targets, and serves as a report card on success in meeting targets. Image courtesy of the Puget Sound Partnership (2013).

5.5.1 Example 1: Alaska Ecosystem Considerations

The AFSC successfully manages groundfish fisheries while incorporating ecosystem considerations (Livingston *et al*., 2011). The AFSC's Ecosystem Considerations report provides an assessment of multiple pressures on ecosystems: fishing, human-induced, and natural pressures such as climate variability (http://access.afsc.noaa.gov/reem/ecoweb/index.php). The Ecosystem Considerations report comprises three main sections: 1) Executive Summary (Report Card), 2) Ecosystem Assessment, and 3) Ecosystem Status and Management Indicators for the different ecosystems in Alaska (Zador, 2013). The Executive Summary provides a Report Card of key status and trend indicators in the eastern Bering Sea, and eastern, western, and central Aleutian Islands. The Ecosystem Assessment contains a synthesis of climate and fishing effects on Alaska ecosystems (Arctic, eastern Bering Sea, eastern, western, and central Aleutian Islands, and the Gulf of Alaska) using a short-list of indicators. Both the Report Card and the Ecosystem Assessment sections utilize selected indicators from the Ecosystem Status and Management section, which provides information on the status and trends of ecosystem components (*e.g.*, physical environment, habitat, plankton, fish, marine mammals, seabirds, community-level indicators, *etc*.), early detection of direct human effects on the ecosystem, and effectiveness of management actions (Zador, 2013). In the Ecosystem Assessment section, indicators were selected using the DPSIR approach (Elliot, 2002) to address four ecosystem-based management objectives: maintain predator–prey relationships, maintain diversity, maintain habitat, and incorporate/monitor the effects of climate change. Drivers and pressures pertaining to those objectives were identified and a list of candidate indicators were selected based on qualities such as availability, sensitivity, reliability, ease of interpretation, and pertinence. Indicators of three broad categories were included: biology/ biodiversity, climate, and fishing. Finally, for the Report Card, an Ecosystem Synthesis Team refined an indicator list focused on broad, community-level indicators to assess the current and potential future ecosystem states (biology/biodiversity, climate, fishing) and included human quality of life indicators (Zador, 2013).

5.5.2 Example 2: Salish Sea and Puget Sound

Two programs assessed the adjoining coastal waters of British Columbia and Washington State. The Puget Sound Partnership assembled a Puget Sound Vital Signs report (PSVS; Puget Sound Partnership, 2013; Fig. 5.2); the United States Environmental Protection Agency (EPA) and Environment Canada jointly assembled a report (http://www2.epa.gov/salish-sea) on the Salish Sea (Georgia Basin–Puget Sound ecosystem). The PSVS report used a DPSIR and an IEA approach to communicate project progression, use of funds, and status of the Puget Sound ecosystem with a longer, but overlapping list of indicators than the EPA report. The EPA report used a DPSIR approach (*e.g.*, sub-section 2.2.2) to communicate the state of the Salish Sea (a larger body of water that includes both the Puget Sound and Strait of Georgia) to the public using a short list of indicators.

5.5.3 Example 3: Baltic Sea – HELCOM

The Helsinki Commission (HELCOM, 2013; http://helcom.fi/) identified a core set of indicators to assess the Baltic Sea ecosystem. The Commission chose core indicators using a PSR (*e.g.*, sub-section 2.2.2) framework to address strategic goals (favourable biodiversity and undisturbed by hazardous substances and eutrophication) and ecological objectives (*e.g.*, clean water, viable populations of species; HELCOM, 2013). The 20 core indicators for biodiversity, 13 for hazardous substances, and 4 for eutrophication met predefined HELCOM principles (*e.g.*, monitored, covers the entire area, reflects pressures, quantitative, updated regularly, *etc*.) and measured the current status relative to targets outlined in the Baltic Sea Action Plan (https://helcom.fi/baltic-sea-action-plan/). Indicators included the main ecosystem components (mammals, birds, fish, and non-indigenous species) and habitats (pelagic, seabed). A unique feature of the HELCOM (2013) report was the pressure indicator matrix that identified the multiple pressures most likely to affect each biodiversity indicator. The strengths of the pressure–indicator interactions were also included. For example, higher trophic level animals were most likely affected by fishing and contaminants, lower trophic level animals were most likely affected by eutrophication, and benthic habitats and communities were most likely affected by fishing and eutrophication.

5.5.4 Example 4: U.S. California Current Integrated Ecosystem Assessment

On the West Coast of the U.S., NOAA is developing an IEA (sub-section 2.2.7) for the California Current (CCIEA; https://www.integratedecosystemassessment.noaa.gov/regions/california-current). The IEA report is intended to deliver integrated, cross-sector science to support ecosystem-based management (Levin *et al.*, 2009). The 5 ecosystem goals on which the IEA is focused include conserving or managing wild fisheries, protected resources, habitat, vibrant coastal communities, and ecosystem integrity. Indicators for each of these goals, along with a set of natural and anthropogenic drivers and pressures, were selected using a hierarchical indicator selection process based on a series of criteria similar to those listed in Table 5.1 (Kershner *et al*., 2011; Andrews *et al*., 2013). Thus each ecosystem state indicator reported in the IEA maps to key ecosystem attributes, which in turn are related to one of the 5 ecosystem goals. Anthropogenic drivers and pressures fall into one of 23 categories as varied as fisheries removals, commercial shipping activity, and pollution. Natural drivers and pressures, due to changes in oceanography and climate, fall into 9 different categories, including influences like changes in ocean temperature, decreasing oxygen, and ocean acidification. All of the IEA indicators were developed *via* data-based, expert judgment, and model-based approaches. To date, the drivers and pressures indicators have not been quantitatively linked to ecosystem states in the IEA, though that is the intention in future iterations of this report.

5.5.5 Example 5: European Marine Strategy Framework Directive

In Europe, the Marine Strategy Framework Directive (MSFD) was introduced to protect and restore Europe's regional seas and designed to achieve good environmental status through coordinated and integrated research by 2121 (COM, 2005a,b). To determine environmental status, 11 descriptors were identified, including biological diversity, non-indigenous species, exploited fish and shellfish, food webs, human-induced eutrophication, seafloor integrity, hydrological conditions, contaminants, contaminants in fish and seafood, litter, and energy, inlcuding noise (European Commission, 2010; Borja *et al*., 2011; Fig. 5.3). Expert groups developed considerations for application and methodological standards for each descriptor (Cardoso *et al*., 2010). Attributes, criteria (29) and indicators (56) were selected for each of the descriptors (European Commission, 2010) and recommendations have been proposed for articulating good environmental status (Mee *et al*., 2008; Borja *et al*., 2013; Tett *et al*., 2013; Fig. 5.3). One goal of the MSFD was to have each EU Member State conduct an initial assessment of the current environmental status of the waters and the environmental impact of human activities (COM, 2005b; Cardoso *et al*., 2010). Towards that goal, Borja *et al.* (2011) implemented the MSFD to assess the environmental status of the Bay of Biscay (Basque Coast) and proposed a method for integrating the descriptors into an overall ecosystem status report.

5.5.6 Comparison of examples

Among the example programs examined here, there were both commonalities and differences in the pressures and indicators that were identified and how responses to multiple pressures were addressed. Some differences were due to the overall goals and objectives of the reports. For example, some reports focused on assessing the state of an ecosystem (*e.g*., Salish Sea EPA, Bay of Biscay MSFD), some reports also assessed progress towards targets (*e.g*., HELCOM, PSVS), and/or addressed ecosystem-based fishery management goals (*e.g*., Alaska) or marine management goals (*e.g*., CCIEA). All programs used a causal-chain conceptual framework such as DPSIR or PSR to address pre-defined strategic goals and ecological or management objectives. HELCOM (2013) identified the difficulty in differentiating pressure and state indicators; for example, dissolved oxygen can be a state indicator of water quality but also a pressure indicator for sessile or low motility animals. This highlights the need for clearly documented conceptual or pathways-of-effects models and risk assessments.

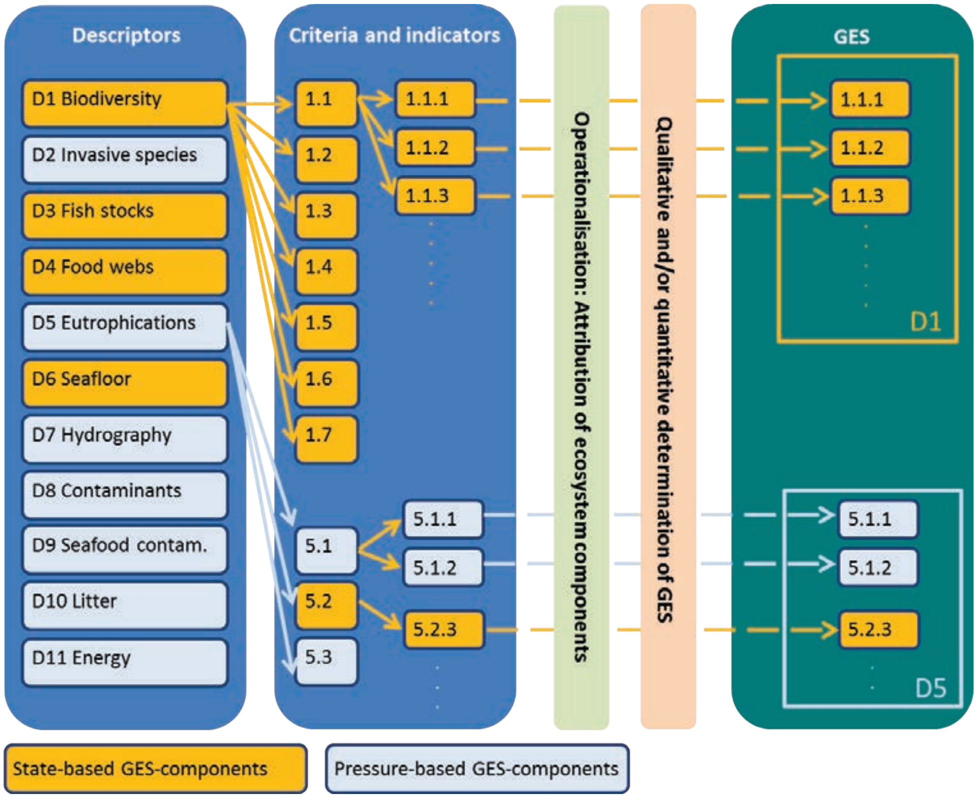

Fig. 5.3 Components for the determination of Good Environmental Status (GES) in the Marine Strategy Framework Directive (MSFD). There are 11 descriptors, 29 criteria, and 56 indicators. Due to variability among ecosystems, descriptors, criteria, and indicators used in assessments may vary. Image courtesy of the MSFD Guideline produced by Knowseas (http://www.msfd.eu/knowseas/guidelines/3-INDICATORS-Guideline.pdf).

For all ecosystem reports examined, a list of potential indicators that reflect identified pressures was established and refined by data availability, selection criteria and, in some cases, expert knowledge. All ecosystem reports included indicators that reflect climate and fishing pressures; however, the other types of pressures included varied among reports (Fig. 5.4). The Alaska Ecosystem Report Card, CCIEA, and the PSVS report had indicators of human quality of life. The HELCOM, CCIEA, and Bay of Biscay MSFD reports included indicators of eutrophication. Five of the reports (CCIEA, HELCOM, PSVS, Salish Sea EPA, and Bay of Biscay MSFD) had indicators of hazardous substances whereas the Alaska reports did not include hazardous substance indicators. Differences in the pressures identified in each report are a reflection of the main pressures acting on ecosystems and the spatial delineation of the ecosystems. For example, most reports that included hazardous substance indicators were for semi-enclosed waters (*e.g.*, Baltic Sea) that included nearshore areas (*e.g.*, Puget Sound) whereas the Alaska ecosystems are large oceanic ecosystems that encompass waters 3 to 200 nmi (5.5 to 370 km) from shore.

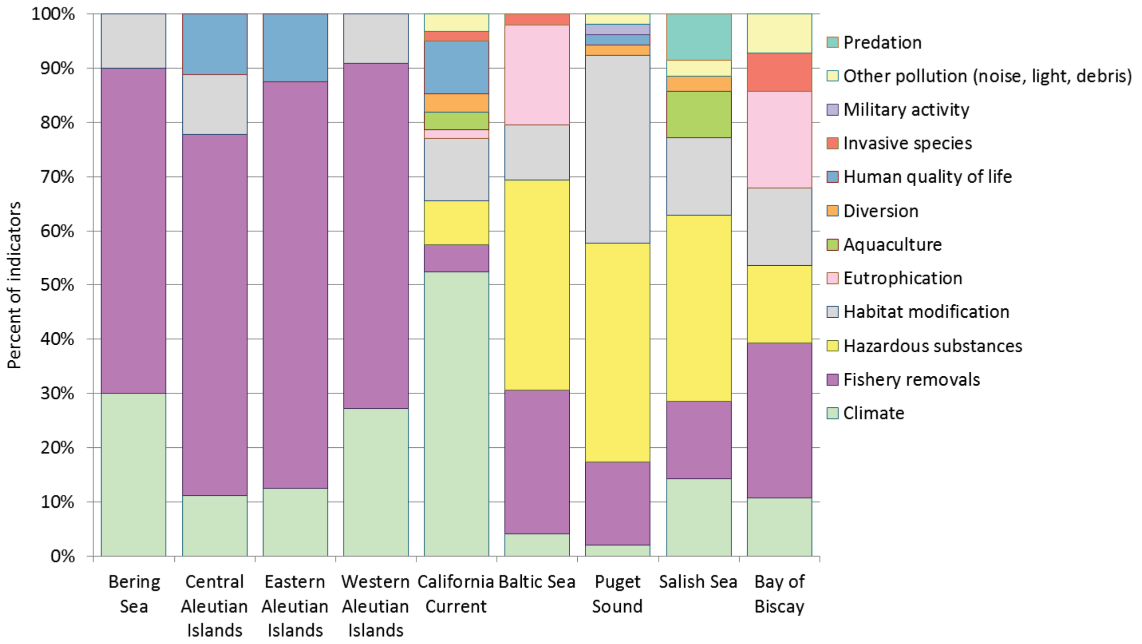

Fig. 5.4 Percent of indicators used to reflect general categories of pressures in ecosystem assessment reports: the California Current Integrated Ecosystem Assessment (Andrews *et al*., 2013; Hazen *et al*., 2013; Norman and Holland, 2013; https://www.integratedecosystemassessment.noaa.gov/regions/california-current), the eastern Bering Sea, and the central, eastern, and western Aleutian Islands (Alaska Ecosystem Report Card; Zador, 2013), the Baltic Sea (HELCOM, 2013), Puget Sound (Puget Sound Partnership, 2013), the Salish Sea (U.S. Environmental Protection Agency (EPA) and Environment Canada report, http://www2.epa.gov/salish-sea), and the Bay of Biscay (Borja *et al*., 2011 using the European Marine Strategy Framework Directive).

Comparisons between ecosystem reports also revealed similarities and differences in response indicator selection (Fig. 5.4). A feature of all the examples is that key functional groups with fast and slow dynamics and essential ecosystem characteristics were represented in the suites of indicators. For example, most reports included indicators of marine mammals, representing key functional groups at high trophic levels with slower dynamics. All reports also included estimates of fish biomass or abundance, representing key functional groups at lower trophic levels with faster dynamics. Differences in indicator selection among reports reflected a variety of factors. For example, differences between the indicators presented in the Salish Sea EPA and PSVS reports, assembled for overlapping waters by different organizations, may reflect the level of detail thought appropriate for communicating to a public non-scientific audience and the experts involved, with perhaps data availability common for both U.S. and Canadian waters. The PSVS report included most of the indicators that were in the EPA Salish Sea report (except air quality indicators); however, there were differences between the two reports in the type of indicator utilized to represent some components of the ecosystem. For example, both reports included an indicator of Chinook salmon; however, the PSVS report used the number of natural origin adult Chinook salmon returning to spawn, and the Salish Sea report used the number caught, number of returns, and total abundance of Chinook salmon. A unique feature of the PSVS report is that it identified the current status of indicators relative to baseline values as well as pre-defined targets. Differences in indicators among the Alaskan ecosystems, assessed by the same organization, highlighted the unique characteristics of each ecosystem and the spatial and temporal differences in: 1) the main climate and human-induced pressures, 2) species composition and key functional groups/features, 3) data availability and extent of knowledge about the ecosystem, and 4) the particular expertise of team members (Zador, 2013). For example, zooplankton times series were available for the eastern Bering Sea, but not for the Aleutian Islands. Instead, planktivorous seabird reproductive success was used as an indicator of zooplankton in the central and western Aleutian Islands, while no indicator was available for the eastern Aleutian Islands.

Each report considered the effect of multiple pressures on ecosystems. The HELCOM project (HELCOM, 2013) clearly outlined multiple pressures that affected each core indicator in a matrix and ranked the expected level of impacts of pressures on each indicator. The CCIEA has created an ecosystem risk assessment framework to assess the risk to marine habitats due to a variety of activities and pressures (Samhouri and Levin, 2012). The Alaska Ecosystem Assessment (upon which the Alaska Ecosystem Report relies) outlined multiple indicators of each pressure in a table (Livingston *et al*., 2011; Zador, 2013). The PSVS and Salish Sea EPA reports outlined single or multiple pressures that affect each indicator in the text of the report. The Bay of Biscay MSFD report proposed an environment status score based on combining indicators that were reflective of multiple pressures (Borja *et al*., 2011). In addition to pressures, all reports had indicators of most ecosystem services as defined by the Millennium Ecosystem Assessment (2005) and adjusted for marine ecosystems (Liquete *et al*., 2013): provisioning (food provisioning, water storage and provision, biotic materials and biofuels), regulating and maintenance (water purification, air quality regulation, coastal protection, climate regulation, weather regulation, ocean nourishment, life cycle maintenance, biological regulation), and cultural (symbolic and aesthetic values, recreation and tourism, cognitive effects).

There are other approaches to assessing ecosystems in addition to those described above. For example, there are several multinational efforts that utilize a comparative approach to identify common pressure–indicator links among ecosystems. Multinational programs that have facilitated effective ecosystem comparisons include the Marine Ecosystems of Norway and the U.S. (MENU; Link *et al*., 2009), GLOBEC (*e.g*., Megrey *et al*., 2007), and CAMEO (*e.g*., Link *et al*., 2012). Also, IndiSeas (Bundy *et al*., 2012; Shin *et al*., 2012) is a collaborative program that selected a suite of 8 indicators to examine the effects of fishing on multiple ecosystems and address defined ecological objectives. A common component of all these multinational projects is the involvement of local experts to provide data and interpret results. The approach of using a common suite of indicators to compare multiple ecosystems is limited by the type, quantity, and quality of data that is common among all ecosystems. However, comparative analyses provide additional insight and improved understanding of pressure effects.

5.6 Conclusions

Given the variability in the types and intensities of pressures affecting ecosystems, key ecosystem features, ecosystem types, data availability, number and background of experts involved, and approaches (single ecosystem *vs*. comparison of multiple ecosystems), it is apparent that one definitive list of specific indicators cannot be exclusively used to assess the state of all types of marine ecosystems. This is the case regardless of the conceptual framework and selection criteria by which potential individual indicators are identified. There are at least two general approaches (within a causal chain framework) in the literature by which suites of indicators are assembled: 1) develop indicators that are specific to individual ecosystems or key ecological features (*e.g*., Hayes *et al*., 2012) or 2) utilize recommended indicators (of important pressures or responses to those pressures) that, given data availability, can be calculated for multiple ecosystems to address ecological or ecosystem-based objectives (*e.g*., Jamieson *et al*., 2010; Bundy *et al*., 2012). The advantage of the former approach is that relevant pressure–indicator interactions are ecosystem-specific, and there is potential to recommend a set of indicators for a range of ecological features. The advantage of the latter approach is that responses to pressures, such as fishing, can be compared across multiple ecosystems, potentially providing further insight into pressure–response interactions common among ecosystems. A third and potentially promising approach (*e.g*., IndiSeas2) is to utilize a core set of recommended indicators for all ecosystems and include additional ecosystem-specific pressure-linked response indicators not reflected in the core set. Additionally, as done in the MSFD, those indicators that are relevant and can be calculated for an ecosystem are selected from a core set of indicators identified by expert groups. These approaches would enable comparisons of common pressure–indicator interactions across ecosystems, and enable a complete characterization of pressures and indicators specific to each ecosystem. Regardless of approach, the selection of suites of indicators should be based on clear conceptual models linking indicators to pressures and drivers, on management objectives (Perry *et al*., 2010a), and on established criteria, while ensuring that the final suite consists of indicators that are complementary, non-redundant, and integrative.

Suites of core indicators have been tested and recommended for evaluating the effects of fishing and assisting with ecosystem-based fisheries management (Table 5.3). For example, Fulton *et al*. (2005) tested the performance of indicators using simulation models and recommended a suite of indicators to examine the effects of fishing on ecosystems. Link (2005) recommended a list of indicators that could be translated into ecosystem-based fishery management decision criteria. Jamieson *et al*. (2010) adapted and added to the indicators recommended by Fulton *et al*. (2005) and Link (2005), including biophysical indicators of climate change. IndiSeas identified a suite of indicators to examine the effects of fishing (Bundy *et al*., 2012). In addition, a factor analysis by Greenstreet *et al*. (2012) indicated a suite of 7 or 8 indicators was necessary to assess the state of the demersal fish community with respect to the goal of restoring biodiversity in the North Sea. These suites of indicators are a valuable starting place for examining the effects of climate change and fisheries on ecosystems, and could be broadened to include other pressure and response indicators for marine management of activities beyond fisheries.

Fishing and climate are two important pressures that have been examined (*e.g*., Perry *et al*., 2010b). However, there are other environmental, human activity, and sociopolitical–economic pressures that may be important in ecosystems (Table 5.4), for example, nutrient loading, contaminants, oil and gas development, aquaculture, seafood demand, and coastal infrastructure. There are many ecosystems with specific management objectives and conceptual frameworks that have identified these types of pressures as important (*e.g*., Halpern *et al*., 2008; Knights *et al*., 2013) and there are programs that have been making progress in assessing multiple pressures, such as HELCOM, the California IEA, and the European MSFD. As regions move towards developing suites of indicators of responses to multiple pressures, it will be valuable to consider the extent to which data are available. Given that data availability will continue to be a challenge, we recommend using a variety of approaches, such as expert opinion, model-based simulation, and empirical analysis to identify indicators and evaluate multiple pressures on marine ecosystems.

Future considerations for assessing the effects of multiple pressures should incorporate uncertainty in indicator development. Sources of uncertainty can include natural variability, observation error, model structural complexity, inadequate communication, unclear objectives, and implementation or outcome uncertainty. Another difficult issue to resolve is the interaction between pressures that are sustained over a long duration and those pressures that are intense, but episodic. Also, it will be valuable to explore the possibility of developing reference levels for indicators, and suitable methods of communicating results. Presenting indicators of responses to multiple pressures succinctly and unambiguously to policy makers and decision makers is a challenge for future ecosystem assessment processes.

Table 5.3 A compiled suite of indicators recommended for ecosystem-based fisheries management by 1) Fulton *et al*. (2005), 2) Perry *et al*. (2010a), 3) Link (2005), 4) Greenstreet *et al*. (2012), and 5) IndiSeas (Bundy *et al*., 2012).

Recommended indicators	**Reference**	**Objective***
Biomass by group or community (*e.g.*, flatfish, pelagic species, piscivores)	1, 2, 3, 5	Maintain resource potential
Total abundance	4	Conserve biodiversity
Abundance of scavengers	3	Maintain structure and function*
Volume of gelatinous zooplankton	3	Maintain structure and function*
Consumption	1	Maintain structure and function*
Species richness (number of species)	1, 2, 3, 4	Conserve biodiversity
Hill’s species evenness	4	Conserve biodiversity
Mean von Bertalanffy growth parameter	4	Conserve biodiversity
Mean number of interactions per species	1, 3	Maintain structure and function*
Slope of size spectrum, all species	1, 2, 3	Conserve biodiversity*
Large fish indicator	4	Conserve biodiversity
Proportion of predatory fish	5	Conserve biodiversity
Number of cycles	3	Maintain structure and function*
Maximum or mean length	2, 3, 5	Maintain structure and function
Mean life span	5	Maintain stability and resistance
Mean length at maturity	2, 4	Conserve biodiversity
Mean individual fish weight	4	Conserve biodiversity
Mean age at maturity	4	Conserve biodiversity
Number of groups representing 80% of biomass	1	Maintain structure and function*
Nutrient cycling; estimated denitrification, particularly for shallow-water ecosystems; DIN, network total production	1	Maintain structure and function*
Production; total primary production	1	Maintain structure and function*
Respiration or total production from network models; otherwise use total production by group, denitrification in shallow-water systems	1	Maintain structure and function*
Biomass ratios (*e.g.*, large:small plankton); length of maximum catch	1, 2	Maintain structure and function*
Mapping biomass indicators	1	Maintain structure and function*
Throughput estimated using network model; alternatively, estimated total production, consumption, respiration	1	Maintain structure and function*
Trophic level or trophic spectrum of catch	1, 2, 3, 5	Maintain structure and function
Biophysical characteristics	2	–

Table 5.3 Continued.

Recommended indicators	Reference	Objective*
Habitat-forming taxa	1, 2, 3	Maintain structure and function*
Fishery removals of all species (landings, bycatch, discards, *etc*.)	2, 3	Maintain structure and function*
Landings of target species	3	Maintain structure and function*
1/(landings /biomass)	5	Maintain resource potential
Proportion of non-fully exploited stocks	5	Conserve biodiversity
1/Coefficient of variation of total biomass	5	Maintain stability and resistance

* indicates objective was identified either in text of the document or deduced for this paper.

Table 5.4 Some broad-scale activities, pressures, and indicators for consideration in suites of indicators for marine ecosystems such as the North Pacific Ocean.

Environmental pressures/indicators	Human activities and pressures	Socio-economic-political
Temperature	Fishing	Seafood demand
Sea ice	Oil and gas	Coastal population trends
Chlorophyll a	Military activity	Marine employment
Nutrients	Wave/wind/tidal energy development	Marine revenue
River discharge	Shipping	Marine exports/domestic consumption
Toxic contaminants	Coastal engineering	Participation/stakeholder involvement
Large-scale climate index (*e.g*., PDO, ENSO)	Aquaculture	Governance
pH	Ecotourism	Happiness
Oxygen	Land-based pollution	Satisfaction with ocean status
		Community vulnerability
		Coastal infrastructure

5.7 *Summary and recommendations*

Human activities in coastal and marine ecosystems provide a suite of benefits for people, but can also produce a number of pressures that affect the system's population dynamics. Multiple pressures can act additively, synergistically, or antagonistically to change ecosystem structure, function, and dynamics in unexpected ways that differ from single pressure responses. Scientific tools that can be used to evaluate the effects of multiple pressures are needed to assist decision making. In this section, indicator selection methods and general approaches to assess indicator responses to multiple pressures were reviewed and example ecosystem assessments were compared.

Identifying indicators and evaluating multiple pressures on marine ecosystems requires a variety of approaches, such as empirical analyses, expert opinion, and model-based simulation. The ultimate goal is to identify a meaningful set of indicators that can be used to assist with the management of multiple types of human interactions with marine ecosystems.

Recommendations

Indicators should be chosen based upon defined criteria, conceptual models linking indicators to pressures and drivers, and defined strategic goals and ecological or management objectives. Indicators should be complementary, non-redundant, and integrate responses to multiple pressures and reflect the status of the ecosystem. An initial core set of indicators could include those that have been tested for the effects of climate and fishing and then expanded to include indicators of other pressures and ecosystem-specific feature-pressure interactions.

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6 Indicators for Ecosystem Responses to Multiple Pressures in the North Pacific

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6.1 Introduction

As noted in the previous sections, there are many pressures impinging upon many habitats in the North Pacific for which many indicators have been proposed. This section reviews proposed indicators and applies frameworks described in Section 2 to the pressures and habitats identified in Section 3 to build on the review of indicators in Section 5. Working Group 28 was not able to identify one single overall indicator of ecosystem responses to multiple pressures in the North Pacific (which is consistent with experiences by others for ocean regions elsewhere). Instead, in this section the Working Group proposes an approach to selecting indicators which consists of two 'toolboxes', the first being a set of indicators integrated from those proposed by several studies for the North Pacific, and the second being a set of methods for selecting leading indicators from this integrated set. In addition, a core set of indicators is proposed for use in all PICES regions, as available data permit, although these may not span the entire range of multiple pressures in this region.

Publications on, and experiences with, cumulative pressure and impact assessments (CPIAs) have become more common over the past 10 years. Korpinen and Andersen (2016) provide an excellent review of 40 recent (2000–2016) marine CPIAs, with a focus on their methodological approaches. Most of the examples selected from the North Pacific are included in previous sections of this Working Group report. Korpinen and Andersen (2016) found that 88% of the assessments assumed cumulative pressures or impacts were additive, and over 50% of the assessments used the approach of Halpern *et al.* (2008). Five of the assessments attempted to consider synergistic or antagonistic effects, usually by the use of ecosystem models. In general, the CPIAs examined in this review had three essential components: spatial data on the intensity of pressures, spatial data on the occurrence of ecosystem components, and some estimate of impacts (Korpinen and Andersen, 2016). What was lacking, however, were definitions of how much pressure was being applied. This was a particular problem with CPIAs which assessed different types of activities producing the same type of pressures. Issues of the spatial extent of pressures (*e.g*., levels of impacts at increasing distance from the source of a pressure) were also not well defined, Overall, Korpinen and Andersen (2016) concluded that the approach of Halpern *et al*. (2008; see also sub-sections 2.2.5 and 3.3) was developing into a global standard, and that tools are becoming available to facilitate and compare these types of CPIAs in a common framework (*e.g*., Robinson *et al*., 2013; Stock, 2016).

6.2 Toolbox 1: Deriving a core set of ecosystem indicators

At its outset, the process for selecting indicators to characterize ecosystem responses to multiple pressures is similar to the process of selecting indicators for single pressures. First, a framework is chosen to guide understanding of the relationships among ecosystem processes (*e.g*., Section 2). Next, (often long) lists are drawn up of all the potentially measurable variables that might be used to describe the relationships among ecosystem processes. These measurable variables are then subjected to a selection process, usually using criteria such as availability, theoretical properties, sensitivity to pressures, *etc*. (*e.g*., Rice and Rochet, 2005; see also Table 5.1 in Section 5.3) to obtain a reduced set of measurable variables (Fig. 6.1). This reduced set of variables may also include outputs from ecosystem simulation models which represent emergent properties of the system, such as material cycling and other network properties. In some studies the variables in this reduced set are called ecosystem Essential Ocean Variables (eEOVs, *e.g*., Constable *et al*., 2016; Muller-Karger *et al*., 2018). Methods (described below in Section 6.3) are then applied to this reduced set of measurable variables to derive an appropriate set of indicators which describe ecosystem conditions and responses to multiple pressures to inform the objective-level criteria or management goals (Fig. 6.1). This section describes indicators that have been proposed for marine ecosystems, with a focus on the North Pacific.

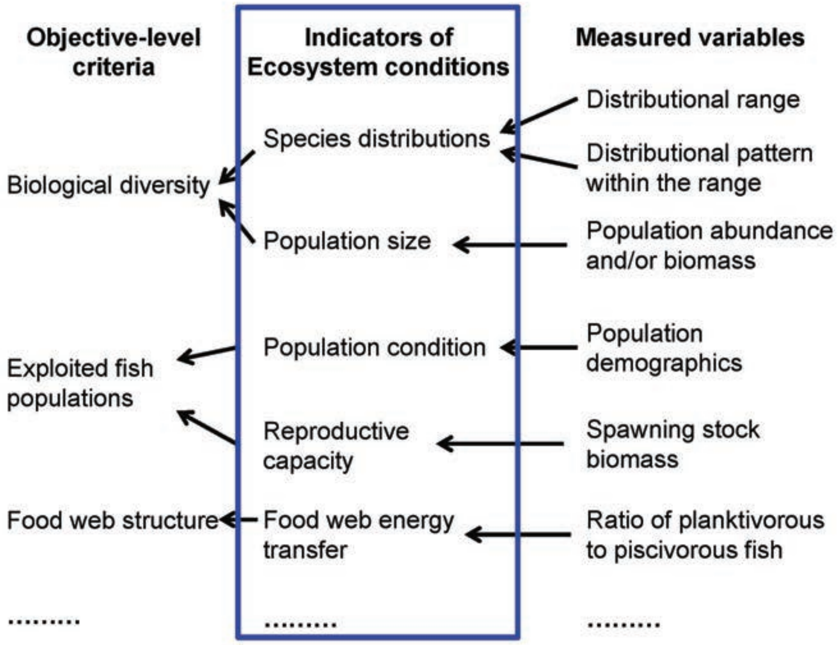

Fig. 6.1 Example of how working back from sets of measurable variables can be used to develop a reduced set of indicators of ecosystem conditions to report on status and trends and to inform the objective-level (or management) criteria.

Broad-scale activities and pressures for consideration in suites of indicators for North Pacific marine ecosystems are shown in Table 5.4, and potential indicators for ecosystem-based fisheries management, integrated from global studies on this topic, are presented in Table 5.3. To this list must be added potential indicators for semi-enclosed marine systems, since the review of regional pressures (Section 3) and the case studies (Section 4) demonstrate that pressures can be more numerous and therefore, with more complex interactions, in coastal and bounded seas than in the open ocean. Kroeze *et al*. (2009) provide a list of potential indicators and their associated drivers for semi-enclosed seas relating to human activities in adjacent drainage basins, human activities in the semi-enclosed seas themselves, and broad-scale external pressures (Table 6.1).

Table 6.1 Potential indicators to assess anthropogenic and natural influences on semi-enclosed marine basins. Modified after Kroeze *et al*. (2009). Reproduced with permission of Island Press.

Pressure	Potential indicator
Human activities in adjacent river basins	
Sediment input	Sediment input to the sea
Habitat loss	Coastal area use for human activities
Eutrophication	Nutrient export by rivers
Shoreline development	Length of shoreline developed
Pollutants	Intensity of chemical industrial activities along the coast
Human activities in semi-enclosed marine systems	
Alien taxa	Intensity of long-distance shipping
Overexploitation	Fishing intensity
Food web alterations	Functional biodiversity
Non-living resource extraction	Area used for resource extractions
External pressures	
Sea level rise	Sea level
Circulation	Current patterns and speed; precipitation
Temperature	Regional temperature
Wind changes	Regional wind patterns
UV changes	UV radiation
Acidification	Atmospheric CO_2

The European Union has done extensive work on potential indicators to describe the environmental status of European seas (see sub-section 5.5.5). Their Commission Decision (EU Commission Decision 2017) codifies criteria and methods for assessing pressures and impacts in marine environments due to biological, physical, substances, litter, and energy pressures. Working Group 28 examined these EU indicators and produced a reduced list of potential indicators for the North Pacific (Table 6.2). This list includes an assessment by Working Group 28 of whether non-additive interactions among pressures (fishing and nutrients were used in the Working Group's assessment to provide a concrete example) may complicate the interpretation of each indicator.

Table 6.2 Selection of indicators proposed by the European Union to assess environmental status of marine ecosystems (derived in part from EU Commission Decision, 2017).

Category or Objective	Criteria/Aspect	Indicator	Possibly complicated by non-additive interactions among pressures
Biological diversity	1.1 Species distribution	1.1.1 Distributional range	yes
Biological diversity	1.1 Species distribution	1.1.2 Distributional pattern within the latter	no
Biological diversity	1.1 Species distribution	1.1.3 Area covered by the species (for sessile/benthic species)	yes
Biological diversity	1.2 Population size	1.2.1 Population abundance and/or biomass	yes
Biological diversity	1.3 Population condition	1.3.1 Population demographic characteristics	no
Biological diversity	1.3 Population condition	1.3.2 Population genetic structure	no
Biological diversity	1.4 Habitat distribution	1.4.1 Distributional range	no
Biological diversity	1.4 Habitat distribution	1.4.2 Distributional pattern	no
Biological diversity	1.5 Habitat extent	1.5.1 Habitat area	no
Biological diversity	1.5 Habitat extent	1.5.2 Habitat volume, where relevant	no
Biological diversity	1.6 Habitat condition	1.6.1 Condition of the typical species and communities	yes
Biological diversity	1.6 Habitat condition	1.6.2 Relative abundance and/or biomass, as appropriate	yes
Biological diversity	1.6 Habitat condition	1.6.3 Physical, hydrological and chemical conditions	yes
Biological diversity	1.7 Ecosystem structure	1.7.1 Composition and relative proportions of ecosystem components (habitats, species)	yes
Exploited fish and shellfish	3.2 Reproductive capacity of the stock	3.2.1 Spawning Stock Biomass (SSB)	yes
Exploited fish and shellfish	3.2 Reproductive capacity of the stock	3.2.2 Biomass indices	yes
Exploited fish and shellfish	3.3 Population age and size distribution	3.3.1 Proportion of fish larger than the mean size of first sexual maturation	yes
Exploited fish and shellfish	3.3 Population age and size distribution	3.3.2 Mean maximum length across all species found in research vessel surveys	yes
Exploited fish and shellfish	3.3 Population age and size distribution	3.3.3 95% percentile of the fish length distribution observed in research vessel surveys	yes
Exploited fish and shellfish	3.3 Population age and size distribution	3.3.4 Size at first sexual maturation	yes

Table 6.2 Continued.

Category or Objective	**Criteria/Aspect**	**Indicator**	**Possibly complicated by non-additive interactions among pressures**
Food webs	4.1 Productivity of key species or trophic groups	4.1.1 Performance of key predator species using their production per unit biomass	yes
Food webs	4.2 Proportion of selected species at the top of food webs	4.2.1 Large fish (by weight)	yes
Food webs	4.3 Abundance/distribution of key trophic groups/species	4.3.1 Abundance trends of functionally important selected groups/species	yes
Human-induced eutrophication	5.1 Nutrient levels	5.1.1 Nutrients concentration in the water column	no
Human-induced eutrophication	5.1 Nutrient levels	5.1.2 Nutrient ratios (silica, nitrogen and phosphorus)	no
Seafloor integrity	6.1 Physical damage, having regard to substrate characteristics	6.1.1. Type, abundance, biomass and areal extent of relevant biogenic substrate	yes
Seafloor integrity	6.1 Physical damage, having regard to substrate characteristics	6.1.2 Extent of the seabed significantly affected by human activities for the different substrate types	yes
Seafloor integrity	6.2 Condition of benthic community	6.2.1 Presence of particularly sensitive and/or tolerant species	yes
Seafloor integrity	6.2 Condition of benthic community	6.2.2 Multi-metric indices assessing benthic community condition and functionality	yes
Seafloor integrity	6.2 Condition of benthic community	6.2.3 Proportion of biomass or number of individuals in the macrobenthos above specified length/size	yes
Seafloor integrity	6.2 Condition of benthic community	6.2.4 Parameters describing the characteristics of the size spectrum of the benthic community	yes

Numbers refer to sequence numbers for category/objective and indicator within objectives. Assessment of whether the interpretation of the potential indicator may be complicated by multiple non-additive interactions among pressures has been added based on Working Group 28 discussions.

The United Nations Environment Programme's (UNEP) Northwest Pacific Action Plan (NOWPAP) is an intergovernmental-level activity which includes China, Japan, Korea, and Russia. It applied the general approach used by the European Union and identified five significant marine ecological problems. For each, it identified high-level indicators and sets of operational indicators which can be used to describe the condition of their ecosystems (Table 6.3; Shul'kin *et al*. 2017).

Table 6.3 Marine ecosystem indicators proposed for the UNEP Northwest Pacific Region. Modified after Shul'kin *et al*. (2017). Reproduced with permission of Springer.

Environmental objectives	**High-level indicators**	**Operational indicators**
Biological diversity	Species diversity of marine mammal and birds	Population, distribution, demographics of marine mammals
		Reproduction of populations of key species of birds
	Species, age, size structure of fish	Ratio of catch to total biomass
		Biomass of spawning population
		Proportion of large fish in catch
	Distribution and state of benthic and pelagic communities	Habitats
		State of typical species and communities
		Hydrological and chemical conditions of habitats
Introduced (and invasive) species	Population and state of introduced species	Changes in numbers and of spatial distributions of introduced species
	Environmental impacts of introduced species	Interactions of local and introduced species
Anthropogenic eutrophication	Concentrations of biogenic elements	Concentrations of biogenic elements in water column
		Relationships among Si, N, P
	Direct effects of biogenic enrichment	Concentration of chlorophyll in water column
		Composition and abundance of toxic algae
		Abundances of opportunistic macroalgae
	Indirect effects of enrichment	Seasonal hypoxia and low oxygen zones
Pollution	Concentration of pollutants	Concentration of pollutants in sediments and water
	Influence of pollutants	Levels of pollutant impacts on ecosystems
Marine litter	Characteristics of litter in marine and coastal environments	Changes in amounts and composition of litter driven ashore
		Amount of litter in water column and sea bottom
		Size, distribution, composition of micro-particles
	Impact of litter on marine biota	Amount and composition of litter absorbed by organisms

In the United States, sets of ecosystem indicators have been proposed for the California Current System and Alaskan ecosystems derived in part from their Integrated Ecosystem Assessment processes (sub-section 2.2.7). The indicators selected are similar in general, but differ in specifics among ecosystems because of their different characteristics. For example, many indicators used in the California Current System relate to various features of upwelling and pelagic fishes (Table 6.4), compared with those in use in Alaskan ecosystems (Table 6.5).

For Canada's Pacific coast, Okey (2018) described an expert-based, adaptive, and hierarchical approach to identifying indicators which represent the objectives of healthy marine ecosystems and community partnerships for monitoring and management of local ecosystems. This approach involved over 200 participants evaluating 1,035 candidate indicators, guided by a panel of topic experts, literature reviews, and surveys. Okey (2018) concluded that the resulting sets of representative indicators (Fig. 6.2) could be used as a basis to select indicators that are appropriate for specific ecosystems at specific spatial scales and locations.

Table 6.4 Marine ecosystem indicators used in the California Current System Integrated Ecosystem Assessments. Modified after Harvey *et al.* (2014).

Activity	**Indicator**
Physical, chemical, climate indicators	Multivariate El Niño Index Northern Oscillation Index North Pacific Gyre Oscillation Pacific Decadal Oscillation Eddy kinetic energy Upwelling Index Sea level height Sea surface temperature Meridional winds Pycnocline depth Pycnocline strength $NO_2 + NO_3$ at 150 m Dissolved oxygen at 150 m Spring transition Julian date Length of upwelling season Total upwelling magnitude Monthly total copepod biomass Monthly copepod community composition Monthly northern copepod biomass anomaly Monthly southern copepod biomass anomaly Multivariate Ocean Climate Index

Table 6.4 Continued.

Activity	**Indicator**
Fishery removals	Total annual fisheries landings Commercial fisheries: Groundfish landings (w/o hake) Pacific hake landings Coastal pelagic species landings Highly migratory species landings Salmon landings Crab landings Shrimp landings Shellfish landings Other species landings Total trawl landings Shrimp trawl landings Hook and line landings Net gear landings Pot and trap landings Troll landings Other miscellaneous gear landings Total fishing mortality – Groundfish (w/o hake) Total fishing mortality – Pacific hake
Fishing effects on habitat	Total distance disturbed Disturbance to shelf, hard substrate Disturbance to shelf, mixed substrate Disturbance to shelf, soft substrate Disturbance to upper slope, hard substrate Disturbance to upper slope, mixed substrate Disturbance to upper slope, soft substrate Disturbance to lower slope, hard substrate Disturbance to lower slope, soft substrate
Aquaculture	Aquaculture production (finfish) Aquaculture production (shellfish)
Atmospheric pollution	Sulfate deposition
Benthic structures	Number of offshore oil and gas wells
Coastal engineering	Coastal population
Commercial shipping	Volume of water disturbed in transit
Dredging	Volume of dredged sediments
Freshwater retention	Volume of freshwater stored behind dams
Inorganic pollution	Toxicity-weighted chemical releases
Invasive species	Tons of cargo moved through ports
Light pollution	Average nighttime light
Marine debris	Predicted debris counts

Table 6.4 Continued.

Activity	**Indicator**
Nutrient input	Nitrogen + Phosphate fertilizer applications
Ocean-based pollution	Volume of water disturbed and cargo moved by shipping activities
Oil and gas activity	Oil and gas production
Organic pollution	Toxicity-weighted pesticide concentrations
Power plants	Volume of saline water withdrawals
Recreation	Beach attendance
Seafood demand	U.S. consumption of fisheries products
Sediment retention	Volume of freshwater impoundments
Trophic structure, pelagic community	Northern copepod biomass anomaly *Aurelia* abundance *Chrysaora* abundance *Aequorea* abundance
Trophic structure, demersal community	Groundfish mean trophic level Scavenger:total biomass ratio Crab scavengers:total biomass ratio Finfish scavengers:total biomass ratio
Biodiversity, pelagic community	Copepods, Simpson diversity Copepods, species richness Ichthyoplankton, Simpson diversity Ichthyoplankton, species number Coastal pelagic fish, Simpson diversity Coastal pelagic fish, species number
Biodiversity, demersal community	Groundfish, Simpson diversity Groundfish, species richness

Table 6.5 Marine ecosystem indicators used in three Alaskan marine ecosystems. Modified after Zador *et al*. (2017). Reproduced with permission of Oxford Journals.

Ecosystem	Category	Indicator
Eastern Bering Sea	Climate	North Pacific index
	Oceanography	Ice retreat index
	Zooplankton	Euphausiid biomass
	Benthic	Motile epifauna biomass
	Fish	Benthic forager biomass
	Fish	Pelagic forager biomass
	Fish	Apex predator biomass
	Seabirds	Multivariate seabird breeding index
	Marine mammals	Northern fur seal pups
	Humans	Area disturbed by trawls
Aleutian Islands	Climate	North Pacific index
	Zooplankton/ seabirds	Auklet reproductive success
	Forage fish/ seabirds	Gadids, sand lance, Ammodytes, Hexagrammids
	Fish	Pelagic forager biomass
	Fish	Apex predator biomass
	Marine mammals	Sea otters
	Marine mammals	Steller sea lion non-pups
	Humans	Area disturbed by trawls
	Humans	K-12 school enrollment
Gulf of Alaska	Climate	Pacific decadal oscillation
	Oceanography	Freshwater input
	Zooplankton	Mesozooplankton biomass
	Benthic	Copepod community size
	Fish	Motile epifauna biomass
	Forage fish	Capelin
	Fish	Apex predator biomass
	Seabirds	Black-legged kittiwake reproductive success
	Marine mammals	Steller sea lion non-pups
	Humans	Population

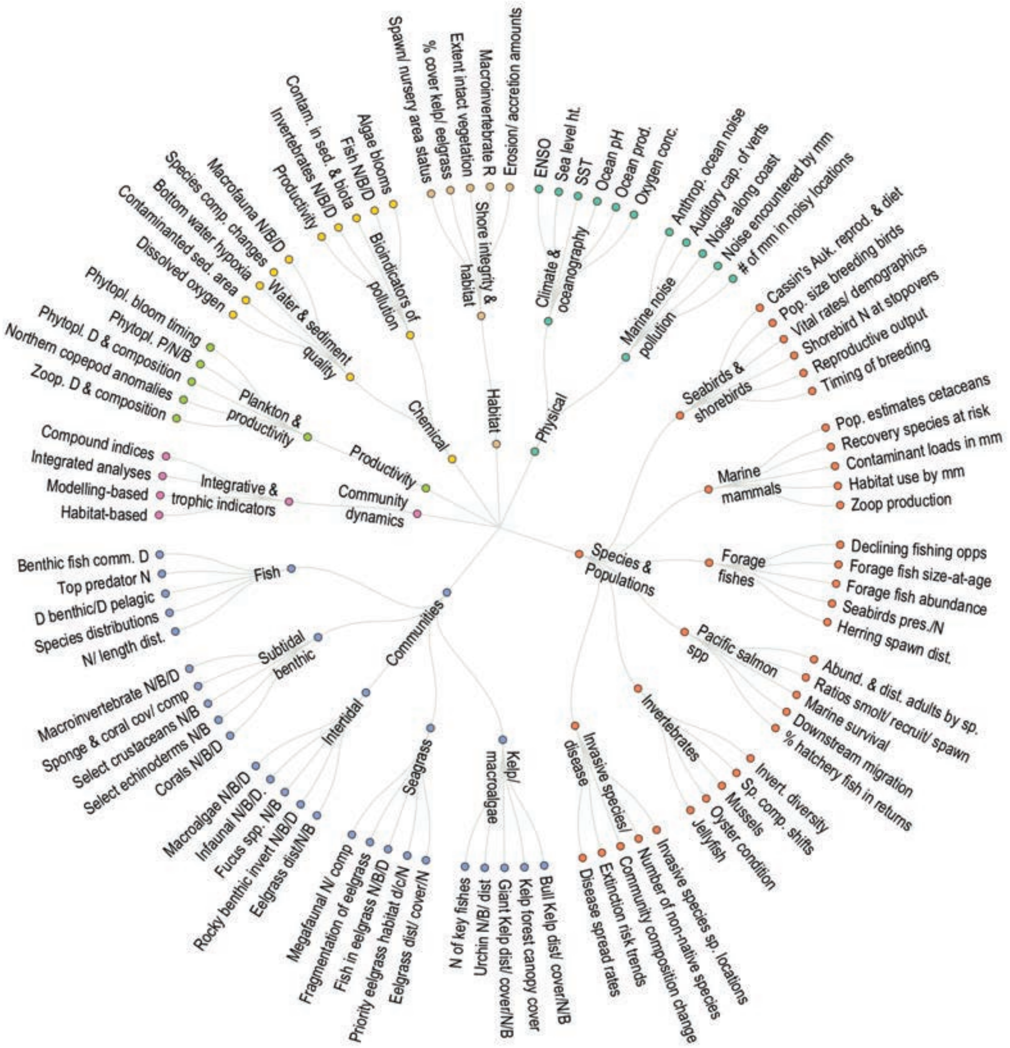

Fig. 6.2 Radial dendrogram of the elements (centre circle), ecosystem features (intermediate circle), and top 5 ranked indicators (outer circle) identified by participating experts as representing the health of Pacific Canadian marine ecosystems. N: number of individuals; B: biomass; D: species diversity. From Okey (2018). Reproduced with permission of Elsevier.

Contaminants can be important pressures in North Pacific marine ecosystems. Contaminants can be from anthropogenic sources, acutely toxic or sub-lethal and persistent, and from point or dispersed locations. They enter the ocean as a result of long-range transport or from local discharges, and usually occur at higher concentrations in coastal areas and semi-enclosed seas than in remote offshore regions. Contaminants are typically grouped into: persistent bioaccumulative and/or toxic contaminants (which include polychlorinated biphenyls (PBCs) and related compounds), hydrocarbons, metals of concern such as mercury, lead, cadmium, tributyltin, and radionuclides, plastics and marine debris, and biological pollution such as bacteria contamination, harmful algal blooms, *etc*. (Ross, 2014).

Many indicators have been proposed globally to monitor and assess contaminants in marine environments. Such indicators can be derived from several physical substrates, such as concentrations in air, water, and sediments, and in biological sources such as finfish and shellfish, the benthos, seaweeds, marine mammals, and seabirds (Ross, 2014; Table 6.6). Seabirds have been particularly useful as indicators and monitors of chemical contaminants in North Pacific regional seas. The glaucous-winged gull (*Larus glaucescens*) has been selected by Environment Canada as a marine indicator species for long-term monitoring of persistent contaminants in Pacific Canada (Davis *et al*., 2017). In Japan, the streaked shearwater (*Calonectris leucomelas*) has been used to track POPs among several regional seas and the open Northwest Pacific (Ito *et al*., 2013). Similarly, marine mammals have been used to monitor trends in PCBs and related chemicals in the Salish Sea between Canada and the United States (Ross *et al*., 2013). Sediment cores have been particularly useful at showing the increasing and decreasing temporal trends of contaminants in selected coastal locations (*e.g*., Johannessen and Macdonald, 2009). Shellfish have also been used extensively to monitor contaminants (*e.g*., in mussels and sea urchins, Lukyanova *et al.*, 2009, 2017). Brown and Takada (2017) provide a brief overview of selected indicators of marine pollution in the North Pacific Ocean.

Table 6.6 Example indicators for selected contaminants in PICES member countries. Modified from Ross (2014).

	Indicator
Canada	Eggs of fish-eating birds (storm petrels, alcids, cormorants), feathers, regurgitate, blood Marine mammal (harbour seals) biopsies (skin/blubber) Sediment (surficial, sediment cores)
China	Shellfish monitoring for organotins (mussels and oysters) PAH fingerprints in sediments Antibiotics and antibiotic resistance in marine aquaculture waters and sediments, and in the harvested product PBDEs in environmental media
Japan	Contaminant measurements in sediments
Korea	Concentrations and congener patterns of POPs and biomarker responses measured in: mussels/oysters, fish, seabirds, marine mammals Abundance of microplastics (< 1 mm) and mesoplastics (> 1 mm, < 25 mm) in: stranded lines onshore, microlayers at sea, subtidal sediments, marine organisms
Russia	Shellfish Fish (flatfish) Marine mammals and seabirds Sediments
USA	Shipboard measurements to research magnitude of the flux of chemicals to the Pacific Ocean, as well as characterize their spatial distribution Development of indicators or study designs aimed at monitoring or characterizing episodic events No standardized methods currently available for microplastics characterization

PAH = polycyclic aromatic hydrocarbon, PBDEs = polybrominated diphenyl ethers, POPs = persistent organic pollutants

Some work has been done to consider the potential interactions of contaminants with other anthropogenic pressures (*e.g.*, climate change). Alava *et al*. (2016) discuss how climate change-associated impacts (including ocean acidification) on the structure and function of marine food webs are likely to affect the transport, fate, and impacts of contaminants. Such interactions may alter the bioaccumulation of fat-soluble persistent organic pollutants, and methyl-mercury which binds to proteins. Situations may occur, therefore, in which climate change may lead to increased contaminant exposure, and/or in which contamination leads to increases in susceptibility to the impacts of climate change (Alava *et al*., 2016).

Most of the above indicators relate to static and directly observable (*i.e*., structural characteristics of each ecosystem). Functional characteristics, which relate to how an ecosystem works, can be more difficult to measure. Food webs and the flow of materials and energy among prey and predators across trophic levels, represent perhaps the key functional feature of ecosystems. Modelling and network statistical methods are often used to derive the characteristics of food webs as they are difficult, and sometimes impossible, to observe directly.

Several indicators of the functional properties of marine food webs have been proposed. Tam *et al*. (2017a) evaluated over 60 potential indicators using an expert workshop approach to identify those suitable to represent the structure, function, and resilience of marine food webs. Their final suite of indicators relates to the primary productivity required to sustain a fishery, the productivity of seabirds and charismatic megafauna, zooplankton, and several integrated trophic indicators (Table 6.7). Samhouri *et al*. (2009) used a model-based approach to evaluate the performance of potential ecosystem indicators. They used seven Ecopath with Ecosim food web models (*e.g*., sub-section 2.2.3) built for Northeast Pacific and Baltic marine ecosystems and examined 22 ecosystem attributes, including food web structure and energy cycling. They then correlated these attributes with 27 empirically observable indicators to evaluate performance. They concluded that no single indicator was sufficient to adequately describe the ecosystem attributes and therefore, that a ‘portfolio’ of indicators was needed (Table 6.8).

Table 6.7 Food web indicator groups and specific indicators proposed by Tam *et al*. (2017a). Reproduced with permission of Oxford Journals.

Suggested indicator groups	Indicator	Ecosystem attribute
Guild-level biomass (and production)	Total biomass of small fish	Structural/functional
	Biomass of trophic guilds	
Primary production required to sustain a fishery	Primary production required to support a fishery	Functional
Seabird (charismatic megafauna) productivity	Seabird breeding success	Functional/resilience
Zooplankton size biomass index	Zooplankton spatial distribution and total biomass	Structural
Integrated trophic indicators	Mean trophic level of the catch	Structural/resilience
	Mean trophic index of the community	
	Mean trophic level of the community	
	Mean trophic links per species	

They found that, in contrast to Tam *et al*. (2017a), seabird biomass did not show a strong correlation with most ecosystem attributes (in the seven models they examined), nor did the trophic level of the catch or the total catch weight. The 'best' indicators were those relating to lower trophic level functional groups and functional groups with higher productivity to biomass ratios, such as the biomass of detritivores, flatfish, phytoplankton, jellyfish, and benthic invertebrates, and the proportion of non-commercial species (Samhouri *et al*., 2009).

As noted above, people are key parts of marine ecosystems, under the marine social-ecological systems concept. People are included in the above lists of potential ecosystem indicators in use by several agencies, and include measures beyond fisheries catch (*e.g*., human population and school enrollment are among the indicators included in the Alaskan ecosystem assessments, Table 6.5). As part of its contributions to the PICES Ecosystem Status Report, the Human Dimensions Committee is assembling time series of a number of human-related indicators of the North Pacific. These indicators are built upon those in use by the United States (*e.g*., Felthoven and Kasperski, 2013; Jepson and Colburn, 2013) and are planned to be expanded to the other PICES member countries. They include: 1) the quantity and value of catches and landings of seaweeds, fish, and invertebrates, 2) the quantity and value of

Table 6.8 Best indicator for each ecosystem attribute derived from comparisons among seven Ecopath with Ecosim food web models constructed for the Northeast Pacific and Baltic Sea. From Samhouri *et al*. (2009). Reproduced with permission of Springer.

Attribute	**Best indicator**
Path length	Detritivores
Finn's cycling index	Herbivores
Predator cycling index	Phytoplankton
Total biomass	Zooplanktivorous fish
Total consumption	Detritivores
Net primary production	Phytoplankton
Total production	Phytoplankton
Total respiration	Benthic invertebrates
Net primary production/Total respiration	Detritivores, forage fish/jellyfish
Net primary production/Total biomass	Zooplanktivorous fish
Total respiration/Total biomass	Demersal fish
Target group biomass	Proportion of non-commercial species
Ecosystem reorganization index	Benthic invertebrates/flatfish
Piscivorous fish reorganization index	Slope of log(biomass) *vs*. trophic level
Zooplanktivorous fish reorganization index	Slope of log(biomass) *vs*. trophic level
Invertivore reorganization index	Benthic invertebrates
Herbivore reorganization index	Herbivores
Average relative change in entire ecosystem	Proportion of non-commercial species
Kemptons Q diversity	Slope of log(biomass) *vs*. trophic level/jellyfish
Shannon diversity	Slope of log(biomass) *vs*. trophic level
Simpson diversity	Marine mammals
Mean trophic level	Demersal fish

mariculture of seaweeds, fish, and invertebrates, 3) the number and power of fishing vessels by gear type, length, and tonnage, 4) catch per unit of effort by gear type and target fishery, 5) numbers of commercial fishers, 6) injury and mortality rates of commercial fishers, 7) income to fishers, 8) number of fishing ports, 9) number of fish processing plants, 10) number of fishing communities, 11) number of fishing households, 12) per capita consumption of seaweeds, fish, and invertebrates, and 13) the amount and value of seafood exports and imports (Criddle and Makino, 2013).

Working Group 28 examined all of the above indicators in use or proposed for North Pacific and global marine ecosystems, and derived an integrated set (Table 6.9). These are presented according to theme (*e.g.*, climate, physical environment, *etc*.), sub-theme (*e.g.*, ecosystem structure, biodiversity, *etc*.), whether they are a pressure or response indicator, whether they are derived from observed data or are model-derived, whether they are state or management indicators, and a citation. In addition, the Working Group identified a 'core set' of indicators which is considered to be appropriate for use in all North Pacific marine ecosystems.

Table 6.9 Working Group 28-recommended integrated list of indicators for use in North Pacific marine ecosystems.

Theme and Sub-theme	Indicator *	Pressure (P) or Response (R)	Observed or Model-derived	State or Management	Reference
Climate	**ENSO (Multivariate ENSO Index MEI; Oceanic Niño Index ONI)**	P	O	S	11
	Pacific Decadal Oscillation (PDO)	P	O	S	11
	North Pacific Gyre Oscillation Index (NPGO)	P	O	S	11
	Aleutian Low Pressure Index (ALPI)	P	O	S	13
	North Pacific Index (NPI)	P	O	S	18
	Southern Oscillation Index (SOI)	P	O	S	12
	Arctic Oscillation index	P	M	S	
Physical Environment	**Sea surface temperature (SST) anomalies by season**	P	O	S	11
	Sea level pressure (SLP) anomalies by season	P	O	S	
	Seasonal projections of SST from national multi-model ensemble	P	M	S	
	Winter maximum sea ice area or extent	P	O	S	11
	Freshwater discharge	P	O	S	11
	Upwelling (strength and/or timing)	P	O	S	14, 15
	Transport (currents)	P	O	S	

Table 6.9 Continued.

Theme and Sub-theme	Indicator *	Pressure (P) or Response (R)	Observed or Model-derived	State or Management	Reference
Chemical Environment	**Nitrate**	P, R	O	S	11
	Phosphate	P, R	O	S	11
	Silicate	P, R	O	S	11
	pH	P, R	O	S	11
	Dissolved oxygen	P, R	O	S	11
Contaminants	**Polychlorinated biphenyls (PCBs)**	P, R	O	M	7
	Persistent organic pollutants (POPs)	P, R	O	M	7
	Total mercury	P, R	O	M	7
	Tributyltin (TBT)	P, R	O	M	7
	Toxics in biota (selected species)	P, R	O	M	16
	Swimming beach closures for coliform bacteria contamination	P, R	O	M	16
Biological Environment *Ecosystem structure*	**Harmful Algal Bloom area or frequency (HABs)**	R	O	S, M	
	Habitat-forming species biomass	R	O	S, M	
	Spawning Stock Biomass (SSB of selected species)	R	M	S, M	
	Mean individual fish weight	R	O	S, M	4
	Mean age at first maturation (for selected species)	R	O	S, M	4
	Mean length at first maturity (for selected species)	R	O	S, M	2, 4
	Distribution range (of selected species)	R	O	S	
	Slope of size spectrum	R	M	M	1,2,3,8
Biodiversity	**Species richness**	R	O	M	1,2,3,4,8
	Taxonomic diversity	R	O	M	1, 2, 3, 4
	Number of taxa representing 80% of biomass	R	O	M	1
Food web energy flows	**Chlorophyll a**	R	O	S	
	Crustacean plankton biomass	R	O	S	
	Gelatinous plankton biomass (or volume)	R	O	S	3
	Cephalopod biomass	R	O	S, M	
	Small pelagic fish biomass	R	O	S, M	
	Demersal fish biomass	R	O	S, M	
	Piscivorous fish biomass	R	O	S, M	

Table 6.9 Continued.

Theme and Sub-theme	**Indicator ***	**Pressure (P) or Response (R)**	**Observed or Model-derived**	**State or Management**	**Reference**
Biological Environment *Food web energy flows*	Nekton (at trophic level >3) biomass	R	O	S, M	
	Top predator biomass	R	O	S, M	
	Seabird breeding success	R	O	S, M	8
	Seabird abundance (selected species)	R	O	S, M	17
	Total primary production	R	O	S	1
	Primary production needed to support fisheries removals	R	M	M	8
	Crustacean zooplankton secondary production	R	O	S	
Ecosystem resilience	Mean number of interactions per node	R	M	S	1,3,8,
	Mean trophic links per species	R	O	S	8
	Diet diversity index	R	O	S, M	8
Exploitation of Living Marine Resources *Fishing*	**Total landings**	P, R	O	M	5
	Mean trophic level of landings	R	O	S, M	1, 2, 3, 4, 5, 8
	Taxonomic diversity of landings	R	O	M	
	Landings (biomass) of selected species	P, R	O	M	5, 6
Aquaculture	Aquaculture production (vertebrates, invertebrates)	P	O	M	
Fishing effort	Annual number of vessels that fish	P, R	O	M	9
	Number of days per calendar/ fishing year the fishery is open	P, R	O	M	9
	Annual total number of days spent fishing (“fishing days”)	P, R	O	M	9
	Catch per unit of effort by gear and target fishery	P, R	O	M	10
	Numbers of commercial fishers	P, R	O	M	10
	Number of fish processing plants	P, R	O	M	10
	Per capita consumption of seafood	P, R	O	M	10

Table 6.9 Continued.

Theme and Sub-theme	Indicator *	Pressure (P) or Response (R)	Observed or Model-derived	State or Management	Reference
Social and Economic *Landings revenue*	Annual total ex-vessel revenue	R	O	M	9
	Average price (selected species)	R	O	M	9
	Revenue per fishing trip	R	O	M	9
	Revenue per fishing day	R	O	M	9
	Value and amounts of seafood exports and imports	R	O	M	10
Other marine activities	Shipping	P	O	M	11
	Hydrocarbon-related activities	P	O	M	11
	Coastal engineering/length of shoreline hardening	P	O	M	11,16

* Indicators in **bold** are part of the recommended ‘core set’ of indicators for all North Pacific marine ecosystems.

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6.3 Toolbox 2: Indicator selection methods

Section 6.2 presented lists of indicators recommended for use globally and in North Pacific marine ecosystems, and concluded with an integrated list and core set recommended by Working Group 28. This core set of indicators is useful in itself, in particular to coordinate data collection and time series comparisons among North Pacific ecosystems. In the Terms of Reference for Working Group 28, however, there is the question of which of the indicators presented in Table 6.9 will be useful to represent ecosystem responses to multiple pressures. This section discusses several tools which can be used to help select indicators which are appropriate for a particular region, ecosystem, and set of multiple pressures, from those presented in Table 6.9 (or any other list of possible indicators).

The first question in selecting appropriate indicators for multiple pressures is whether data are available. If there are no measured data or model outputs for a particular indicator, then its use can only be conceptual, or perhaps its potential effect modelled in sensitivity studies. Table 6.10 presents an assessment by Working Group 28 of the availability in PICES member countries of broad sets of data suitable to begin populating the indicators proposed in Table 6.9, and Table 6.11 presents a similar assessment specifically for biological indicators.

The next question is whether the potential indicators may actually relate to the issues and pressures under investigation. Criteria for indicator selection have been proposed by Rice and Rochet (2005) and other authors. Table 6.12 presents the criteria proposed by Tam *et al.* (2017a; see also Section 5, Table 5.1). Not all of these criteria need to be met for an indicator to be useful, although to some extent the importance or priority of criteria follow the order presented in Table 6.12.

Table 6.10 Availability of selected broad-scale indicators for PICES member countries as identified by Working Group 28.

Indicators, activities, and stressors	**Canada**	**Japan**	**Russia**	**USA**	**High Seas**
Environmental stressors/indicators					
Temperature	Y,Y,Y*	Y,Y,Y	Y,Y,Y	Y,Y,Y	Y,Y,Y
Sea ice	N/A	Y,Y,Y	Y,Y,Y	Y,Y,Y	N/A
Chl-*a*	Y,Y,Y	Y,Y,Y	Y,Y,Y	Y,Y,Y	Y,Y,Y
Nutrients	Y,Y,S	Y,Y,S	Y,Y,S	Y,Y,S	Y,Y,S
River discharge	Y,Y,Y	Y,Y,Y	S,Y,N	Y,Y,Y	N/A
Toxic contaminants	Y,S,S	Y,S,S	Y,S,S	Y,S,S	S,S,S
Large scale climate index (*e.g.*, PDO)	Y,Y,Y	Y,Y,Y	Y,Y,Y	Y,Y,Y	Y,Y,Y
pH	Y,S,S	Y,S,S	Y,S,S	Y,S,S	Y,S,S
Oxygen	Y,Y,S	Y,Y,S	Y,Y,S	Y,Y,S	Y,Y,S
Human activities and stressors					
Fishing	Y,Y,Y	Y,Y,Y	Y,Y,Y	Y,Y,Y	S,S,S
Oil and gas	N,N,N	N,N,N	Y,Y,S	Y,Y,S	N,N,N
Military activity	N,N,N	N,N,N	N,N,N	N,N,N	N,N,N
Wave/Wind/Tidal	Y,Y,Y	Y,Y,Y	Y,Y,Y	Y,Y,Y	Y,Y,Y
Shipping	Y,Y,Y	Y,Y,Y	Y,Y,Y	Y,Y,Y	Y,Y,Y
Coastal engineering	Y,S,S	Y,S,S	Y,N,S	Y,N,S	N/A
Aquaculture	Y,S,S	Y,S,S	Y,S,S	Y,S,S	N/A
Ecotourism	Y,S,S	Y,S,S	Y,S,S	Y,S,S	N/A
Land-based pollution	Y,S,S	Y,S,S	Y,S,S	Y,S,S	N/A
Socio-economic-political					
Seafood demand	S,S,S	S,S,S	S,S,S	S,S,S	N/A
Coastal population trends	Y,Y,Y	Y,Y,Y	Y,Y,Y	Y,Y,Y	N/A
Marine employment	S,Y,Y	Y,Y,Y	S,Y,Y	Y,Y,Y	N/A
Marine revenue	S,Y,Y	Y,Y,Y	S,Y,Y	Y,Y,Y	N/A
Marine exports/domestic consumption	S,S,N	S,S,N	S,S,N	S,S,N	N/A
Participation/stakeholder involvement	S,N,N	S,N,N	S,N,N	S,N,N	N/A
Governance	Y,N,N	Y,N,N	Y,N,N	Y,N,N	Y,N,N
Happiness	S,N,N	S,N,N	S,N,N	S,N,N	N/A
Satisfaction with ocean status	S,N,N	S,N,N	S,N,N	S,N,N	N/A
Community vulnerability	N,N,N	S,N,S	N,N,N	Y,Y,S	N/A
Coastal infrastructure	Y,N,S	Y,N,S	Y,N,S	Y,N,S	N/A

* Each cell contains three responses representing: the existence of data (left), availability of time series data (center), and spatial extent of data (right). Y = Yes, N = No, S = Some, N/A = Not applicable.

Table 6.11 Availability of selected biological indicators for PICES member countries as identified by Working Group 28.

		Canada	**China**	**Japan**	**Korea**	**Russia**	**USA**
Relative biomass	Gelatinous zooplankton	N,N*	Y,N	N,N	Y,Y	Y,Y	Y,Y
	Cephalopods	N,N	Y,N	Y,Y	Y,Y	Y,Y	N,N
	Small pelagic fishes	Y,Y	Y,Y	Y,Y	Y,Y	Y,Y	Y,Y
	Scavengers	N,S	N,N	N,N	S,S	Y,Y	N,Y
	Demersals	Y,Y	Y,Y	Y,Y	Y,Y	Y,Y	N,Y
	Piscivores	Y,Y	Y,Y	Y,Y	Y,Y	Y,Y	N,Y
	Top predators	Y,Y	Y,Y	Y,Y	S,S	Y,Y	Y,Y
Biomass ratios	Piscivore:planktivore	N,Y	Y,Y	Y,Y	Y,Y	S,Y	N,Y
	Pelagic:demersal	N,Y	Y,Y	Y,Y	Y,Y	N,Y	N,Y
	Infauna:epifauna	N,N	N,N	N,N	N,S	N,Y	N,N
Habitat-forming taxa	Nearshore	Y,Y	S,N	S,S	S,S	Y,Y	N,N
	Offshore	N,N	S,N	N,N	S,S	Y,Y	Y,Y
Size spectra		N,N	Y,Y	N,N	Y,Y	Y,Y	Y,Y
Taxonomic diversity		S,S	Y,Y	S,S	Y,Y	S,S	N,Y
Total fishery removals		Y,Y	S,Y	Y,Y	S,S	Y,Y	Y,Y
Max. (or mean) length		N,Y	Y,N	Y,Y	Y,Y	Y,Y	N,Y
Size-at-maturity	Target species	Y,Y	Y,Y	Y,Y	Y,Y	Y,Y	Y,S
	Bycatch	N,N	N,N	N,N	Y,Y	Y,Y	N,S
	Top predators	Y,Y	Y,Y	Y,Y	Y,Y	Y,Y	Y,Y
Trophic level or trophic spectrum of the catch		Y,Y	Y,Y	Y,Y	Y,Y	S,Y	Y,Y
Biophysical characteristics		S,S	Y,Y	Y,Y	Y,Y	S,S	S,S

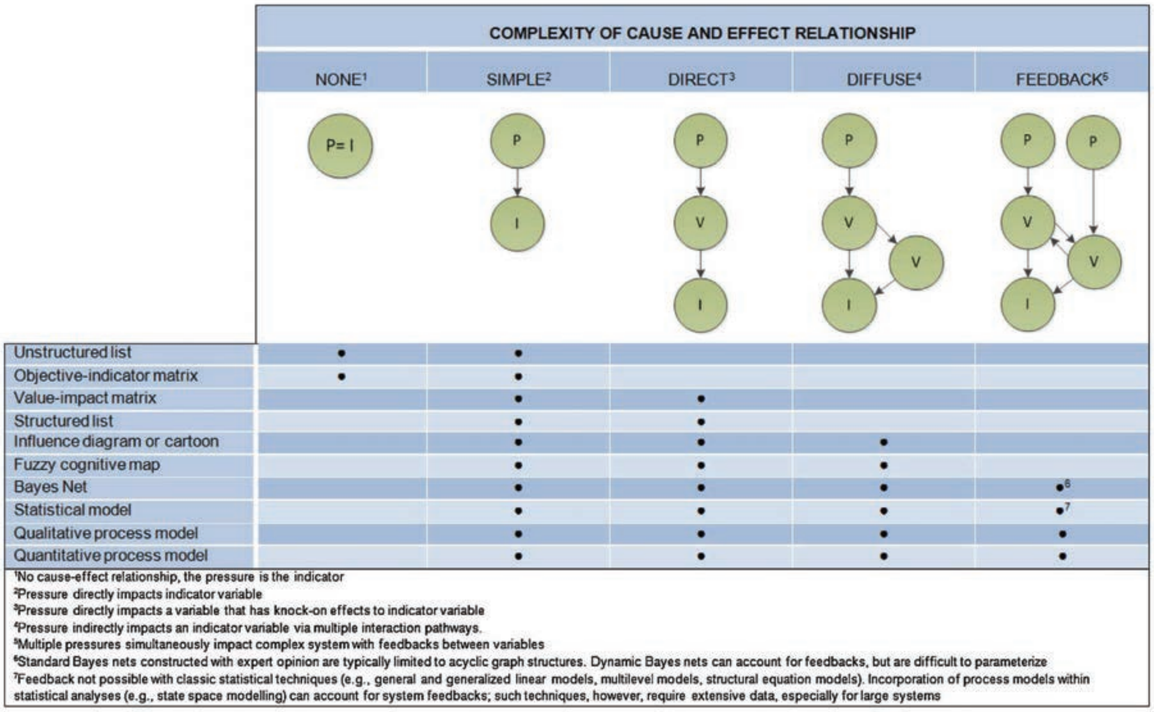
* Each cell contains two responses representing: the existence of data (left), and the availability of time series data (right). Y = Yes, N = No, S = Some.

Table 6.12 Criteria proposed by Tam *et al*. (2017a) to assist in the selection of marine ecosystem indicators.

Criteria	Sub-criteria	Rationale
Availability of underlying data	Existing and ongoing data	Indicators are supported by current or planned monitoring programmes that provide the data necessary to derive the indicator. Ideal monitoring programmes should have a time series capable of supporting baselines and reference point setting. Data should be collected on multiple sequential occasions using consistent protocols.
	Relevant spatial coverage	Data should be derived from an appropriate proportion of the regional sea, at appropriate spatial resolution and sampling design, to which the indicator will apply.
	Relevant temporal coverage	Data should be collected at appropriate sampling frequency and for an appropriate extent of time relevant to the time scale of the process or attribute the indicator describes.
Quality of underlying data	Indicators should be technically rigorous	Indicators should ideally be easily and accurately determined using technically feasible and quality assured methods.
	Reflects changes in ecosystem component that are caused by variation in any specified manageable pressures	The indicator reflects change in the state of an ecological component that is caused by specific significant manageable pressures (*e.g.*, fishing mortality, habitat destruction). The response should be based on theoretical or empirical knowledge, thus reflecting the effect of change in pressure on the ecosystem component in question; signal-to-noise ratio should be high. Ideally the pressure–state relationship should be defined under both the disturbance and recovery phases.
	Magnitude, direction and variance of indicator is estimable	The indicator should exhibit a predictable direction, exhibit clear sense of magnitude of any change, and estimates of precision should allow for detection of trends or distinct locales – requiring that some measure of sampling error or variance estimator is available.
Conceptual basis	Scientific credibility	Scientific, peer-reviewed findings should underpin the assertion that the indicator provides a true representation of process, and variation thereof, for the ecosystem attribute being examined.
	Associated with key processes	The link between the indicator and a process that is essential to food web functioning should be clear and established, based on our current understanding of trophic dynamics.
	Unambiguous	The indicator responds unambiguously to a pressure.
Communication	Comprehensible	Indicators should be interpretable in a way that is easily understandable by policymakers and other non-scientists (*e.g.*, stakeholders) alike, and the consequences of variation in the indicator should be easy to communicate.
Management	Relevant to management	Indicator links directly to mandated management needs, and ideally to management response. The relationship between human activity and resulting pressure on the ecological component is clearly understood.
	Management thresholds targets are estimable	Clear targets that meet appropriate target criteria (absolute values or trend directions) for the indicator can be specified that reflect management objectives, such as achieving good ecological status. Ideally control rules can be developed.
	Cost-effectiveness	Sampling, measuring, processing, analysing indicator data, and reporting assessment outcomes should make effective use of limited financial resources.

Once a set of potential ecosystem indicators has been selected, it is important to be clear about how these indicators may relate to the pressures and the ecosystem responses to these pressures. Section 2 provides an overview of several methods for developing an understanding of these relationships. For example, Hayes *et al*. (2015) developed a structured process to identify indicators for nine marine ecosystems around Australia, based on the DPSIR framework (sub-section 2.2.2). Their process involved using a combination of expert elicitation and data-driven analyses to construct cause and effect networks (Sign Directed Graphs) and then using statistical or model-based analyses to identify suitable indicators. Figure 6.3 provides their summary of appropriate methods to identify indicators based on the complexity of the Sign Directed Graph. As a consequence, this approach is suitable for systems with multiple pressures. Hayes *et al*. (2015) recommend a strategy of model building that combines qualitative models (such as loop analyses, *e.g*., Harvey *et al*., 2016) with quantitative and statistical models, recognizing the strengths and weaknesses of each approach (*e.g*., Fig. 6.3).

Araujo *et al*. (2013) provide an example of the use of a semi-quantitative model to identify leading ecosystem indicators of the survival of juvenile Coho salmon in the Strait of Georgia. They assembled time series of data for several physical and biological variables believed to have potential effects on the early marine survival of these salmon. Their data were drawn from literature, expert opinion, oceanographic models, and *in-situ* observations. They analyzed these data using a probabilistic network method (Bayesian network, or Bayes net; Fig. 6.4). They concluded that the best indicators of early marine survival of Coho salmon in the Strait of Georgia system were the zooplankton biomass anomaly, calanoid copepod biomass, and herring biomass. Bayesian networks are good candidate methods when data from a variety of sources, and of differing qualities, are to be combined, but can perform poorly if too many nodes are included or there are internal cycles in the model.



	COMPLEXITY OF CAUSE AND EFFECT RELATIONSHIP				
	NONE[1]	SIMPLE[2]	DIRECT[3]	DIFFUSE[4]	FEEDBACK[5]
Unstructured list	•	•			
Objective-indicator matrix	•	•			
Value-impact matrix		•	•		
Structured list		•	•		
Influence diagram or cartoon		•	•	•	
Fuzzy cognitive map		•	•	•	
Bayes Net		•	•	•	•[6]
Statistical model		•	•	•	•[7]
Qualitative process model		•	•	•	•
Quantitative process model		•	•	•	•

[1] No cause-effect relationship, the pressure is the indicator

[2] Pressure directly impacts indicator variable

[3] Pressure directly impacts a variable that has knock-on effects to indicator variable

[4] Pressure indirectly impacts an indicator variable via multiple interaction pathways.

[5] Multiple pressures simultaneously impact complex system with feedbacks between variables

[6] Standard Bayes nets constructed with expert opinion are typically limited to acyclic graph structures. Dynamic Bayes nets can account for feedbacks, but are difficult to parameterize

[7] Feedback not possible with classic statistical techniques (e.g., general and generalized linear models, multilevel models, structural equation models). Incorporation of process models within statistical analyses (e.g., state space modelling) can account for system feedbacks; such techniques, however, require extensive data, especially for large systems

Fig. 6.3 Assessment of methods for identifying indicators using a Driver-Pressure-State-Impact-Response (DPSIR) conceptual model. Multiple pressures are explicitly included in the 'Feedback'-type models. P = Pressure, V = Variable, I = Indicator. From Hayes *et al*. (2015). Reproduced with permission of Elsevier.

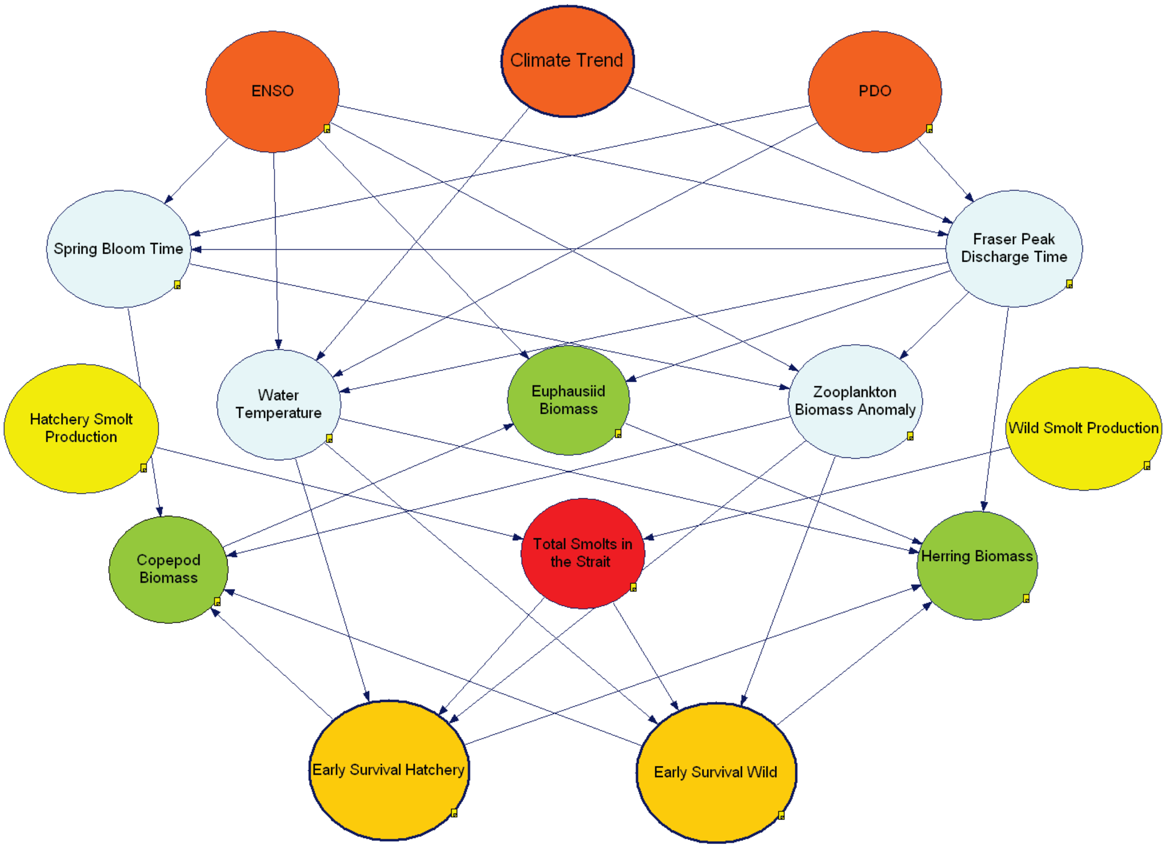


Fig. 6.4 Network structure representing the Strait of Georgia ecosystem and relationships with the early marine survival of Coho salmon. Biological variables are represented in green, physical variables in light blue, and target variables (early marine survival for both hatchery and wild Coho salmon) are represented in dark yellow. Modified after Araujo *et al*. (2013). Reproduced with permission of Elsevier.

Various statistical models have been used in several studies to identify appropriate indicators for marine ecosystems when multiple pressures are involved. However, they have much more stringent data requirements. Perry and Masson (2013) used a DPSIR conceptual model of the Strait of Georgia to identify six response variables which captured regime-like changes in the productivity of the Strait of Georgia ecosystem. They assembled 37 time series, of which 24 were pressure variables (including natural and anthropogenic variables), with sufficiently few missing years over a 40-year period. Potentially important variables, such as zooplankton (*e.g.*, Araujo *et al*., 2013), had to be excluded from the analysis because their data series were too short. They used the statistical method of redundancy analysis, which is a combination of regression with principal components analysis, to analyse 15 natural and human pressure (explanatory) variables against 22 response variables. They concluded that ecosystem-level changes in the productivity of the Strait of Georgia (Fig. 6.5) could be represented by the use of only six of the explanatory variables: sea surface temperature, wind speed, the North Pacific Gyre Oscillation, the human population around the Strait of Georgia, recreational fishing effort, and the number of Chinook salmon released into the Strait of Georgia from local hatcheries. They proposed these six variables as key indicators for the Strait of Georgia ecosystem.

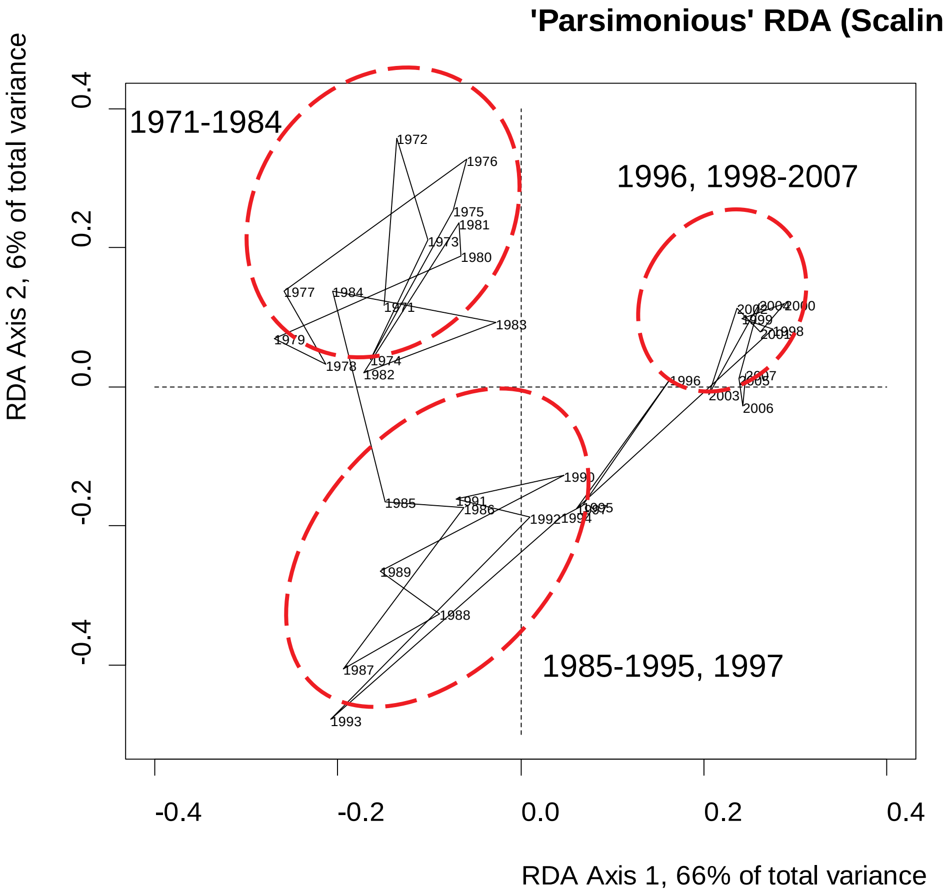


Fig. 6.5 Illustration of the ability of redundancy analysis to reproduce the regime-like behaviour of the Strait of Georgia social-ecological system. The axes represent the first two redundancy axes (similar to the first two axes of a principal components analysis) derived from the six explanatory variables (indicators) of the Strait of Georgia ecosystem. Modified after Perry and Masson (2013). Reproduced with permission of Elsevier.

Random forest and gradient forest methods are another set of statistical techniques that have been used to assess the importance of multiple pressures on ecosystems and to select ecosystem indicators (*e.g.*, Large *et al.*, 2015; Tam *et al.*, 2017b). Random forest methods are useful for quantifying how well pressure variables can predict response variables, whereas gradient forest methods can integrate several random forest analyses over multiple response variables (Tam *et al.*, 2017b). Tam *et al.* (2017b) used these methods to compare six ecological indicators derived from fishery-independent surveys (and therefore, all were specific to fish), with 24 pressure variables (including natural and anthropogenic variables) in four marine ecosystems of the United States. They concluded that the Northeast U.S. and California Current ecosystems were strongly impacted by anthropogenic pressures (indicators), whereas environmental pressures (indicators) dominated in the eastern Bering Sea ecosystem (Fig. 6.6). They also found that regionally-specific indicators, such as ice cover in the eastern Bering Sea, were less important than large-scale climate pressures (indicators) such as the Pacific Decadal Oscillation. Using these methods, Tam *et al.* (2017b) were also able to identify thresholds and reference points for many of the indicators in response to the multiple pressures in their ecosystems.

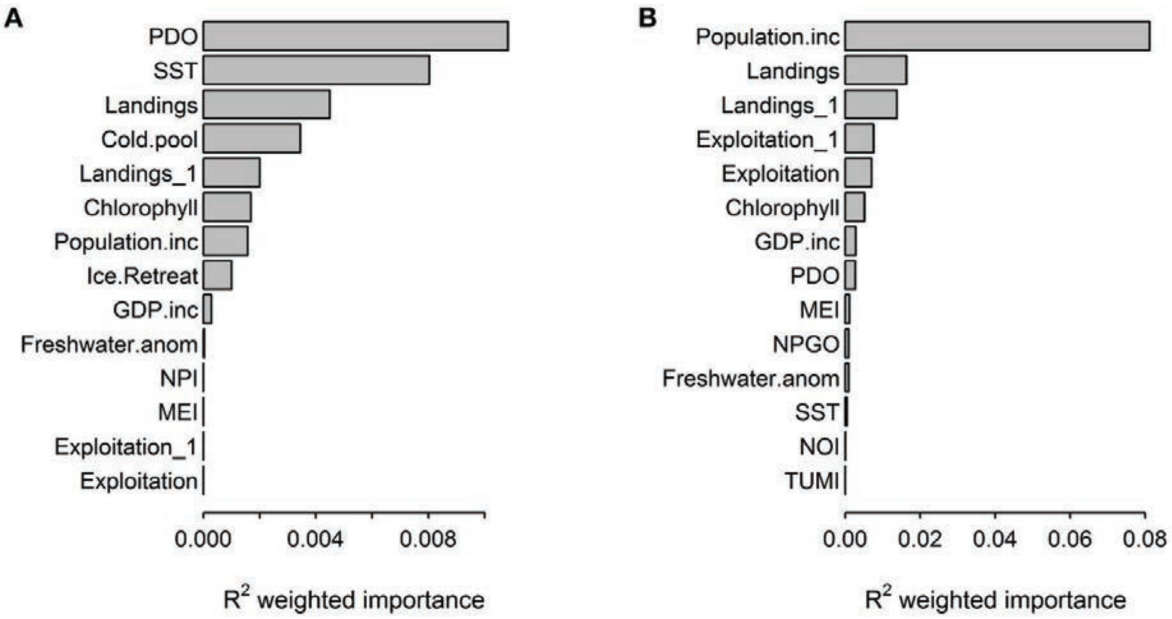


Fig. 6.6 Importance of human and environmental pressure variables across ecological indicator outputs (*x*-axes: R^2 weighted importance) derived from gradient forest analyses for A) the eastern Bering Sea ecosystem, and B) the California Current ecosystem. "Landings_1" and "Expoitation_1" refer to variables with 1-year lags. Modified after Tam *et al.* (2017b). Reproduced with permission of Frontiers Media S.A.

Preikshot *et al.* (2013) provide an example of the use of a quantitative ecosystem simulation model (*e.g.*, sub-section 2.2.3) to identify integrated ecosystem indicators. They developed a model of the Strait of Georgia marine ecosystem which focused on changes in fish, marine mammal, and bird populations over a 60-year period. They found that the annual phytoplankton biomass was a reasonable representation of changes in the production of the entire system, although they also recognized this may be a proxy for processes not included in the model, such as the secondary production of zooplankton, the timing of plankton production relative to the hatching of fish, and/or other environmental factors such as temperature or salinity.

In general, these simulation and statistically-based modelling approaches have similar strengths in their abilities to get directly to the questions and details being considered, but have the disadvantages of often intense data requirements and significant efforts needed to construct and/or run these models.

6.4 Communicating indicators

No discussion of indicator selection and use is complete without some consideration given to how to present the information contained by these indicators. Some indicators simply provide information on the state of an environmental condition over which there is no human control (*e.g.*, temperature or sea ice). Other indicators provide information directly about properties that can be important for management objectives (*e.g.*, fish catch). Other indicators provide information on properties which may be among the objectives for marine ecosystems but which are only indirectly influenced by human actions, such as biodiversity and food web metrics. Clearly communicating the current value of an indicator and its time trend is essential for understanding the condition of the ecosystem and, in the case of multiple pressures, for understanding the extent of influence of each pressure. In addition, being able to interpret and communicate indicators so that decision makers and non-scientists are able to understand the meaning of variations in the indicator is a criterion for a good indicator (Table 6.12). For management-related indicators, being able to communicate its current value also enables the development of targets, limits, and thresholds to achieve some management goal.

A detailed study of how best to communicate indicators is beyond the Terms of Reference for Working Group 28. However, we can point to styles of presentation which show promise. The Integrated Ecosystem Assessment process that is in use by the United States for the Alaskan and California Current ecosystems (*e.g.*, sub-section 2.2.7) has developed a concise style of presentation for multiple indicators (Harvey *et al.*, 2014; Zador *et al.*, 2017; Fig. 6.7). These display key information about the indicator in a concise and intuitive way. Such displays work well when a modest number of indicators are being displayed, but can become overwhelming when many indicators must be presented. In addition, they are not aggregated into higher-level summaries.

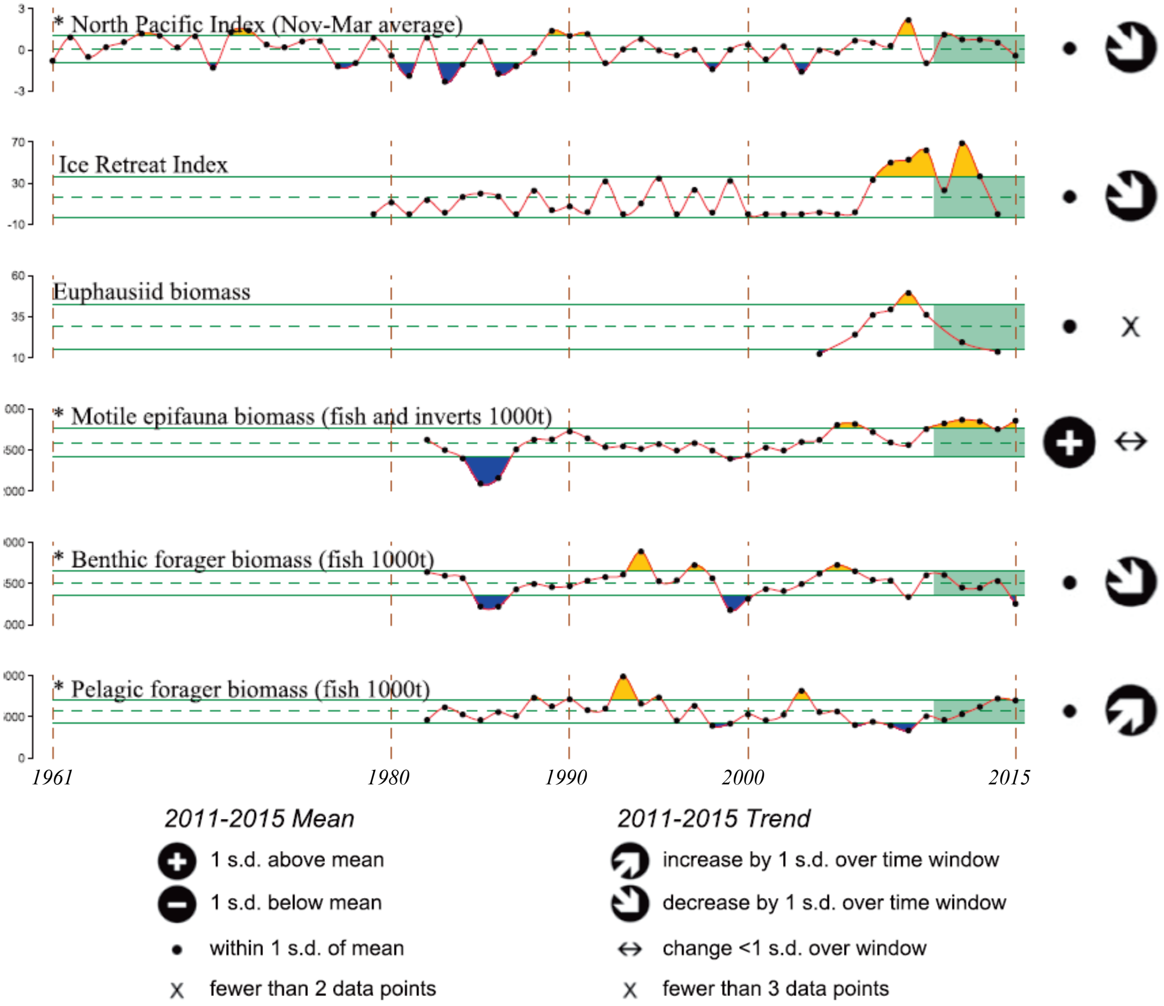


Fig. 6.7 Presentation of values and trends for selected indicators from the eastern Bering Sea report card. Dashed line denotes long-term mean, solid lines denote 1 standard deviation (s.d.), 2011–2015 is shaded green. Modified after Zador *et al*. (2017). Reproduced with permission of Oxford Journals.

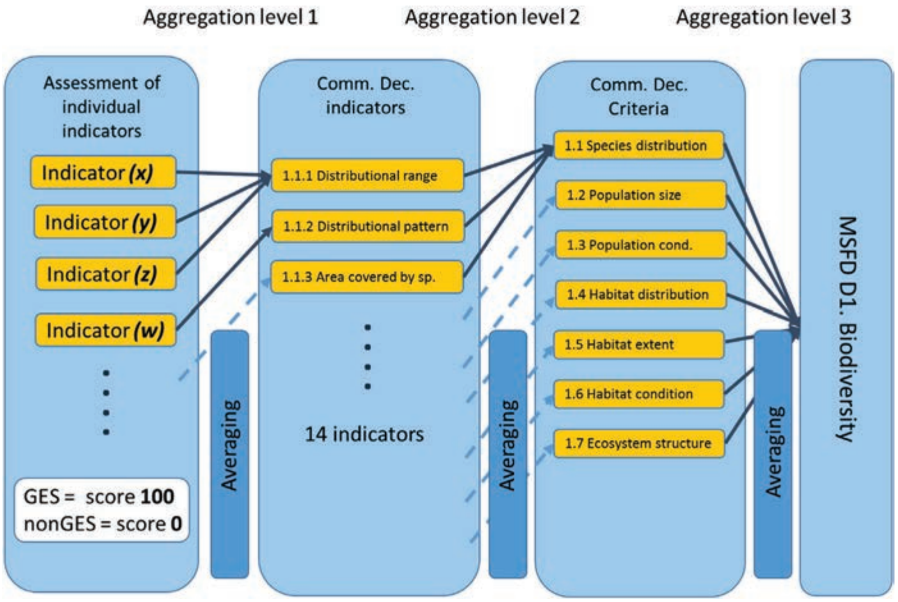


Fig. 6.8 Hierarchical aggregation approach to indicators used in the MARMONI Tool. From Borja *et al.* (2016). Reproduced with permission of Frontiers Media S.A.

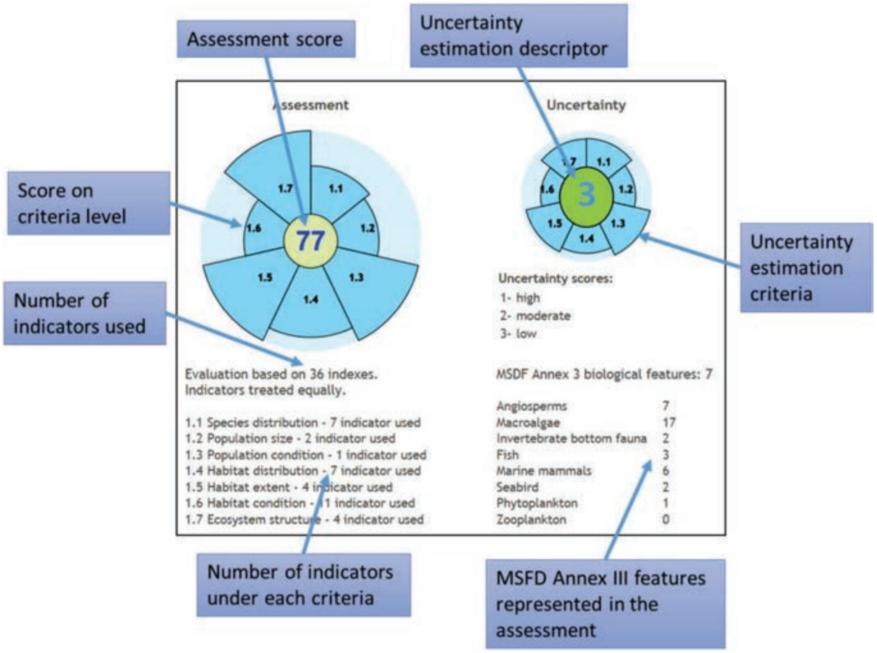


Fig. 6.9 Indicator information as aggregated and displayed by the MARMONI biodiversity assessment tool. From Borja *et al*. (2016). Reproduced with permission of Frontiers Media S.A.

Examples of aggregating indicators into higher level summaries, and how they may be communicated efficiently, are provided by Borja *et al*. (2016). Among the examples they describe is the MARMONI Tool (MSFD Marine Biodiversity Assessment Tool), which is a publically available web-based application (focused on marine biodiversity assessments; http://www.sea.ee/marmoni/; see also Section 5.5.5). This tool uses a hierarchical approach (Fig. 6.8) to average the EU Commission Decision indicators (Table 6.2). A separate process is used to estimate the uncertainty of the assessment. Ultimately, the tool displays information at the descriptor and Community Decision indicator levels, an overall assessment score, and an indication of its uncertainty (Fig. 6.9). More work on efficient displays of indicator values and their interpretation is needed, as is training of users (such as decision makers) on how to use these displays.

6.5 Conclusions and recommendations

This section discusses how to select indicators for assessing the effects of multiple pressures in North Pacific marine ecosystems. It proposed two ‘toolboxes’, the first with a set of indicators for use in North Pacific ecosystems, and the second with a selection of statistical and modelling techniques to identify which indicators are most appropriate for the multiple pressures of any specific marine ecosystem. Indicators for potential use in the North Pacific, derived from relevant global and specific North Pacific-focused studies, are presented as Toolbox 1. Many of these are broadly derived from on-going work in the European Union, work on the concept of essential ocean variables, and work on Integrated Ecosystem Assessments being conducted by the United States. Many of these indicators are directly measurable but several, in particular relating to features of ecosystem function and resilience, can only be derived from statistical or model analyses. Working Group 28 reviewed these lists of indicators and provided an integrated list, and a reduced core set, of indicators for use in North Pacific marine systems (Table 6.9).

In order to apply these indicators to assess marine ecosystem responses to multiple pressures, issues of data availability and the characteristics of good indicators need to be considered. Methods to identify which indicators may be best suited to assess multiple pressures in particular systems are presented as Toolbox 2. These range from expert elicitation to statistical to model-based approaches, each with their own strengths and weaknesses. The section concludes with a short discussion of the importance of clearly communicating indicators, and provides some examples.

Recommendations

To the extent possible, PICES member countries are recommended to make observations of the core set of ecosystem indicators presented in Table 6.9 as a starting point to facilitate ecosystem comparisons and analyses of multiple pressures. These core set indicators are:

- ENSO-related indices (Multivariate ENSO Index MEI; Oceanic Niño Index ONI), Pacific Decadal Oscillation (PDO), North Pacific Gyre Oscillation Index (NPGO)
- Sea surface temperature (SST) anomalies by season
- Sea level pressure (SLP) anomalies by season
- Winter maximum sea ice area or extent
- Freshwater discharge
- Nitrate
- pH
- Dissolved oxygen
- PCBs
- POPs
- Total mercury
- Harmful algal bloom area or frequency,
- Spawning Stock Biomass (SSB of selected species)
- Slope of size spectrum
- Species richness
- Taxonomic diversity
- Number of taxa representing 80% of biomass
- Chlorophyll a
- Crustacean plankton biomass
- Gelatinous plankton biomass (or volume),
- Small pelagic fish biomass
- Demersal fish biomass
- Piscivorous fish biomass
- Top predator biomass
- Total primary production
- Total landings
- Mean trophic level of landings
- Taxonomic diversity of landings
- Landings (biomass) of selected species

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7 Conclusions and Recommendations

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This report presents the findings of PICES Working Group 28 on the *Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors*. The Working Group met during PICES Annual Meetings from 2011 to 2015. The report responds to the Terms of Reference for this Working Group by discussing frameworks that link pressures to changes in North Pacific marine ecosystems (Section 2), by identifying multiple pressures on North Pacific marine ecosystems (Section 3), by presenting original case studies which use these frameworks and identifying multiple pressures to examine their impacts on coastal marine ecosystems in the PICES region (Section 4), by discussing approaches to identifying indicators for ecosystem responses to multiple pressures in the North Pacific (Section 5), and by presenting indicators for use by PICES members countries to address this issue (Section 6).

Linking multiple pressures to impacts and changes in North Pacific marine ecosystems is complex, in part because of the potentially large number of pressures, even larger number of interactions, and often low system knowledge and available data. A conceptual framework is essential to organize an approach and to systematically work through and record decisions of what to include, and why. Eight frameworks which have been applied to North Pacific waters were reviewed. Five of these frameworks can be considered as 'multi-sector impacts' frameworks, and include: pathways of effects, driver-pressure-state-impact-response, ecosystem simulation models, and marine health and geospatial methods. Three approaches can be considered as 'management' frameworks, as they explicitly require management objectives to guide the selection of variables, exploration of alternative management actions and scenarios, and evaluation of trade-offs among these alternative scenarios. Each framework has advantages and disadvantages in the extent of system knowledge and data required, their optimal spatial and temporal scales, and the effort required for their development.

North Pacific marine ecosystems are exposed to many and varied pressures, including from natural and anthropogenic sources. Studies have found there are more pressures in coastal than in oceanic regions. All marine ecosystems in the North Pacific appear to experience more than one pressure which means that multiple pressures are to be expected. Pressures identified for North Pacific marine systems tend to be similar throughout the region, with the differences in the types of pressures relating more to the type of ecosystem being examined. For example, coastal systems surrounded by millions of people have similar pressures around the North Pacific, but these are different from the pressures experienced by open ocean systems which are far from major population centers. Many studies have examined the impacts of a set of about 15 pressures on 20 habitat types (*e.g.*, Table 3.2), often using an expert elicitation method. Experimental evidence for the impacts of multiple pressures on multiple habitat types is rare because of the logistical difficulties of controlling and evaluating many interacting factors.

These frameworks and identified pressures and habitats were used to explore the main pressures and their impacts on habitats in two similar coastal marine ecosystems in the North Pacific: the Seto Inland Sea, Japan, and the Strait of Georgia, Canada. Using an expert elicitation method, the studies revealed there are similar intense pressures on each ecosystem, such as coastal development (a local pressure) and ocean warming (a large-scale pressure). Most sub-habitats had more than two or three pressures; for the Strait of Georgia, the most common number of pressures per 4 km^2 planning unit was 20 to 25. This makes assessment of the impacts of multiple pressures impossible using standard experiment-type approaches. Since many effects of anthropogenic pressures are focused in coastal areas, further studies such as those presented here but done at coastal embayment scales, and compared among regions, may provide further understanding of local responses to both large-scale and local pressures.

A number of criteria have been proposed to assist with the selection of individual indicators, and many of these are suitable for assessing the effects of multiple pressures. However, determining *a priori* the effects of multiple pressures is complicated by the fact that they can act additively, synergistically, or antagonistically to change ecosystem structure, function, and dynamics in unexpected ways that differ from single pressure responses. Scientific tools that can be used to evaluate the effects of multiple pressures are needed to assist decision making. Indicators should be chosen based upon defined criteria, conceptual models linking indicators to pressures and drivers, and defined strategic goals and ecological or management objectives. Indicators should be complementary, non-redundant, integrate responses to multiple pressures, and reflect the status of the ecosystem. Identifying indicators and evaluating multiple pressures on marine ecosystems requires a variety of approaches, such as empirical analyses, expert opinion, and model-based simulation. The ultimate goal is to identify a meaningful set of indicators that can be used to assist with the management of multiple types of human interactions with marine ecosystems.

Working Group 28 examined many sets of indicators proposed for or already in use in North Pacific marine ecosystems. The Working Group proposed two ‘toolboxes’, the first with an integrated set of indicators for use in North Pacific ecosystems, and the second with a selection of statistical and modelling techniques to identify which indicators are most appropriate for the multiple pressures of any specific marine ecosystem. Many of the indicators proposed in Toolbox 1 are broadly derived from on-going work in the European Union, work on the concept of essential ocean variables, and work on Integrated Ecosystem Assessments being conducted by the United States. Many of these indicators are directly measurable but several, in particular relating to features of ecosystem function and resilience, can only be derived from statistical or model analyses. The Working Group identified a reduced core set of indicators for use in North Pacific marine systems (Table 6.9). To apply these indicators to assess marine ecosystem responses to multiple pressures, issues of data availability and the characteristics of good indicators need to be considered. Methods to identify which indicators may be best suited to assess multiple pressures in particular systems are presented as Toolbox 2. These range from expert elicitation to statistical to model-based approaches, each with their own strengths and weaknesses. Finally, the importance of clearly communicating indicators was discussed.

There are several issues Working Group 28 did not discuss. Boyd *et al.* (2018) presented the need to understand biological responses to multiple pressures at physiological, evolutionary, and ecological levels. They noted that the field of multiple pressure research is taking two directions: mechanistic approaches to develop understanding of the impacts of multiple pressures on ecosystems, and scenario-based approaches which aim to quantify the responses of marine ecosystems to projected future ocean changes. The work of Working Group 28 is situated in the former (mechanistic) approach, as most indicators proposed by the group are based on observed data. However, elaboration of these indicators into ecosystem models will allow them to be used to summarize future responses of ecosystems to multiple pressures under global change scenarios better than reliance on statistical models, which are based on past conditions. In addition, the Working Group recognized that many of the multiple pressures impacting marine ecosystems have anthropogenic and societal origins. This means that human social organization and dynamics also need to be considered in a complete analysis of multiple pressures, their impacts to marine ecosystems, indicators of these impacts, and the setting of decision points and policies to reach societal goals (Lundquist *et al*., 2016). Figure 7.1 shows how pressures, scales of impacts, and interests of resource users can combine with science, institutions, and policy concerns to increase the risk of ecological surprises.

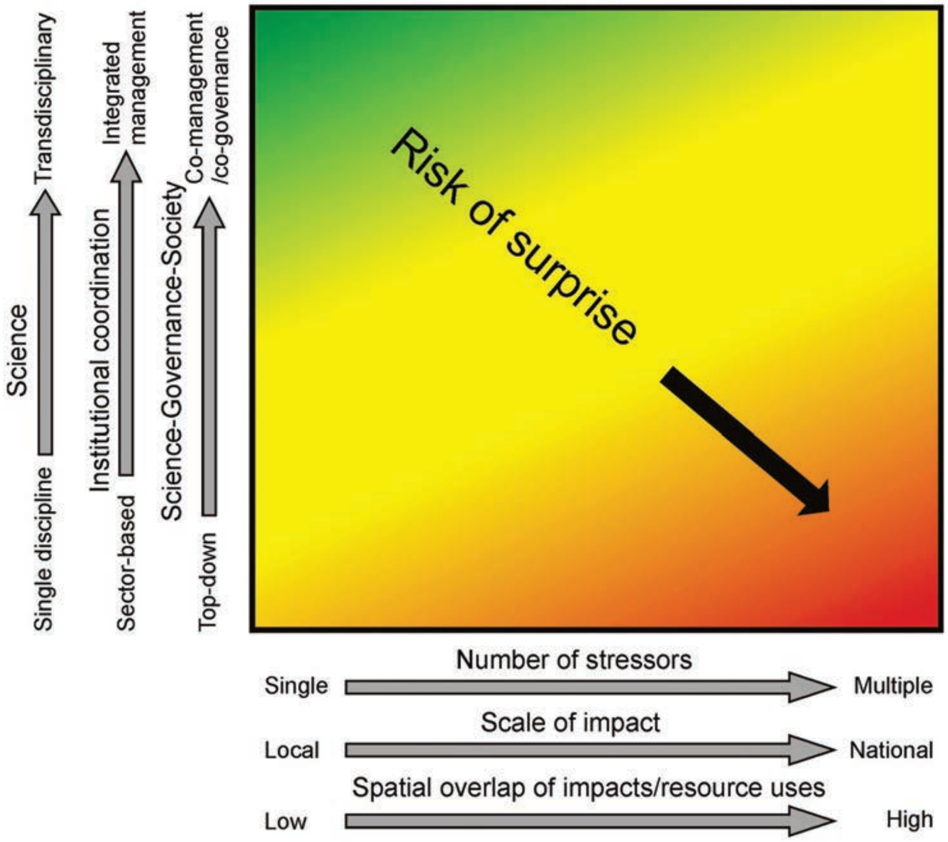

Fig. 7.1 Schematic showing how the relationships among aspects of multiple pressures (*x*-axis) can interact with human social institutions to cause unexpected ecosystem outcomes. From Lundquist *et al*. (2016). Reproduced with permission of Frontiers Media S.A.

The other major issue not discussed by the Working Group was how to respond to changes in values of the indicators. Two types of responses are possible: active, in which decisions and/or policies are changed to modify human behaviours to try to move the value of one or more indicators in a specific direction, or passive, which is usually the case for indicators which describe conditions that are outside of direct human control and for which only mitigation of the consequences may be possible. Active responses assume there are objectives for which indicators have been developed, and targets and limits are in place with some understanding of threshold responses (*e.g.*, Foley *et al*., 2015). Therefore, as the value of an indicator or set of indicators approaches a limit or threshold, some management action should take place. The indicator therefore, acts as a potential early warning of impending changes. This is the task of PICES Working Group 36 on *Common Ecosystem Reference Points across PICES Member Countries*, which is expected to complete its work in 2019.

The issue of developing ecosystem indicators to characterize ecosystem responses to multiple pressures is central to many of the activities of PICES and its member countries. In particular, this issue is central to the PICES FUTURE (Forecasting and Understanding Trends, Uncertainty and Responses of North Pacific Marine Ecosystems) program. The work of Working Group 28 contributes explicitly to the three primary questions of FUTURE, as detailed in this report:

1. *What determines an ecosystem's intrinsic resilience and vulnerability to natural and anthropogenic forcing?*
   The frameworks outlined in Section 2 on linking pressures to impacts and changes in North Pacific marine ecosystems can be used to sort through and organize information on what drives changes to these ecosystems, and the ecosystem characteristics that buffer or amplify these changes.

2. *How do ecosystems respond to natural and anthropogenic forcing, and how might they change in the future?*
   Ecosystems can respond to pressures in a large variety of ways, some overt, and other subtle. The work of Working Group 28 can help with sifting through these responses (*e.g.*, Sections 3 and 4) and with developing concise indices to represent how the ecosystems respond (*e.g.*, Sections 5 and 6).

3. *How do human activities affect coastal ecosystems and how are societies affected by changes in these ecosystems?*
   The indicators proposed by Working Group 28, and the toolbox approach recommended in Section 6, provide methods to work through how pressures on marine ecosystems in the North Pacific can impact coastal ecosystems and their dependent human communities.

In addition, the outcomes from Working Group 28 have connections with a number of concluded PICES Working Groups, and recommendations for many of the current set of Working Groups. Table 7.1 provides a brief survey of these other groups and their potential connections with the work of Working Group 28.

Table 7.1 PICES Working Groups and their potential links with Working Group 28.

WG objective relevant to WG 28	Connections with WG 28
WG 19 Working Group on *Ecosystem-based Management Science and its Application to the North Pacific*	
• Describe relevant national marine ecosystem monitoring approaches and plans and types of models for predicting human and environmental influences on ecosystems; • Identify key information gaps and research and implementation challenges.	Provides consistent frameworks to identify pressures on ecosystem components, identifies pressures on marine ecosystem of the North Pacific, and recommends toolboxes for use in developing relevant indicators of multiple environmental and human pressures.
WG 26 Working Group on *Jellyfish Blooms around the North Pacific Rim: Causes and Consequences*	
• Compile data on temporal variations in jellyfish abundance in the North Pacific; • Elucidate the role of jellyfish in coastal and oceanic marine food webs and assess the impacts of jellyfish blooms on marine ecosystems and socio-economies such as fisheries and aquaculture; • Provide jellyfish metrics as indicators of ecosystem change and resiliency.	Gelatinous plankton metrics are among the recommended core set of indicators.
WG 27 Working Group on *North Pacific Climate Variability and Change*	
Understand and fill the gaps between what physical models can currently produce and what ecosystem scientists suggest are the important physical forcing factors required for predicting species and ecosystem responses to climate variability and change.	Frameworks for characterizing the impacts of multiple pressures, including environmental and anthropogenic, on North Pacific ecosystems. Identification of multiple pressures on these ecosystems, including environmental and anthropogenic pressures.
WG 31 Working Group on *Emerging Topics in Marine Pollution*	
Compile data on pollution indicators describing spatial and temporal status, trends and impacts in the North Pacific Ocean.	Marine pollution indicators are among those identified in particular marine ecosystems (*e.g.*, Section 3) and in the two coastal ecosystem case studies. Particular problematic pollution indicators are included among the recommended core set.
WG 35 Working Group on *Third North Pacific Ecosystem Status Report*	
• Lead the regional syntheses trends in ecological time series observations of North Pacific ecosystems; • Lead the production of the Third North Pacific Ecosystem Status Report.	The recommended core set of indicators will provide consistent variables for comparisons among North Pacific marine ecosystems. The toolbox approach provides methods for selecting other key variables.

Table 7.1 Continued.

WG objective relevant to WG 28	**Connections with WG 28**
WG 36 Working Group on *Common Ecosystem Reference Points across PICES Member Countries*	
Summarise previous efforts identifying data availability for geographic areas and time periods of particularly strong climate influence and dependence on marine systems within specific North Pacific ecosystems, fish stocks, and fishing communities (building upon the work of WG 28, among other groups).	This is Working Group 28's 'daughter' group, formed as a direct follow-on from the results of WG 28. It is intended to build upon the recommended core set of indicators and develop methods for determining limit and threshold reference points.
WG 37 Working Group on *Zooplankton Production Methodologies, Applications and Measurements in PICES Regions*	
Produce recommendations and procedures for both traditional and biochemical zooplankton production rate measurement methodologies.	Various metrics of marine plankton communities are among the recommended core set of indicators. Understanding what causes them to change will further understanding of ecosystem variability.
WG 39 Working Group on an *Integrated Ecosystem Assessment (IEA) for the Central Arctic Ocean*	
Prepare an IEA for the Central Arctic Ocean ecosystem and potential effects and vulnerability in relation to climate variability and change and human activities.	The frameworks presented in Section 2, and the identification of ecosystem pressures and recommended core set of indicators, are part of the necessary information on which to build an integrated ecosystem assessment for any region.
WG 40 Working Group on *Climate and Ecosystem Predictability*	
• Identify North Pacific ecological indicators and/or marine ecosystem functional responses of fish and shellfish, showing predictable responses to large- and regional-scale climate forcing; • Identify climate and ocean products that can be used for making predictions of North Pacific marine ecosystems.	The frameworks, pressures, and recommended core set of variables and indicators developed by WG 28 are directly related to these objectives of WG 40.
WG 41 Working Group on *Marine Ecosystem Services*	
• Develop a typology of marine ecosystem services, tools and methodologies; • Collaborate with WG 36 and WG 40 to develop an indicator-based framework of the resilience of social-ecological systems.	The frameworks for linking pressures to impacts and changes in North Pacific marine ecosystems, the identification of leading pressures on these marine ecosystems, and the recommended core set (and toolboxes) of indicators for multiple pressures can help with developing this typology and related indicator-based framework.

Table 7.1 Continued.

WG objective relevant to WG 28	**Connections with WG 28**
WG 42 Working Group on *Indicators of Marine Plastic Pollution*	The frameworks for linking pressures to impacts and changes in North Pacific marine ecosystems, the identification of leading pressures on these marine ecosystems, and the recommended core set (and toolboxes) of indicators for multiple pressures can help with developing this work on this specific type of pollution issue.

Working Group 28 recommends the following:

- The selection of a framework for an analysis of indicators for multiple pressures must be done with full consideration of the advantages and disadvantages of each approach and of the goals of the assessment. Analyses should consider multiple pressures as the default.
- The list of pressures and habitats proposed by Halpern *et al*. (2008; see Table 3.2) should be used as a starting point for analyses and comparisons of multiple pressures on North Pacific marine ecosystems. Such analyses should also consider explicitly the spatial and temporal scales of pressures and the habitats they are impacting.
- The expert elicitation method is appropriate for marine ecosystems of the North Pacific, and may be the only way to adequately assess more than three simultaneous pressures, in particular when sufficient data are not available to develop ecosystem simulation models.
- Indicators should be chosen based upon defined criteria, conceptual models linking indicators to pressures and drivers, and defined strategic goals and ecological or management objectives. Indicators should be complementary, non-redundant, and integrate responses to multiple pressures and reflect the status of the ecosystem. An initial core set of indicators could include those that have been tested for the effects of climate and fishing and then expanded to include indicators of other pressures and ecosystem-specific feature-pressure interactions.
- To the extent possible, PICES member countries are recommended to make observations of the core set of ecosystem indicators presented in Table 6.9 as a starting point to facilitate ecosystem comparisons and analyses of multiple pressures. The additional indicators in Table 6.9 should be used as appropriate for each specific ecosystem. These core set indicators are: ENSO-related indices (Multivariate ENSO Index MEI; Oceanic Niño Index ONI), Pacific Decadal Oscillation (PDO), North Pacific Gyre Oscillation Index (NPGO), sea surface temperature (SST) anomalies by season, sea level pressure (SLP) anomalies by season, winter maximum sea ice area or extent, freshwater discharge, nitrate, pH, dissolved oxygen, PCBs, POPs, total mercury, harmful algal bloom area or frequency, Spawning Stock Biomass (SSB of selected species), slope of size spectrum, species richness, taxonomic diversity, number of taxa representing 80% of biomass; chlorophyll a, crustacean plankton biomass, gelatinous plankton biomass (or volume), small pelagic fish biomass, demersal fish biomass, piscivorous fish biomass, top predator biomass, total primary production, total landings, mean trophic level of landings, taxonomic diversity of landings, and landings (biomass) of selected species.

7.1 References

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Appendix 1

WG 28 Terms of Reference

WG 28 term: 2011–2015
Parent Committees: BIO and MEQ

1. Identify and characterize the spatial (and temporal) extent of critical stressors in North Pacific ecosystems both coastal and offshore and identify locations where multiple stressors interact. Identify trends in these stressors if possible.
2. Review and identify categories of indicators needed to document status and trends of ecosystem change at the most appropriate spatial scale (*e.g.*, coastal, regional, basin).
3. Using criteria agreed to at the 2011 PICES FUTURE Inter-sessional Workshop in Honolulu, determine the most appropriate weighting for indicators used for:
   a. documenting status and trends
   b. documenting extent of critical stressors
   c. assessing ecosystem impacts/change.
4. Review existing frameworks to link stressors to impacts/change, assessing their applicability to North Pacific ecosystems and identify the most appropriate for application to North Pacific ecosystems.
5. Determine if ecosystem indicators provide a mechanistic understanding of how ecosystems respond to multiple stressors and evaluate the potential to identify vulnerable ecosystem components.
6. For 1–2 case studies, identify and characterize how ecosystems respond to multiple stressors using indicators identified above. Are responses to stressors simply linear or are changes non-linear such that small additional stressors result in much larger ecosystem responses? Do different parts of the ecosystem respond differently (*e.g.*, trophic level responses)? How do stressors interact?
7. Publish a final report summarizing results with special attention to FUTURE needs. This WG will focus primarily on delivery of FUTURE Questions 3 and 1 (outlined below).

Linkages to the FUTURE Science Plan:

1. What determines an ecosystem's intrinsic resilience and vulnerability to natural and anthropogenic forcing?
2. How do ecosystems respond to natural and anthropogenic forcing, and how might they change in the future?
3. How do human activities affect coastal ecosystems and how are societies affected by changes in these ecosystems?

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Appendix 3

WG 28 Questions on the On-line survey of Pressures *versus* Habitats for the Expert Elicitation Case Studies

1. **What is the name of the marine ecosystem for which you will be providing your comments?**

   For example, it might be the Sea of Okhotsk if you are responding for a large spatial region, or perhaps Peter the Great Bay if you are responding for a smaller location within the larger region.

2. **Your name (Family name first, then Given name)**
3. **Who do you work for?**
4. **Where do you work (location)?**
5. **Your contact Email?**
6. **Your job expertise? (e.g. physical oceanographer, fisheries management, fisher, etc.)**
7. **Please select as many Habitats as you wish for which you will be identifying activities and stressors.**

INTERTIDAL – rocky
INTERTIDAL – mud
INTERTIDAL – beach
INTERTIDAL – salt marsh
COASTAL – seagrass
COASTAL – kelp forest
COASTAL – rocky reef
COASTAL – suspension-feeder reef (e.g. oysters, corals)
COASTAL – sub-tidal soft bottom
SHELF – pelagic water column
SHELF – soft bottom (30–200 m depth)
SHELF – hard bottom (30–200 m depth)
SHELF – ice
OCEANIC – soft bottom slope (200–2000 m depth)
OCEANIC – hard bottom slope (200–2000 m depth)
OCEANIC – soft bottom benthic (>2000 m)
OCEANIC – seamount
OCEANIC – vents
OCEANIC – soft bottom canyon
OCEANIC – hard bottom canyon
OCEANIC – upper (near surface) pelagic water column
OCEANIC – deep pelagic water column

8. **Which Habitat are you considering? Please select one - you will be able to select others later in this survey, if you wish.**

9. **Which human activity and natural stressors are affecting this Habitat (within past 5 years)? Please select one - you will be asked to select others (if any) later in this survey.**
   For this combination of Habitat and Activity/Stressor, please identify the 5 features of 'vulnerability' of this Habitat to this Activity/Stressor, below.

10. Spatial Extent

The spatial scale at which a single event of the activity/stressor impacts this habitat, in km^2. Please consider a single event rather than the cumulative impacts. For example, spatial scale of a single bottom trawl rather than the area over which all bottom trawling occurs.

VALUES:
1 = <10 km^2;
2 = 10–100 km^2;
3 = 100–1000 km^2;
4 = >1000 km^2.

Please also identify how certain you are of your estimate: 1: very low (<15%); 2: low (15–50%);
3: high (50–85%); very high (>85%).

11. Frequency

The average annual frequency at which the activity/stressor occurs at a particular location in this habitat (note this is not a measure of 'duration').

VALUES:
1 = rare, e.g. once every >5 yrs;
2 = occasional, e.g. once every >1–5 yrs;
3 = seasonal, e.g. every season to once a year;
4 = persistent, e.g. daily or continual.

Please also identify how certain you are of your estimate: 1: very low (<15%); 2: low (15–50%);
3: high (50–85%); 4: very high (>85%).

12. Trophic impact

The primary level of marine life affected by the activity/stressor within the habitat.
VALUES: 1 = species (single or multiple); 2 = single trophic level; 3 = >1 trophic level; 4 = entire community

Please also identify how certain you are of your estimate: 1: very low (<15%); 2: low (15–50%);
3: high (50–85%); 4: very high (>85%)

13. Resistance to change

The degree to which the species, trophic level(s), or entire habitat's "natural" state is impacted by the activity/stressor, i.e. how good is the resistance of this habitat to change caused by this activity/stressor.

VALUES:
1 = activity/stressor has a positive impact;
2 = high resistance to change (i.e. little significant negative change in biomass);
3 = moderate resistance to negative change;
4 = low resistance to negative change (i.e. significant negative biomass changes result from small stresses).

Please also identify how certain you are of your estimate: 1: very low (<15%); 2: low (15-50%); 3: high (50-85%); 4: very high (>85%)

14. Recovery time

The average time (years) required for the affected species, trophic level(s), or entire community to return to its 'natural' state following disturbance by this activity/stressor.

VALUES: 1 = <1 year; 2 = 1–10 years; 3 = 10–100 years; 4 = >100 years

Please also identify how certain you are of your estimate: 1: very low (<15%); 2: low (15-50%); 3: high (50-85%); 4: very high (>85%)

15. Does this Habitat have other Activities/Stressors for which you would like to estimate these vulnerability features, or does this ecosystem have other Habitats for which you would like to describe Activities and Stressors?

If you answer "No", you will jump to the Final page of the survey to conclude.

16. Which Habitat are you considering? Please select one - you will be able to select others later in this survey, if you wish.

…..

Are there key literature references or information sources that you would recommend to help us identify the impacts of multiple human activities and natural stressors in this ecosystem?

Would you like to make any other comments?

Appendix 4

Meeting Reports and Topic Session/Workshop Summaries from Past Annual and Inter-sessional Meetings Related to WG 28

PICES-2011

October 14–23, 2011, Khabarovsk, Russia

Report of Working Group on *Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors*

The meeting of the Working Group on *Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors* (WG 28) was held from 14:00–18:00 h on October 15, 2011 at PICES-2011 in Khabarovsk, Russia. Dr. Motomitsu Takahashi (Japan) acted as meeting Chair. Seventeen people were present, representing 5 PICES member countries (*WG 28 Endnote 1*). Dr. Takahashi recommended asking Drs. Ian Perry (Canada) and Chaolun Li (China) to serve as Co-Chairs of the Working Group. This report reflects discussions at the meeting on some of the Agenda Items (*WG 28 Endnote 2*).

AGENDA ITEM 2
Schedule of Working Group activities

Each of 7 terms of reference of WG 28 was divided into the year when it would be addressed.

Year 1

1. Identify and characterize the spatial (and temporal) extent of critical stressors in North Pacific ecosystems both coastal and offshore and identify locations where multiple stressors interact. Identify trends in these stressors if possible.
2. Review and identify categories of indicators needed to document status and trends of ecosystem change at the most appropriate spatial scale (*e.g.*, coastal, regional, basin).

Year 2

1. Using criteria agreed to at the 2011 PICES FUTURE inter-sessional workshop in Honolulu, determine the most appropriate weighting for indicators used for:
   a. documenting status and trends,
   b. documenting extent of critical stressors,
   c. assessing ecosystem impacts/change.
2. Review existing frameworks to link stressors to impacts/change, assessing their applicability to North Pacific ecosystems and identify the most appropriate for application to North Pacific ecosystems.
3. Determine if ecosystem indicators provide a mechanistic understanding of how ecosystems respond to multiple stressors and evaluate the potential to identify vulnerable ecosystem components.

Year 3

1. For 1–2 case studies, identify and characterize how ecosystems respond to multiple stressors using indicators identified above. Are responses to stressors simply linear or are changes non-linear such that small additional stressors result in much larger ecosystem responses?
2. Do different parts of the ecosystem respond differently (*e.g.*, trophic level responses)? How do stressors interact? Publish a final report summarizing results with special attention to FUTURE

needs. This Working Group will focus primarily on delivery of FUTURE Questions 1 and 3 (see http://www.pices.int/members/scientific_programs/FUTURE/FUTURE_IP_final_2009.pdf).

AGENDA ITEM 4

Proposals for Working Group activities at PICES-2012

The first year of WG 28's activities include a broad range of tasks, so the following activities were proposed for PICES-2012:

- 1-day WG meeting;
- 1-day Workshop on "*Identifying critical multiple stressors of North Pacific marine ecosystems and indicators to assess their impacts*" (*WG 28 Endnote 3*);
- ½-day Topic Session on "*Ecosystem responses to multiple stressors in the North Pacific*" (*WG 28 Endnote 4*).

WG 28 Endnote 1

WG 28 participation list

Members	Observers
Jennifer Boldt (Canada)	Robin Brown (Canada)
Ik Kyo Chung (Korea)	George Hunt (USA)
Shigeru Itakura (Japan)	Sangjin Lee (NOWPAP of UNEP)
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Jameal Samhouri (USA)	
Motomitsu Takahashi (Japan, Co-Chairman)	
Naoki Yoshie (Japan)	
Chang-Ik Zhang (Korea)	

WG 28 Endnote 2

WG 28 meeting agenda

1. Welcome, Introduction and sign-in (all)
2. General review of Terms of Reference and discussion about WG frameworks
    - WG deliverables
    - Contributions to FUTURE
    - Timelines
    - Leads
3. Review of recent PICES activities related to this WG
    - Review of FUTURE Inter-sessional Workshop in Honolulu in April 2011
    - Forthcoming related workshop/symposium

4. Discussion on possible topic session at PICES-2012 and -2013
   - Review of a topic session proposal
   - Terms, invited speakers, program
   - Other related issue
5. Discussion on how to activate our WG
   - How to share papers and ideas
   - Next meeting (PICES-2012)

WG 28 Endnote 3

Proposal for a 1-day workshop at PICES-2012 on *"Identifying critical multiple stressors of North Pacific marine ecosystems and indicators to assess their impacts"*

Co-Convenors: Jennifer Boldt (Canada), Vladimir Kulik (Russia), Chaolun Li (China), Jameal Samhouri (USA), Motomitsu Takahashi (Japan), Chang-Ik Zhang (Korea)

Multiple natural and human stressors on marine ecosystems are common throughout the North Pacific, and may act synergistically to change ecosystem structure, function and dynamics in unexpected ways that can differ from responses to single stressors. Further, these stressors can be expected to vary by region, and over time. This workshop seeks to understand responses of various marine ecosystems to multiple stressors, and to identify and characterize critical stressors in PICES regional ecosystems including appropriate indicators of their impacts. The goal is to help determine how ecosystems might change in the future and to identify ecosystems that may be vulnerable to the combined impacts of natural and anthropogenic forcing. Contributions are invited which identify and characterize the spatial and temporal extent of critical stressors in marine ecosystems (both coastal and offshore regions) of PICES member countries, and in particular the locations at which multiple stressors interact. Contributions will include a review and identification of broad categories of indicators which document the status and trends of ecosystem change at the most appropriate spatial scale (*e.g*., coastal, regional, basin) in response to these multiple stressors. This workshop is linked with the topic session titled "Ecosystem responses to multiple stressors in the North Pacific" but is designed to provide more in-depth examination and discussion of the spatial and temporal extents of critical marine ecosystem stressors and their potential indicators. It will assist with progress towards the goals of PICES WG 28 on *Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors* (http://www.pices.int/members/working_groups/wg28.aspx).

WG 28 Endnote 4

Proposal for a ½-day Topic Session at PICES-2012 on *"Ecosystem responses to multiple stressors in the North Pacific"*

Co-Convenors: Vladimir Kulik (Russia), Ian Perry (Canada), Motomitsu Takahashi (Japan)

Marine ecosystems of the North Pacific, both coastal and offshore, are influenced by multiple stressors, such as increased temperature, change in iron supply, harmful algal blooms, invasive species, hypoxia/eutrophication, ocean acidification, and intensive fishing. These multiple stressors can (but do not always) act synergistically to change ecosystem structure, function, and dynamics in unexpected ways that can differ from responses to single stressors. Further, these stressors can be expected to vary by region and over time. This session seeks to understand the responses of various marine ecosystems to multiple stressors and to identify appropriate indicators of these effects. Contributions are invited which review and define categories of indicators to document the status and trends of ecosystem change at a variety of spatial scales (*e.g.*, coastal, regional, basin) in response to multiple stressors. Emphasis will be placed on empirical and theoretical approaches that forge links between ecosystem change and the intensities of multiple stressors. This session will form a contribution to the work of PICES WG 28 on *Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors* (http://www.pices.int/members/working_groups/wg28.aspx).

Invited Speakers: Natalie Ban (James Cook University, Australia), Ben Halpern (University of California Santa Barbara, USA)

PICES-2012

October 12–21, 2012, Hiroshima, Japan

Excerpted from:

Summary of Scientific Sessions and Workshops at PICES-2012

BIO/MEQ/FUTURE Topic Session (S10)
Ecosystem responses to multiple stressors in the North Pacific

Co-sponsored by: *SOLAS*

Co-convenors: *Vladimir Kulik (Russia), Ian Perry (Canada) and Motomitsu Takahashi (Japan)*

Background

Marine ecosystems of the North Pacific, both coastal and offshore, are influenced by multiple stressors, such as increased temperature, change in iron supply, harmful algal blooms, invasive species, hypoxia/eutrophication, ocean acidification, and intensive fishing. These multiple stressors can (but do not always) act synergistically to change ecosystem structure, function, and dynamics in unexpected ways that can differ from responses to single stressors. Further, these stressors can be expected to vary by region and over time. This session seeks to understand the responses of various marine ecosystems to multiple stressors and to identify appropriate indicators of these effects. Contributions were invited which reviewed and defined categories of indicators to document the status and trends of ecosystem change at a variety of spatial scales (*e.g.*, coastal, regional, basin) in response to multiple stressors. Emphasis was placed on empirical and theoretical approaches that forge links between ecosystem change and the intensities of multiple stressors. This session was a contribution to the work of PICES WG 28 on *Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors*.

Summary of presentations

Session S10 was held on Friday, October 19, 2012 (half day). It was launched with an invited speaker, Natalie Ban (Australian Research Council Centre of Excellence for Coral Reef Studies, Australia) and included 5 other oral presentations, 8 poster presentations, and time for discussion.

Dr. Ban discussed issues related to mapping cumulative impacts, including advances, relevance and limitations to marine management. She began by noting there is global concern about multiple stressors and currently a lot of interest in mapping where multiple stressors might be interacting. She identified the purpose of her presentation as providing examples of methods and data for mapping multiple stressors in a given region. She concluded that such approaches do provide informative uses of existing data and information, baselines for future mapping, new opportunities to improve mapping approaches, but cautioned that there is a need to ground-truth these mapping efforts. She also recommended caution when scores for the vulnerabilities of different habitats to different stressors developed in one region (*e.g.*, the California Current system) are applied to a different region (*e.g.*, the coast of British Columbia) without critical consideration of their “transferability”. An important next step in these types of habitat vulnerability analyses is the use of Bayesian methods to assess multiple stressors, which are now being investigated in some coral reef regions. Discussion following her presentation included how to move from GIS analyses of multiple stressors to impacts; it was noted that some of this needs to come from directed studies of impacts. However, such studies currently often examine only one stressor at a time.

Dr. Ian Perry, with co-author Dr. Jennifer Boldt, provided an example of a study to identify multiple stressors on multiple habitats in a specific region, the Strait of Georgia, British Columbia, featuring the early work of Working Group 28. The objectives of his study were to develop a structured process to identifying multiple stressors in the Strait of Georgia, and the responses of selected (key) habitats to these stressors, to identify which habitats might be more vulnerable to which stressors, and to provide base information that is needed to develop indicators of ecosystem responses to multiple stressors in this area. He described a GIS-based approach to identify which stressors occur in the Strait of Georgia and how they might impinge upon various habitats, and then described an expert-based project to identify the potential vulnerabilities of these habitats to which stressors. He concluded that considerable (but not complete) information is available for the Strait of Georgia on spatial patterns of important marine habitat features and human stressors, that we are beginning to understand the knowledge gaps concerning measures of habitat vulnerability and resilience, and that expert surveys are one method to obtain information but they need to be cross-linked with empirical data. Ecosystem models may provide useful "platforms" to understand ecosystem responses to multiple stressors, but they also need to be supported and cross-checked with empirical data and expert surveys. This type of analysis does not permit inclusion of temporal trends in stressors, which can be important in assessing current conditions when the information base is from past conditions.

Dr. Vladimir Kulik provided a detailed and thorough statistical analysis of mapping cumulative human and natural impacts in the Sea of Okhotsk, based on the monitoring of energy emissions from fishing activities. He derived time series of this information and applied statistical analyses to extract the dominant underlying features and trends. Planned activities include additional stressors such as SST and sea ice, adding nearshore human activities (specifically small-scale fishing), involving experts in a survey to get weights for ecosystem vulnerability, clustering the bottom area by ground type and depth, and summarizing impact scores by clusters.

Dr. Motomitsu Takahashi and co-authors provided an initial comparative study of ecosystem responses to anthropogenic activities and natural stressors among inland, shelf and oceanic waters around Japan. They used the expert-based screening method developed by Working Group 28 to identify the impacts of human activities and natural stressors in each of these regions. They then compared the outcomes from the expert-based approach with observed data. They concluded that increasing sea temperatures affect all three ecosystems, that coastal development and engineering have strong impacts on the East China Sea and the Seto Inland Sea, that demersal and pelagic fishing impacts the East China Sea and the Kuroshio/Oyashio region, respectively, and that nutrient inputs have synergistic impacts to Harmful Algal Blooms and hypoxia. They also identified problems with the expert-based scoring method, including that the certainty of the experts on the impacts differ among ecosystems because of the quality and quantity of information available, that the evaluation of impacts can differ among experts with different experience and expertise, that more information in the intertidal and coastal waters along China are needed for the East China Sea region, and that for oceanic waters, a lack of information may preclude appropriate evaluation of ecosystem responses.

Dr. Mingyuan Zhu and co-authors examined ecosystem changes under multiple stressors in the Yellow Sea, including the natural environment of Yellow Sea and East China Sea, their multiple stressors, the resulting changes in pelagic and benthic communities, and the consequent response of the ecosystems. They concluded that multiple stressors on the ecosystems of these Chinese seas occur from both climate change and anthropogenic activities and that they are increasingly severe, that there are clear ecosystem changes as evidenced by loss of biodiversity, declines in living marine resources, increasing HABs, "green tides", jellyfish blooms, *etc.*, and that further studies and management actions to reduce environmental stresses are urgently needed.

The presentation by Mr. Kyung-Su Kim and co-authors received the Best Paper award from the MEQ Committee (see the end of Session Summaries for the list of recipients). They examined the combined effects of elevated carbon dioxide concentrations and temperature on the development of olive flounder, the most important aquaculture species in Korea. It provided an example of the type of directed study that is needed to begin to understand the joint effects of more than one stressor. They concluded that larval growth was similar at the two lower CO_2 concentrations examined and within the range of seawater temperature range of 18~22°C, but that growth was enhanced at the highest CO_2 concentration at both temperatures. They also noted that the calcium component in larval bone was significantly increased at the highest CO_2 concentration. This study provided a nice example of the (often) non-linear relationships that can occur with multiple stressors interact.

General discussion considered whether these expert-based survey approaches should be done with a regional or global focus, *i.e.*, whether the respondents should be asked to consider just the range of values and experiences in a particular geographic region or on a global comparison. No consensus was reach other than to note this question can be important and should be considered in such surveys and their questions. In addition, how can the impacts of multiple stressors on habitats be examined when more than two stressors are occurring? For example, Perry and Boldt found that the mode number of stressors on any 4 km^2 region in the Strait of Georgia was between 20 and 25. When developing indices for multiple stressors, they need to be "simple" but at the same time allow for users to "drill down" to obtain more details about how particular sets of stressors might be driving particular responses in habitats. An important shortcoming in these approaches was noted regarding temporal changes, and how to update the analyses. A stepwise process was recommended, involving identification of habitats, stressors, and their vulnerabilities, noting that these vulnerabilities of specific habitats to different stressors likely do not need to be updated on a regular basis. Updates for new time periods would then use the established vulnerabilities and simply update the stressor information.

List of papers

Oral presentations

Natalie C. Ban, Stephen S. Ban and Hussein M. Alidina (Invited)
Mapping cumulative impact: Advances, relevance and limitations to marine management and conservation in Pacific Canada, and emerging Bayesian approaches

R. Ian Perry and Jennifer Boldt
Identifying multiple stressors and potential habitat responses in marine ecosystems of Pacific Canada

Vladimir V. Kulik
Mapping cumulative human and natural impacts in the Sea of Okhotsk

Motomitsu Takahashi, Sachihiko Itoh, Naoki Yoshie, Kazuhiko Mochida, Masakazu Hori and Shigeru Itakura
Comparative study on ecosystem responses to anthropogenic activities and natural stressors among inland, shelf and oceanic waters around Japan

Mingyuan Zhu, Ruixiang Li and Zongling Wang
Ecosystem Changes under multi-stressors in the Yellow Sea

Kyung-Su Kim, JeongHee Shim and Suam Kim
The combined effects of elevated carbon dioxide concentration and temperature on the early development stage of olive flounder *Paralichthys olivaceus*

Poster presentations

Evgeniya Tikhomirova
Typical distributions of primary production at the surfaces of Peter the Great Bay (Japan Sea)

Kanako Naito, Setsuko Sakamoto, Mineo Yamaguchi, Ichiro Imai and Ken-ichi Nakamura
Iron as a triggering factor for harmful dinoflagellate blooms

Aya Morinaga and Kazumi Matsuoka
Eutrophication suggested by the heterotrophic signal of dinoflagellate cyst assemblages; Case of Omura Bay, West Japan

Yuta Inagaki, Tetsuya Takatsu, Masafumi Kimura, Yota Kano, Toyomi Takahashi, Yoshihiko Kamei, Naoto Kobayashi and Tatsuaki Maeda
Effects of hypoxia on annual changes in growth and somatic condition of flathead flounder *Hippoglossoides dubius* in Funka Bay, Japan

Tetsuya Takatsu, Koji Shinoda, Shoichi Inoue, Tomofumi Seta and Yuta Inagaki
Drastic reduction of demersal fish abundance by hypoxia in Mutsu Bay Japan in the fall of 2011

Stephani Zador and Kirstin Holsman
Identifying and comparing ecosystem stressors in the eastern Bering Sea and Gulf of Alaska

Yumiko Yara, Meike Vogt, Masahiko Fujii, Hiroya Yamano, Claudine Hauri, Marco Steinacher, Nicolas Gruber and Yasuhiro Yamanaka
Ocean acidification limits temperature-induced poleward expansion of coral habitats

Anastasiia Strobykina
Spatial and temporal variability of nutrients in the Okhotsk Sea shelf zone

BIO Workshop (W1)

Identifying critical multiple stressors of North Pacific marine ecosystems and indicators to assess their impacts

Co-Convenors: *Jennifer Boldt (Canada), Vladimir Kulik (Russia), Chaolun Li (China), Jameal Samhouri (USA), Motomitsu Takahashi (Japan) and Chang-Ik Zhang (Korea)*

Background

Multiple natural and human stressors on marine ecosystems are common throughout the North Pacific, and may act synergistically to change ecosystem structure, function and dynamics in unexpected ways that can differ from responses to single stressors. Further, these stressors can be expected to vary by region, and over time. This workshop seeks to understand responses of various marine ecosystems to multiple stressors, and to identify and characterize critical stressors in PICES regional ecosystems including appropriate indicators of their impacts. The goal is to help determine how ecosystems might change in the future and to identify ecosystems that may be vulnerable to the combined impacts of natural and anthropogenic forcing. Contributions are invited which identify and characterize the spatial and temporal extent of critical stressors in marine ecosystems (both coastal and offshore regions) of PICES member countries, and in particular the locations at which multiple stressors interact. Contributions will include a review and identification of broad categories of indicators which document the status and trends of ecosystem change at the most appropriate spatial scale (*e.g.*, coastal, regional, basin) in response to these multiple stressors. This workshop is linked with the Topic Session titled "*Ecosystem responses to multiple stressors in the North Pacific*" but is designed to provide more in-depth examination and discussion of the spatial and temporal extents of critical marine ecosystem stressors and their potential indicators. It will assist with progress towards the goals of PICES WG 28 on *Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors*.

Summary of Workshop

The BIO Workshop (W1) was held on Friday, October 12, 2012 (full day), and was launched with a talk by invited speaker, Dr. Natalie Ban (Australian Research Council Centre of Excellence for Coral Reef Studies, Australia) and included 6 other oral presentations.: Olga Lukyanova (TINRO-Centre, Russia), Stephani Zador (NMFS, USA), Christopher Mulanda Aura (Hokkaido University, Japan), Elliott Hazen (University of Hawaii and NMFS, USA), Jameal Samhouri (NMFS, USA), and Jennifer Boldt (Fisheries and Oceans Canada). In addition, there were general discussions after the morning presentations, and in-depth discussions in the afternoon.

Workshop presentations and discussion focused on three apparent approaches to evaluating stressors: (1) expert-based surveys, (2) model-based analyses, and (3) empirical/data based analyses.

The invited presentation was given by Dr. Ban who provided a view of cumulative human impacts in the marine environment, using an expert-based survey approach as well as combinations of all approaches. Utilizing the empirical analyses approach, Dr. Lukyanova introduced her research showing that eggs, embryos and larvae of marine fish and echinoderms may be used as bioindicators of early disturbances due to multiple stressor interactions in vulnerable ecosystems, in particular from hydrocarbons in water. Dr. Zador (presented by Ms. Patricia Livingston) summarized indicator-based ecosystem assessments in the Bering Sea and Aleutian Islands regions, utilizing a team-based approach, thereby addressing the expert-based survey approach. Three broad conclusions from this study were provided: (1) the physiological and biological nature of the ecosystem, the extent of scientific knowledge about the ecosystem, and the particular expertise of team members will influence the final assessment product; (2) team discussion of assessment structuring themes should occur before indicator selection, and (3) developing assessments should be an iterative process with frequent review by fisheries managers. Dr. Aura's presentation highlighted a model-based approach to evaluating stressors and features suitable for aquaculture sites in northern Japan. Dr. Aura's research included the development of a site suitability model, conducted using geographic information system (GIS)-based, multi-criteria evaluation (MCE) with weighted linear combinations to assess suitable scallop culture sites. For scallop culture, requisite biophysical (sea temperature, chlorophyll-*a*, secchi disk depth and bathymetry) and social infrastructure (distance to pier and town) parameters formed thematic layers that were limited by a constraint layer, and results were consistent with existing scallop culture locations. Dr. Hazen's presentation focused on the data-based analytical approach. He developed a quantitative indicator selection framework by looking for composite indices and links between pressure and state variables for the California Current region. Dr. Samhouri highlighted expert-based survey approaches to evaluating stressors. He compared and contrasted results from multiple efforts to elicit the opinions of regional experts about the vulnerability of coastal habitats along the U.S. west coast. These assessments encompass stressors as varied as pollution, climate change, invasive species, and overharvest in relationship to habitats from rocky shorelines and sandy beaches to the deep sea. Dr. Aseeva's presentation highlighted a data-based analytical approach to evaluating environmental stressors that explain fluctuations in flounder species composition on the shelf of West Kamchatka. Dr. Boldt gave an overview of the Indicators for the Seas 2 (IndiSeas2) research program, which uses all three approaches (data-based, model-based, and expert surveys) to evaluating stressors. The goal of IndiSeas2 is to evaluate the status of marine ecosystems in a changing world using a suite of indicators that reflect effects of multiple drivers on the states and trends of exploited marine ecosystems.

Morning Discussion

During the discussion after the morning presentations, workshop participants discussed the pros and cons of the three alternative approaches for evaluating stressors: (1) expert elicitation, (2) model-based simulation, and (3) empirical analysis (Table 1), as well as a general discussion on indicators.

Main discussion points:

- Some pros and cons derived from the presentations were listed by the group. There was general agreement that, despite pros and cons of each approach (Table 1), there is a need to use multiple approaches due to data availability and, where data are available, constraints and assumptions of analyses, *e.g.*, the constraint that Principal Components Analyses represent only linear relationships, and that most approaches conducted to date of the impacts of multiple stressors assume their effects to be additive.
- The pros and cons of the three approaches depend on the objectives. For example, is the objective to know the state of ecosystems or to identify management interventions? WG 28 is looking at the state of ecosystems and ecosystem responses; linking that to management actions could be a next step.
- The selection of indicators and stressors will be affected by the behaviour of species and ecosystem properties (surroundings and hydrodynamics).
- The goal of WG 28 is not to forecast future indicator responses, but rather, to choose indicators (or at minimum to develop a process for choosing indicators of ecosystem responses to multiple stressors) that will be of interest in the future. One goal of WG 28 is to understand if ecosystems are responding to human activities (and climate), so that management actions can control human impacts. Separating human and climate effects is very difficult; can we identify indicators of interactions (*e.g.*, fishing and climate change) that will help us identify deteriorating ecosystem conditions?

Table 1. Some pros and cons of three alternative approaches for evaluating stressors: (1) expert elicitation, (2) model-based simulation, and (3) empirical analysis.

Approach	Pros	Cons
Expert elicitation	Solution to the no data problem	Difficult to validate responses
	Appropriate for global and regional visualization	
Empirical analysis	Track emerging stressors where expert input is untested or models are unavailable	Difficult to find data at appropriate scales
	Appropriate indicators can be tailored to the physical and biological nature of ecosystem	Least common denominator issue (shortest time series, smallest common spatial domain)
	Remotely sensed data available for many physical variables	
Model based analyses	Can generate as much data as you need	Must have a model
	Can create an ensemble of models using different frameworks	Outputs are only as good as the data that go into the model

Afternoon discussion

After presentations in the afternoon, workshop participants discussed and compared indicators that are used in different regions to characterize the spatial and temporal extents of critical stressors and understand responses of ecosystems to multiple stressors.

Main discussion points:

- There was acknowledgement that indicators are collected and used for varying temporal and spatial scales, thereby making it difficult to combine indicators. One solution is to leave indicators disaggregated and ensure discussions around the indicator responses are framed within the varying response times (and scales). Composite indices need to preserve enough information so that the driving factors of index variability are understood. Another related point raised was that what we see is how ecosystems respond to multiple stressors, and as part of our analyses we attempt to separate these responses into effects of individual stressors. We may not need to disaggregate individual effects of each stressor in order to choose appropriate indicators of ecosystem responses; however, we will need to tease these effects apart if we want to ensure a process-based understanding that can be used for forecasting the future.
- The group then discussed and identified four groups of indicators, stressors, and activities: environmental, biological, human activities and stressors, and sociopolitical-economic. Broad categories of indicators were then listed for each of three of these groups (environmental, human activities and stressors, and sociopolitical-economic); this was *not* meant to represent a complete list, and could be supplemented with existing knowledge in the literature. For each country and each category of indicators (Table 2), member countries established the existence of data, and the temporal and spatial extent of the data (3 responses for each indicator). The tables were not filled out completely (indicators or data availability), but this could be a WG 28 activity. For the biological indicators, some information can be acquired from the work of PICES Working Group 19 on

Ecosystem-based Management Science and its Application to the North Pacific, in their Ecosystem-Based Fisheries Management 2010 report (PICES Scientific Report 37, Table 3.1.3). Note that this table would not include information about data availability for habitats.

Table 2. Some broad-scale indicators identified in the workshop to address three main categories (environmental, human activities and stressors, and sociopolitical-economic). Each cell contains three responses for the existance of data, availability of time series data, and spatial extent of data. Y = Yes, N = No, S = Some, N/A = Not applicable

Indicators, Activities, and Stressors	Canada	Japan	Russia	U.S.A.	High Seas
Environmental stressors/indicators					
Temperature					
Sea Ice					
Chla					
Nutrients	Y,Y,N	Y,Y,S	Y,Y,N	Y,Y,N	
River discharge	Y,Y,Y	Y,Y,Y	S,Y,N	Y,Y,Y	N/A
Toxic contaminants	Y,N,N	Y,N,N	Y,N,N	Y,N,N	S,N,N
Large scale climate index (e.g., PDO, ENSO)					
pH	Y,N,N	Y,N,N	Y,N,N	Y,N,N	Y,N,N
Oxygen	Y,Y,N	Y,Y,S	Y,Y,N	Y,Y,N	
Human activities & stressors					
Fishing	Y,Y,Y	Y,Y,Y	Y,Y,Y	Y,Y,Y	S,S,S
Oil and Gas					
Military Activity	N,N,N	N,N,N	N,N,N	N,N,N	N,N,N
Wave/Wind/Tidal					
Shipping					
Coastal engineering	Y,S,S	Y,S,S	Y,N,S	Y,N,S	N/A
Aquaculture					
Ecotourism					
Land-based pollution					
Socio-economic-political					
Seafood demand					
Coastal population trends	Y,Y,Y	Y,Y,Y	?,?,?	Y,Y,Y	N/A
Marine Employment	S,Y,Y	Y,Y,Y	N?,N?,N?	S,Y,Y	S,S,S
Marine Revenue					
Marine exports/domestic consumption					
Participation/stakeholder involvement					
Governance					
Happiness					
Satisfaction with ocean status					
Community vulnerability					
Coastal infrastructure					

Recommendations

- Use multiple approaches (expert elicitation, model-based simulation, and empirical analysis) to identify and evaluate critical multiple stressors of North Pacific marine ecosystems and indicators to assess their impacts.
- Finish filling out the tables with help from other PICES working groups, sections, and committees. For example, the Section on *Human Dimensions on Marine Ecosystems* could provide expertise on socio-economic indicators. The FIS and BIO committees could provide help on biological indicators and the MONITOR committee could provide expertise environmental indicators and stressors.
- A next step might be to identify the gaps in the tables and those that are important for which to get information.

List of papers

Oral presentations

Natalie C. Ban, Stephen S. Ban and Hussein M. Alidina (Invited)
Combining stressor information – Experiences from Canada's Pacific waters and Australia's Great Barrier Reef

Olga N. Lukyanova, Elena V. Zhuravel, Sergey A. Cherkashin, Denis N. Chulchekov, Viktor A. Nadtochyi and Olga V. Podgurskaya
Bioindicators of multiple stressors interaction in the North-Eastern shelf of Sakhalin Island (Sea of Okhotsk)

Stephani Zador, Kirstin Holsman, Sarah Gaichas and Kerim Aydin
Developing indicator-based ecosystem assessments for diverse marine ecosystems in Alaska

Christopher Mulanda Aura, Sei-Ichi Saitoh, Yang Liu and Toru Hirawake
Spatio-temporal model for mariculture suitability of Japanese scallop (*Mizuhopecten yessoensis*) in Funka and Mutsu Bays, Japan

Elliott L. Hazen, Jameal F. Samhouri, Isaac D. Schroeder, Brian K. Wells, Steven J. Bograd, David G. Foley, Nick Tolmieri, Phillip S. Levin, Greg Williams, Kelly Andrews, Sam McClatchie, William T. Peterson, Jay Peterson, Jessica Redfern, John C. Field, Ric Brodeur and Kurt Fresh
Ecosystem indicators for the California Current: A quantitative approach towards indicator development

Jameal F. Samhouri
Much ado about everything: Comparison of expert-based vulnerability assessments for coastal habitats along the U.S. west coast

Jennifer Boldt, Alida Bundy, Caihong Fu, Lynne Shannon and Yunne Shin
An overview of IndiSeas2: Evaluating the status of marine ecosystems in a changing world

Poster presentation

Nadezhda L. Aseeva
Reconstructions of flounder community on the shelf of West Kamchatka (Okhotsk Sea) under influence of environmental changes and interspecies relationships

Working Group 28 on *Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors*

The Working Group met from 9:00 to 17:00 on October 13, 2012 at the International Conference Center, Hiroshima, Japan. The main objective of the meeting was to review activities during the first year of WG 28 and discuss the methodologies and outcomes for characterizing critical stressors and indentifying locations where multiple stressors interact in North Pacific ecosystems. Participants at this meeting are identified in *WG 28 Endnote 1* and the agenda for the meeting can be found in *WG 28 Endnote 2*.

AGENDA ITEM 2
Review of activities during the first year

Terms of Reference

The Terms of Reference (*WG 28 Endnote 3*) were reviewed and discussed. It was recognized that they are very ambitious, each of which could be an entire research project on their own. However, the WG felt that progress made on any of the Terms of Reference would be an important contribution to PICES and its FUTURE program.

Report on PICES-2012 Workshop W1

Co-convenors, Drs. Jennifer Boldt and Jameal Samhouri, of PICES Workshop W1 on "*Identifying critical multiple stressors of North Pacific marine ecosystems and indicators to assess their impacts*" presented their report (see Session Summaries elsewhere in the PICES-2012 annual report). Seven papers were presented. Three types of approaches were proposed: (1) expert-based surveys, (2) model-based analyses, and (3) empirical/data based analyses, although it was recognized that the boundaries between the approaches are fuzzy and often more than one approach is used. High level advantages and disadvantages of each of these approaches were identified. Tables were developed to assess the general availability of data in four categories to develop indices of multiple stressors on marine system. These categories were environmental, biological, human activities and stressors, and social-political-economic indicators. The purpose was to identify information gaps, and which categories have similar or different levels of information available in each of the PICES member countries (Do they data exist? Are time series available? and What is the extent of spatial coverage?). The concept for these tables is similar to that used by WG 19 on *Ecosystem-based Management Science and its Application to the North Pacific* which developed a table to assess the information potentially available in each PICES member country for ecosystem indicators (*PICES Scientific Report 37, Chapter 3, Table 3.1.3*).

WG 28 expressed its appreciation to the Convenors for an excellent session.

Action: Korean and Chinese members of the Working Group are asked to complete the tables for their countries.

Report on PICES-2012 Topic Session S10

Co-convenors, Drs. Vladimir Kulik, Ian Perry, and Motomitsu Takahashi, gave a short presentation on the general contents and expected outcomes from Topic Session S10, "*Ecosystem responses to multiple* *stressors in the North Pacific*”, which was held later in the week, on Friday 19, October. This session was co-sponsored by SOLAS (Surface Ocean – Lower Atmosphere Study), a core program of the International Geosphere-Biosphere Program (IGBP). See the Session Summaries section of the PICES-2012 annual report for a complete description of the Topic Session.

National Reports on related activities

WG 28 members provided brief reports on additional activities in their countries relevant to the work of WG 28.

Canada: Dr. Perry made a short presentation on the work by DFO Pacific Region to develop a risk-based assessment framework to identify priorities for ecosystem-based oceans management in the Pacific Region. The work is based on a recent report (DFO 2012. Risk-based Assessment Framework to Identify Priorities for Ecosystem-based Oceans Management in the Pacific Region. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2012/044. Available at http://www.dfo-mpo.gc.ca/csas-sccs/Publications/SAR-AS/2012/2012_044-eng.html). It develops an ecological risk assessment framework (ERAF) to support the identification of risks and threats to Valued Ecosystem Components (VECs). It is suitable for identifying and assessing relative risks of harm to VECs from human activities and their associated stressors, and for ranking the significance of activities and stressors based on the relative risks to VECs in support of ecosystem-based management. In addition, a Driver-Pressure-State-Impact-Response (DPSIR) model can be used to identify priority drivers and pressures.

Korea: Dr. Ik Kyo Chung presented a brief overview of the IFRAME concept as developed by Dr. Zhang (Zhang *et al.* 2010, *Fisheries Research*; Zhang *et al.* 2011, *ICES J. Mar Sci.*).

USA: Dr. Samhouri suggested that NOAA’s Integrated Ecosystem Assessment activities for the California Current could be leveraged for WG 28 purposes. These activities include recent efforts to compile time series for drivers and pressures (which are good for characterizing the temporal extents of stressors) and a paper which integrates expert opinion with empirical data to evaluate risk to habitats. In collaboration with Stanford University and NCEAS at UC Santa Barbara, Dr. Samhouri is also part of a new project, focused on identifying thresholds for marine spatial planning (http://thresholds.nceas.ucsb.edu/static/Welcome.html), which may bear some relevance to WG 28 activities.

AGENDA ITEM 3

Methodologies to address the Terms of Reference (*WG 28 Endnote 3*)

Framework for identifying multiple interacting stressors and their trends

WG 28 developed an applied web-based questionnaire regarding expert opinions on habitats which may be vulnerable to multiple stressors. For each question, respondents were asked to identify how certain they are of their estimates: 1: very low (<15%); 2: low (15–50%); 3: high (50–85%); 4: very high (>85%).

- *Spatial Extent*: spatial scale at which a single event of the activity/stressor impacts this habitat. Values were scored as 1 = <10 km^2; 2 = 10–100 km^2; 3 = 100–1000 km^2; 4 = >1000 km^2.

- *Frequency*: average annual frequency at which the activity/stressor occurs at a particular location in this habitat. Values were scored as 1 = rare, *e.g.* once every >5 yrs; 2 = occasional, *e.g.* once every >1–5 yrs; 3 = seasonal, *e.g.* every season to once a year; 4 = persistent, *e.g.* daily or continual.

- *Trophic impact*: primary level affected by the activity/stressor within the habitat. Values were scored as 1 = species (single or multiple); 2 = single trophic level; 3 = >1 trophic level; 4 = entire community.

- *Resistance to change*: degree to which the species, trophic level(s), or entire habitat's "natural" state is impacted by the activity/stressor, *i.e.*, how good is the resistance of this habitat to change caused by this activity/stressor. Values were scored as 1 = activity/stressor has a positive impact; 2 = high resistance to change (*i.e.* little significant negative change in biomass); 3 = moderate resistance to negative change; 4 = low resistance to negative change (*i.e.* significant negative biomass changes result from small stresses).

- *Recovery time*: average time required for the affected species, trophic level(s), or entire community to return to its "natural" state following disturbance by this activity/stressor. Values were scored as: 1 = <1 year; 2 = 1–10 years; 3 = 10–100 years; 4 = >100 years.

This survey of experts to identify habitats, stressors, and the vulnerability of habitats to each stressor was discussed:

Canada: The survey was distributed to over 50 experts; the geographic focus was the Strait of Georgia. The response rate was rather low, with some respondents replying that the survey was too difficult and they felt they did not have the expertise to respond to habitats and stressors beyond the research areas. Other respondents replied that the survey was too simplistic and could not possibly capture what is really going on. Dr. Perry presented the results in Topic Session S10.

China: no information was obtained from China yet, but Dr. Takahashi received some responses from some Chinese experts and will follow up on this.

Japan: Dr. Takahashi provided a brief overview of his presentation for Topic Session S10, reviewing the survey results for Japanese waters. He focused on the survey results from the Seto Inland Sea, in which coastal development has reduced the natural shore lines (majority of effects are artificial and semi-natural) and decreased tidal flat and sea grass beds due to coastal development. Problems for scoring encountered in survey: evaluation of impacts could be different among experts with different expertise; certainty of impacts are different among ecosystems due to quality and quantity of information. For the East China Sea, more information on intertidal and coastal waters along China are needed.

Korea: Dr. Chung did the survey with his students, and they found it difficult. He suggested conducting a preliminary review of information and then reducing the list and sending it out to survey participants. He commented that there is a lot of activity in member countries, and it was important to collate that information and not re-invent the wheel.

Russia: Dr. Kulik described that Dr. Olga Lukyanova does research on small spatial scales and human activities/stressors on ecosystems, which is regulated by government standards. Dr. Kulik's research is on a broader spatial scale. Ecosystem status; surveys sampled all the fish caught by trawl with 1 cm mesh, targeting mainly to estimate commercially important species, and the project to estimate energy flows in ecosystems through carbon (C/N) and nutrients among species moved to a new stage this year. Geographic and temporal (seasonal) variation will be taken into account. He noted that environmental information including water property profiles (T, S and sometimes acidity, pH, alkalinity, phosphate, silicate, nitrite, nitrate and DO), zooplankton composition and stomach contents almost at every trawling station are available, but at the first stage of extracting environmental pattern fluctuations, more frequent and regular time series such as SST and sea ice were chosen. Human information has been estimated through ship tracks taking into account maximum power of each vessel and type of trawling (is it bottom trawling or not?) through the area since 2003.

USA (Washington): Dr. Samhouri made a presentation at Workshop W1 on his results from the survey sent to experts on Puget Sound. He is restricted to sending the survey to federal employees only, but distributed the survey to ~45 of them.

USA (Alaska): Dr. Patricia Livingston attended the WG meeting on behalf of Dr. Stephani Zador. She described the Ecosystem Considerations document that is developed each year to accompany their stock assessment advice reports. They developed a team-based approach to derive a focused set of indicators and to provide ecosystem-specific assessments with state information. The main conclusions are: 1. the physiological and biological nature of the ecosystem, the extent of scientific knowledge about the ecosystem, and the particular expertise of team members will influence the final assessment product; 2. team discussion of assessment structuring themes should occur before indicator selection, and 3. developing assessments should be an iterative process with frequent review by fisheries managers. Some experts have expertise in only some areas; could target expert opinion in particular habitats.

WG 28 participants went over the scoring for the survey. Did the metrics work well? It can be difficult for experts to simplify things to fill out the survey. Some people did not want to do the survey because they did not have expertise on all things; others who know a lot about the ecosystem had difficulty because they know too much – *i.e.*, it can be difficult for experts to think generally. However, the value of this type of survey is having many people respond to the survey (provides an idea of consensus). In addition, the conclusions drawn from the responses can be verified in situations where empirical data exist. For the survey, respondents were asked to provide an estimate of their certainty for each question. These results can be used to identify components of vulnerability of habitats to stressors where information and understanding is lacking. For example, in the Canadian survey it appears that resistance to change and recovery time was usually scored with lower certainty than the other three components.

There was a long discussion on how to combine scores, and in particular how to include the certainty estimates for each component. For example, add them up or weight the responses based on their certainties estimates? In general, the goal is to produce a scaling in which a larger number represents a stronger impact. Dr. Perry proposed re-scaling the certainty scores, for example:

		Low certainty	High certainty
		Certainty scores 1 or 2	Certainty scores 3 or 4
Low impact	Certainty scores 1 or 2	2	1
High impact	Certainty scores 3 or 4	1	2

These weightings would then be multiplied by the scores for each vulnerability component, and then summed to derive the overall vulnerability score for that habitat to that stressor.

Dr. Samhouri proposed weighting the certainty values and multiplying them by the impact score. Alternatively, responses for which uncertainty >50% (*i.e.*, certainty <50%) could be deleted. In Alaska, Dr. Zador asked for uncertainties for each entry, which were then entered as a decimal. For example: enter 1–4 according to the definition (column B) for each vulnerability (x) AND include the decimal value in each cell corresponding to how certain you are of this value:
(x.1) best guess,
(x.2) some evidence of interaction from other systems,
(x.3) some evidence of interaction from this system,
(x.4) evidence of interaction from this specific habitat in this system (*e.g.*, published paper).
If there is no interaction, just leave the cell blank. For example: a value of 3.2 would represent moderate certainty seasonal changes in freshwater flow affecting intertidal mud habitats based on studies from other systems.

Another suggestion was to use a certainty score of 0 and 1; however, it was pointed out that a score of 0 would eliminate too much information and having more than 2 scores provides more information.

In conclusion to this agenda item, it was suggested to examine different methods for this, and consider performing a sensitivity analysis on different weighting scenarios. The goal would be to recommend a common method for all members of WG 28 to use. It was also noted that the Teck *et al.* paper (*Ecological Applications* 20(5): 1402–1416, 2010) suggests that vulnerability is better represented by the resistance to change and the trophic level components.

Action: Drs. Samhouri and Perry to explore options for dealing with the certainty values.

Potential indicators for these stressors and interactions, and how they relate to ecosystem responses and identification of vulnerable ecosystem components

The Working Group discussed whether ecosystem indicators for multiple and interacting stressors would be any different from those developed for single stressors, such as fishing.

It was noted that the 'management class' of ecosystem indicators perhaps depends on the objectives constructed for those indicators more so than the type of stressor that is present. For example, say that indicators are relevant to objectives and the indicators will change for the objectives. However, knowing which stressors are causing ecosystems to respond is important for understanding how and why the ecosystem is changing. The indicators developed from the IndiSeas (www.indiseas.org) and the Alaska Ecosystems Considerations chapter may provide good starting points for baseline indicator sets that could be examined to determine if they need to be expanded to address issues of multiple stressors. Another suggestion was to develop indicators of ecosystem responses, followed by how stressors are changing, and then conduct correlative type analyses to relate the two sets of time series.

It was recommended that this topic be given further thought and be a main item for discussion at the Working Group meeting next year.

AGENDA ITEM 4

Discussion on draft Table of Contents and outline for the WG 28 final report

A draft Table of Contents (*WG 28 Endnote 4*) for the final report of WG 28 was reviewed and modified, and proposed chapter leads were identified. It was recommended to consider the use of a web-based platform (*e.g.*, Google docs) to access and track edits and version changes to the evolving chapters. Alternatively, a private page on the PICES website could be requested for the Working Group. The Group chose to leave it to the discretion of each set of chapter authors as to how they wish to handle their writing process. In addition, it was agreed that the delivery date for the Working Group could be no earlier than 2014 (which is the expected due date to the parent BIO and MEQ committees), but could possibly need to be extended to 2015.

Action:

- Chapter leads and contributing authors (see *WG 28 Endnote 4*) are to develop outlines for their chapters and detailed contents (for those chapters where this is possible) over the next year, and have ready for discussion at the next meeting.
- Working Group Chairs to notify the parent Committees about the anticipated delivery dates for the WG 28 final report.

AGENDA ITEM 5

Discussion of interactions with other PICES groups

Working Group members anticipate interactions with the following PICES groups:

- Section on *Climate Change Effects on Marine Ecosystems*
- MAFF-funded project on marine ecosystems and human well-being
- Section on *Human Dimensions of Marine Systems*
- Any expert groups working on harmful algal blooms or invasive species
- MONITOR Committee, re: environmental indicators

Interactions with other PICES groups are also welcome.

AGENDA ITEM 6

Topic Session at PICES-2013

A proposal for a Topic Session at the next PICES Annual Meeting was submitted through a new on-line submission system to the PICES website (*WG 28 Endnote 5*). The Working Group felt this was a very ambitious topic, but appropriate for this Working Group to begin to address. Suggestions for possible invited speakers include: Marten Scheffer (The Netherlands), Steve Carpenter (USA), an expert from the IndiSeas program, Shinsuke Tanabe (CMES, Ehime University, Japan) – eco-toxicologist, and Isabel Coté (Canada) or her student Emily Darling.

The next meeting of the Working Group is expected at PICES-2013 to be held in Nanaimo, Canada.

AGENDA ITEM 7

Adjourn

The meeting adjourned at 1700 h, followed by a sake sampling and yakitori dinner party.

WG 28 Endnote 1

WG 28 meeting participation list

Members

Jennifer L. Boldt (Canada)
Ik Kyo Chung (Korea)
Sachihiko Itoh (Japan)
Vladimir V. Kulik (Russia)
Ian Perry (Canada, Co-Chairman)
Jameal Samhouri (USA)
Motomitsu Takahashi (Japan, Co-Chairman)
Naoki Yoshie (Japan)
Stephani Zador (by WebEx for the first half of the meeting)

Observers

Christopher Aura (Japan)
Karin Baba (Japan)
Natalie Ban (Australia)
Yoichiro Ishibashi (Japan)
Patricia Livingston (USA)
Kazuhito Mochida (Japan)
Masakatsu Ohyama (Japan)
Takafumi Yoshida (Japan)
Hiroaki Saito (Japan)

WG 28 meeting participants at PICES-2012 in Hiroshima, Japan. Left to right: Motomitsu Takahashi, Hiroaki Saito, Sachihiko Itoh, Takafumi Yoshida, Christopher Aura, Naoki Yoshie, Jameal Samhouri, Natalie Ban, Yoichiro Ishibashi, Patricia Livingston, Karin Baba, Jennifer Boldt, Ik Kyo Chung, Vladimir Kulik, Ian Perry.

WG 28 Endnote 2

WG 28 meeting agenda

1. Welcome, Introduction and sign-in (all)
2. Review of activities during the 1st year of WG 28
   a) General review of Terms of Reference
   b) Report on outcomes of Workshop W1
   c) Report on Topic Session S10
   d) Report on additional related activities from each PICES country
3. Discuss methodologies to address the Terms of Reference
   a) Framework for identify multiple interacting stressors and their trends (e.g. session S10)
   b) Potential indicators for these stressors and interactions, and how they relate to ecosystem responses and identification of vulnerable ecosystem components (e.g. W1)
4. Discussion on draft Table of Contents, outline for the WG 28 final report, and assignment of tasks: begin developing the outline for the final report, discuss the general contents of each chapter, and who will take the lead on each chapter.
5. Discussion of interactions with other PICES groups
   a) Relationships between WG 28 and other Working Groups and Committees
   b) Contributions to FUTURE
6. Discussion on Topic Session at PICES-2013
   a) Review of a topic session proposal
   b) Other related issues
7. Adjourn

WG 28 Endnote 3

Terms of Reference

1. Identify and characterize the spatial (and temporal) extent of critical stressors in North Pacific ecosystems both coastal and offshore and identify locations where multiple stressors interact. Identify trends in these stressors if possible.
2. Review and identify categories of indicators needed to document status and trends of ecosystem change at the most appropriate spatial scale (e.g., coastal, regional, basin).
3. Using criteria agreed to at the 2011 PICES FUTURE Inter-sessional Workshop in Honolulu, determine the most appropriate weighting for indicators used for:
   a. documenting status and trends
   b. documenting extent of critical stressors
   c. c. assessing ecosystem impacts/change
4. Review existing frameworks to link stressors to impacts/change, assessing their applicability to North Pacific ecosystems and identify the most appropriate for application to North Pacific ecosystems.
5. Determine if ecosystem indicators provide a mechanistic understanding of how ecosystems respond to multiple stressors and evaluate the potential to identify vulnerable ecosystem components.
6. For 1-2 case studies, identify and characterize how ecosystems respond to multiple stressors using indicators identified above. Are responses to stressors simply linear or are changes non-linear such that small additional stressors result in much larger ecosystem responses? Do different parts of the ecosystem respond differently (*e.g.*, trophic level responses)? How do stressors interact?

7. Publish a final report summarizing results with special attention to FUTURE needs. This WG will focus primarily on delivery of FUTURE Questions 3 and 1 (outlined below).

Linkages to the FUTURE Science Plan:

1. What determines an ecosystem's intrinsic resilience and vulnerability to natural and anthropogenic forcing?
2. How do ecosystems respond to natural and anthropogenic forcing, and how might they change in the future?
3. How do human activities affect coastal ecosystems and how are societies affected by changes in these ecosystems?

WG 28 Endnote 4

DRAFT Final Report Table of Contents

(Note: all WG members are expected to contribute to each main chapter; names listed are those who will likely take the leads for each chapter)

1. Introduction (Co-Chairs)
   – background to WG 28
   – Terms of Reference / Objectives
   – brief overview of the issue of multiple activities/stressors on marine ecosystems:
     - *e.g.*, use of the phrase "activities/stressors (or "pressures") to indicate both natural and anthropogenic pressures, and that not all of these are always "bad" for the ecosystem,
     - include definitions for "stressors", issue that information to construct indicators is often available at multiple but different time and space scales, *etc*.

2. Frameworks linking pressures to impacts and changes in North Pacific marine ecosystems (Perry, Takahashi, Samhouri, Zhang, Lee)
   – brief review of potential frameworks that could be used to link activities and stressors to ecosystem responses,
   – assessment of their applicability to North Pacific marine ecosystems,
   – recommendations for applications,
   – *e.g.*, Pathways of Effects and Driver-Pressure-States-Impact-Response models; simulation and other analytical modeling approaches, *e.g.* Ecopath with Ecosim, probabilistic (Bayesian) networks; Integrated Ecosystem Analyses; IFRAME, others?
   – addresses ToR 4.

Multiple pressures on North Pacific marine ecosystems
   – identification of the spatial (and temporal, if available) extent of important activities and stressors in North Pacific marine ecosystems,
   – identify habitats and general locations (if possible) where multiple stressors overlap,
   – identify trends in these activities/stressors if possible,
   – sub-sections of this chapter for each PICES country, preferably using a common approach, plus a synthesis section,
   – *e.g.*, PICES Topic Session S10 at 2012 Annual Meeting (Hiroshima),
   – addresses ToR 1.

3. Ecosystem indicators (Boldt, Ito?, Samhouri, Yoshie, Kulik, Chung – re filing W1 tables)
   – brief review of indicators proposed in the literature to document status and trends of ecosystem conditions,
   – present criteria proposed for the selection of indicators, *e.g.*, Rice and Rochet (2005. *ICES J. Mar. Sci.* 62: 516–527), PICES-2011 FUTURE Workshop,
   – focus in particular on indicators relevant for assessing multiple pressures,
   – addresses ToR 2 and 3.

Indicators for ecosystem responses to multiple pressures
   – identify ecosystem indicators which might be used to provide an understanding of how ecosystems respond to multiple stressors
   – (could use case studies to provide mechanistic understanding where these are known)
   – evaluate their potential to identify vulnerable ecosystem components
   – *e.g.*, PICES Workshop W1 at 2012 Annual Meeting (Hiroshima)
   – Include tables produced in W1 regarding available data
   – addresses ToR 5

4. Case study examples (or embed in above chapters??) (Samhouri, Perry, Boldt, Takahashi, Itakura?)
   – which areas:
   - Salish Sea (Strait of Georgia; Puget Sound),
   - Seto Inland Sea,
   - Possibly: Sea of Okhotsk, Bering Sea (?Lukyanova, Kulik, Zador?)

5. Conclusions and recommendations (Co-Chairs)

Appendices
1. Terms of Reference
2. Membership
3. Reports of sessions held by WG28
etc.

WG 28 Endnote 5

Proposal for a 1-day Topic Session on "*Ecosystem indicators to characterize ecosystem responses to multiple stressors in North Pacific marine ecosystems*" at PICES-2013

Multiple natural and human stressors on marine ecosystems are common throughout the North Pacific, and may act synergistically to change ecosystem structure, function and dynamics in unexpected ways that can differ from responses to single stressors. Further, these stressors can be expected to vary by region, and over time. Understanding the impacts of multiple stressors, and developing indicators which capture their behaviours and changes, are major challenges for an ecosystem approach to the North Pacific and for the PICES FUTURE project. The objective of this session is to present potential indicators of ecosystem responses to multiple stressors in the North Pacific (with the focus on multiple, rather than single, stressors). One goal of the session is to determine if these proposed ecosystem indicators provide a mechanistic understanding of how ecosystems respond to multiple stressors and to evaluate their potential to identify vulnerable ecosystem components. For example, 1) are responses to stressors simply linear or are changes non-linear such that small additional stressors result in much larger ecosystem responses; 2) do different parts of the ecosystem respond differently (e.g., trophic level responses); 3) how do stressors interact and can these interactions be adequately captured by the proposed indicators? Both empirical and model-based analyses are welcome. This session will provide input to Working Group 28 on ecosystem indicators for multiple stressors on the North Pacific, and will feature progress and presentations from within and outside of this Working Group.

Sponsoring Committee/Program: BIO/FIS/MEQ/TCODE/FUTURE

Co-convenors: Ian Perry (Canada), Vladimir Kulik (Russia), Chaolun Li (China), Jameal Samhouri (USA), Motomitsu Takahashi (Japan) , Chang-Ik Zhang (Korea)

NOWPAP/NEASPEC Joint Workshop on Marine Biodiversity Conservation and Marine Protected Areas in the Northwest Pacific

March 13–14, 2013, Toyama, Japan

UNITED NATIONS ESCAP
Economic and Social Commission for Asia and the Pacific
SUBREGIONAL OFFICE FOR EAST AND NORTH-EAST ASIA

NEASPEC/NOWPAP Joint Workshop on Marine Biodiversity Conservation and Marine Protected Areas in the Northwest Pacific

13-14 March 2013, Toyama, Japan

REPORT OF THE WORKSHOP

1. NEASPEC and NOWPAP jointly organized the Workshop on Marine Biodiversity Conservation and Marine Protected Areas in the Northwest Pacific on 13-14 March 2013 in Toyama, Japan, to share information of methodologies for marine environment assessment and the current status of Marine Protected Areas (MPAs) in member States, and discuss the programmes and operational modality of the proposed North-East Asian MPA Network.

2. The Workshop brought together national focal points of the Network and experts from China, Japan, Republic of Korea and the Russian Federation and international marine programmes including the Helsinki Commission (HELCOM), the North Pacific Marine Science Organization (PICES) and IOC Sub-Commission for the Western Pacific (WESTPAC).

3. The Workshop on the first day led by NOWPAP focused on the Status of MPAs and Future Plans for Conservation of Marine Biodiversity, and Current Status and Challenges of Assessing Marine Environment for Marine Biodiversity Conservation. The summary of the discussion on these topics is attached as annex.

4. The Workshop on the second day led by NEASPEC focused on MPA and Potential Areas of Subregional Cooperation, and Programme and Operational Modality of North-East Asia MPA Network. Major findings from the Workshop's review of MPAs in member States are as follow.

5. **China**: Since 1963, China has established 235 MPAs consisting of 171 Marine Nature Reserves (at both national and provincial levels), 40 Special Marine Reserves (Ocean Park, Marine Ecological Reserve, Marine Resource Reserve, etc) and 24 Fisheries Genetic Resources Reserves. Amongst them, national Marine Nature Reserve has the strictest regulations for management by not allowing any human activity in core and buffer zones except scientific and educational activities which require prior approval from the State Council. In terms of institutional arrangements, four main agencies including Ministry of Environmental Protection (MEP), State

Oceanic Administration (SOA), States Forestry Administration (SFA) and Bureau of Fisheries under the Ministry of Agriculture (MOA) are responsible for the management of MPAs.

6. **Japan:** Existing systems that may correspond with some features of MPAs are following:
   29 Natural Parks, 56 Quasi National Parks, 91 Natural Coastal Protected Zones, 1 Nature Conservation Area (in Okinawa), 82 Wildlife Protection Areas, 55 Protected Water Surface, Natural Habitat Conservation Area, and Natural Monuments of which Nature Conservation Area, National Park and Natural Monument are under the IUCN protected area categories of I-III. In order to strengthen and improve MPA management, in 2011 the Government made a further clarification of MPA definition in Marine Biodiversity Conservation Strategy, highlighting the goals of supporting the sound structure and function of marine ecosystems and ensuring the sustainable use of marine ecosystem services.

7. **Republic of Korea**: Since 1968, Republic of Korea has created 565 protected areas adjacent to/or related to marine environment. The protected areas include 6 Protected Marine Areas, 12 Wetland Protection Areas, 4 Marine Environment Conservation Areas, 10 Fisheries Resource Protection Areas, 167 Special Islands, 4 National Parks, 3 Ecosystem/Landscape Conservation Areas, 166 Wildlife Protection Areas, and 193 Natural Heritages, while many of them may not necessarily fall under the strict definitions of MPAs. In terms of institutional mechanisms, Ministry of Land, Transport and Maritime Affairs (MLTM) is responsible for managing three areas including protected marine area, wetland protection area, and marine environment conservation area, while Ministry of Environment is responsible for special islands, national parks, ecosystem/landscape conservation areas and wildlife protection areas. For fisheries resource protection areas, both MLTM and Ministry of Food, Agriculture, Forestry and Fisheries (MIFAFF) are engaged in their management. Also Cultural Heritage Administration (CHA) takes responsibilities of cultural heritage.

8. **Russian Federation**: Russian Federation’s MPAs at federal level include 19 marine nature reserves, 2 national parks, and 10 wildlife refuges. In order for the Russian Federation to fulfill the goals of CBD, it introduced a draft concept of development of MPAs in 2012 which aims to develop MPA system by improving the efficiency of management and operation, and to ensure environmental safety, protection of biological and landscape diversity, conservation and sustainable management of natural and cultural heritage.

9. Regarding the programme and operational modality of the Network, the Workshop came to the following conclusions:

   a. **Objective**: Strengthen roles of marine protected areas in the conservation of marine biodiversity with aim to reach ecologically coherent (adequacies and representatives, replication and connectivity) network of well managed MPAs.

   b. **Activity Areas of the Network**: Information and knowledge sharing; Knowledge building through collaborative work; Capacity building for management; Networking with relevant regional and global mechanisms; and Raising public awareness and stakeholder involvement.

c. **Target MPAs**: The Workshop decided to enlist all of the above-mentioned MPAs in each member States for further consideration, and requested the national focal points to communicate with the Secretariat about the scope of target MPAs for the Network. While the selection of target MPAs are subject to further consultations with each member State, in the case of the Russian Federation, the national focal point proposed to focus on MPAs in Russian Far East only.

d. **Network Membership**: Central and local Management authorities of member States for MPA; National institutions and academic institutions; and International organizations and non-governmental organizations.

e. **Organizational Structure**: The Workshop discussed the proposed format of the structure which may consist of steering committee, advisory committee and network secretariat, and requested the Secretariat to reformulate options based on the review of organizational structure of similar networks.

f. **Budget:** The Workshop came to a general understanding that the core budget would be covered by NEASPEC while other funding sources including Asia- Pacific Network for Global Change Research (APN) could be explored for programme.

g. **Secretariat and Programme Operation**: The Workshop agreed that the Network Secretariat will be operated by NEASPEC in collaboration with NOWPAP. With regard to programme, the Workshop reviewed two options: Option 1. The activities of the Network shall be coordinated by NEASPEC in cooperation with NOWPAP and other relevant mechanisms including YSLME, PEMSEA and WWF; Option 2. The activities of the Network shall be jointly coordinated by NEASPEC and NOWPAP in cooperation with other relevant mechanisms including YSLME, PEMSEA and WWF. A decision on the two options will be made after further consultations within NEASPEC and NOWPAP, respectively.

h. **Roles of Member States**: The Secretariat stressed the importance of member States-driven programme and contributions of member States to program formulation and implementation. In this regard, the Secretariat informed that a template for collecting views of member States on their contribution to and expectations about the Network will be circulated to national focal points in due course.

i. **Expected process**: The Secretariat presented a tentative timeline for preparing terms of reference and programme of the Network as follow: (1) March-July 2013: Developing a detailed terms of reference and programme through close consultations; (2) October-December 2013: Approval of the SOM-18 on the TOR and programme and reporting to NOWPAP IGM; and (3) early 2014: launching seminar and commencing activity implementation.

…….

Annex

NOWPAP/NEASPEC Joint Workshop on Marine Biodiversity Conservation and Marine Protected Area in the Northwest Pacific

Summary of Joint Workshop

Marine biodiversity conservation is one of the most significant marine environmental issues in the NOWPAP region. To conserve marine biodiversity and achieve “Aichi Target”, each NOWPAP member state is expected to promote their measures as much as possible. NOWPAP/CEARAC is expected to provide the NOWPAP member states with useful information and tools in line with its designated roles and responsibilities to contribute to marine biodiversity conservation and sustainable use of marine ecosystem services in the NOWPAP region. The results of discussion in each session are summarized as follows.

Session 1: Status of MPAs and future plans for conservation of marine biodiversity

1. The meeting shared information on details of MPA, including definition, categories and monitoring/management status in each member state, and develop an information sheet on MPA definition/categorizations to be finalized based on additional information provided after the workshop.

2. The meeting discussed the similarities and differences of definition/categorization of MPA in the member states and recognized the usefulness of such information for future considerations in improving the management and/or expanding the area of MPAs.

3. The meeting shared information on challenges in properly maintaining and managing MPAs as well as future plans to design/expand MPAs including the possible application of “Ecologically or Biologically Significant Sea Area (EBSA)” concept developed by CBD.

4. The meeting recommended that CEARAC will further collect and compile the above-mentioned information in the Regional Report to be published in the end of 2013 and make best effort to widely disseminate such information for the use of the member states.

Session 2: Current status and challenges of assessing marine environment for marine biodiversity conservation

5. The meeting learned prior/ongoing related activities for assessing marine environment for marine biodiversity conservation conducted by PICES, HELCOM and IOC/WESTPAC and recognized the usefulness and necessity of marine environmental assessment especially for conservation of marine diversity in the NOWPAP region.

6. The meeting recognized that the "Procedures for assessment of eutrophication status including evaluation of land-based sources of nutrients for the NOWPAP region" could be a good base to consider a marine environmental assessment tool for marine biodiversity conservation.

7. The meeting stressed the necessity of Ecological Quality Objectives for the NOWPAP region as the basis of setting targets for assessment and appropriate management. The meeting also noted that necessity of collaborative regional activities toward the conservation of marine biodiversity in the whole NOWPAP region.

8. The meeting recommends the followings:

- CEARAC assesses the availability of data and considers the collection of meta data and development of assessment tool based on the available data for marine biodiversity conservation in the NOWPAP;

- while recognizing that the indicators employed by HELCOM and indicators being studied by PICES are useful reference for the NOWPAP region, CEARAC fully takes into account the availability of data, and the different conditions of marine environment in the NOWPAP region when selecting indicators;

- CEARAC prepare a workplan for the above-mentioned work to be further discussed in its Expert Meeting and Focal Point Meeting;

- CEARAC strengthens collaboration with relevant partners, for example PICES, HELCOM and IOC/WESTPAC in conducting the above tasks.

Session 2

Current status and challenges of monitoring and assessing marine biodiversity conservation

Presentations

"Development of Ecosystem Indicators to Characterize Ecosystem Response to Multiple Stressors", Dr. Vladimir V. Kulik (PICES WG 28)

"Comprehensive ecosystem assessment for marine biodiversity conservation", Dr. Maria Laamanen (HELCOM)

"Activity on marine biodiversity conservation in the IOC/WESTPAC", Dr. Yasuwo Fukuyo (IOC/WESTPAC)

PICES-2013

October 11–20, 2013, Nanaimo, Canada

Excerpted from:

Summary of Scientific Sessions and Workshops at PICES-2013

BIO/FIS/MEQ/TCODE/FUTURE Topic Session (S8)

Ecosystem indicators to characterise ecosystem responses to multiple stressors in North Pacific marine ecosystems

Co-Convenors: *Vladimir Kulik (Russia), Chaolun Li (China), Ian Perry (Canada), Jameal Samhouri (USA)*, Peng Sun (China), Motomitsu Takahashi (Japan) and Chang-Ik Zhang (Korea)*

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* Jameal Samhouri was unable to attend PICES-2013 due to the U.S. government partial shutdown.

Invited Speakers:
Isabelle Côté (Simon Fraser University, Canada)
Yunne-Jai Shin (Institut de Recherche pour le Développement, France)
Mingyuan Zhu (First Institute of Oceanography, SOA, PR China)

Background

Multiple natural and human stressors on marine ecosystems are common throughout the North Pacific, and may act synergistically to change ecosystem structure, function and dynamics in unexpected ways that can differ from responses to single stressors. These stressors can be expected to vary by region, and over time. Understanding the impacts of multiple stressors, and developing indicators which capture their behaviours and changes, are major challenges for an ecosystem approach to the North Pacific and for the PICES FUTURE project. The objective of this session was to present potential indicators of ecosystem responses to multiple stressors in the North Pacific (with the focus on multiple, rather than single, stressors). One goal of the session was to determine if these proposed ecosystem indicators can provide a mechanistic understanding of how ecosystems respond to multiple stressors. For example, 1) are responses to stressors simply linear or are changes non-linear such that small additional stressors result in much larger ecosystem responses; 2) do different parts of the ecosystem respond differently (*e.g.*, across trophic levels); 3) how do stressors interact and can these interactions be adequately captured by the proposed indicators? Conceptual, empirical and model-based analyses were welcome. The results of this session contribute to the work of PICES Working Group 28 on *Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors*.

The session was deeply saddened by the untimely death of Dr. Mingyuan Zhu, and a moment of silence was held in his honour. He was a very important scientist for PICES.

Summary of presentations

The session was well-attended, and with strong participation in questions and discussions. All of the presenters were congratulated for leaving time for questions after their presentations. The session introduced much new information and new ideas, all of which are relevant for the work of Working Group 28. A number of presentations proposed ecologically-based indicator sets and/or methods to evaluate the efficacy of the indicators. A number of talks also discussed how multiple stressors can interact. One important finding from a meta-analysis was that 35% of studies examined found that multiple stressors interacted synergistically, and that antagonistic interactions occurred in 42% of the studies examined. The conclusion from this analysis was that interactions were not additive in the majority of analyses studied, which is usually the default assumption in frameworks examining the impacts of multiple interacting stressors. An important implication of these results is that management actions may not produce the intended result because such actions may alter the interactions among multiple stressors, in particular if the interactions are antagonistic. Overall, discussions questioned how well existing indicators can address temporal scaling issues and the interactions of processes at larger (and smaller) temporal and spatial scales. The issue of sub-lethal stressors and their effects was also discussed, with the potential for indirect stressors to interact with direct stressors. It was recognised that many indicators can be proposed; when developing indicators of human actions and responses an inclusive process is needed. Overall, the consensus was that a good job is being done currently of beginning to model and evaluate responses of indicators to observed and modelled ecosystem changes, although questions remain as to whether these models can adequately address the three types of stressor interactions (additive, synergistic, antagonistic). Participants felt the current state of the art was doing a better job simulating fishing and climate interactions in models. Participants also concluded that no single indicator will be adequate and the use of multiple models was recommended to reduce model-based uncertainties. But an important question was raised: how, and whether, multiple indicators can be combined into smaller sets of summary indicators. At present, it seems the most common way to assess the impacts of more than two stressors is via expert opinion, and sometimes modelling. These techniques have their own important limitations and biases.

List of papers

Oral presentations

Isabelle M. Côté and Emily S. Darling (Invited)
Testing and predicting synergy between multiple stressors

Stephen Ban
Expert elicitation of a Bayesian Belief Network for climate change effects on the Great Barrier Reef

Helen J. Gurney-Smith, Catherine A. Thomson, Dan S. Sanderson, Jennifer Kimball and Stewart C. Johnson
A functional genomics approach to assessing ecosystem health and resilience in keystone bioindicator species

Andrew Day, Thomas A. Okey, Micha Prins and Stephanie King
Developing social-ecological indicators for Canada's Pacific Marine regions: Steps, methods, results and lessons

Joanna Smith, Charlie Short, Steve Diggon, John Bones, Matthew Justice, Andrew Day and Stephanie King
Ecosystem-based management indicators for a marine planning process in BC's north coast- Marine Planning Partnership (MaPP)

Cathryn Clarke Murray, Megan E. Mach, Rebecca G. Martone, Gerald G. Singh, Kai M.A. Chan and Miriam O
Assessing direct and indirect risk from human activities to significant ecosystem components in the Northeast Pacific

Rebecca G. Martone, Melissa M. Foley, Megan E. Mach, Corina I. Marks, Carrie V. Kappel, Kimberly A. Selkoe and Benjamin S. Halpern
Groundtruthing cumulative impact models in nearshore ecosystems of the California Current

Yunne-Jai Shin, Jennifer Houle, Alida Bundy, Marta Coll, Penny Johnson, Chris Lynam, Lynne Shannon and Laure Velez (Invited)
A multi-model evaluation of ecosystem indicators' performance

Caihong Fu and Yunne-Jai Shin
Exploring ecological indicators to evaluate fishing and environmental impacts on ecosystem attributes

Vladimir V. Kulik
Comparing environmental changes over the past 10 years with the states and trends of the ecosystem indicators proposed by IndiSeas in the Sea of Okhotsk

Kirstin K. Holsman and Stephani Zador
Methods to characterize risk of Alaskan marine habitats to multiple stressors and establish ecosystem reference points

Stephen B. Brandt and Cynthia Sellinger
Growth rate potential as a quantitative ecosystem indicator of habitat quality

Doug Hay, Jake Schweigert, Jennifer L. Boldt, Jaclyn Cleary, Thomas A. Greiner and Kyle Hebert
Decadal change in eastern Pacific herring size-at-age and gonad size: A climate connection?

Kisaburo Nakata
The pelagic and benthic coupled biogeochemical cycle model study for Mikawa Bay estuary

Kyung-Su Kim, JeongHee Shim and Suam Kim
The combined effects of elevated CO_2 and temperature on the survival, growth and skeletal formation of olive flounder larvae *Paralichthysolivaceus*

Skip McKinnell
A quantitative method for assessing the interactions of multiple stressors; How I learned to compare apples and oranges

Motomitsu Takahashi and Mingyuan Zhu
Ecosystem responses to anthropogenic activities and natural stressors in the East China and Yellow Seas

R. Ian Perry, Jameal F. Samhouri and Motomistu Takahashi
Developing indicators for ecosystem responses to multiple pressures: Case studies between the eastern and western North Pacific

Sarah Ann Thompson, William J. Sydeman, Heather Renner and John F. Piatt
Regionalizing seabirds as indicators of forage fish in Alaska

Yuxue Qin, Yuichi Shimizu and Masahide Kaeriyama
Risk management for recovering chum salmon populations in the Iwate coastal ecosystem after the Tohoku catastrophic earthquake and tsunami

Yongjun Tian
Interannual-decadal variability in the large predatory fish assemblage in the Tsushima Warm Current regime of the Japan Sea with an emphasis on the impacts of climate regime shifts

Poster presentations

R. Ian Perry and Diane Masson
A statistical approach to the development of ecosystem indicators for multiple pressures in the Strait of Georgia, Canada

Peng Sun, Zhenlin Liang, Yang Yu, Yanli Tang, Fenfang Zhao and Liuyi Huang
Trawl selectivity induced evolutionary effects on age structure and size at age of hairtail (*Trichiurus lepturus*) in East China Sea, China

Guanqiong Ye, Jie Liu and Loke M. Chou
Designing a network of coral reef marine protected areas in Hainan Island, South China

Report of Working Group 28 on *Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors*

WG 28 met from 9:00 to 18:00 h on October 12, 2013 in Nanaimo, Canada, under the chairmanship of Drs. Motomitsu Takahashi (Japan) and Ian Perry (Canada). The meeting objective was to review activities during the 2nd year (2012–2013) of WG 28, plan for activities during the 3rd year (2013–2014), and discuss the contents of the final report. Note that reports from previous WG 28 meetings and sponsored sessions are on the WG 28 web page at http://www.pices.int/members/working_groups/wg28.aspx.

The participants at this meeting are listed in *WG 28* ***Endnote 1***. The agenda for this meeting is presented in *WG 28* ***Endnote 2***. The members of WG 28 are listed in *WG 28 Endnote 3*.

AGENDA ITEM 2
Review of activities during the 2nd year of WG 28

a) Review of Terms of Reference:

The terms of Reference for WG 28 (*WG 28 Endnote 4*) were reviewed and discussed. It was recognized they are very challenging and ambitious. WG 28 is making progress on addressing them, but may not be able to fully respond to all questions. Since this WG is connected to the FUTURE program, it was agreed that requesting an additional one or two years to the duration of WG 28's term is reasonable considering the complexities of the Terms of Reference and the contributions of WG 28 to this program.

WG 28 was requested by the FUTURE Advisory Panels to identify how it will link to the FUTURE. WG 28 will contribute directly to goals 1 and 3 of the FUTURE Science Plan and partially to goal 2:

1. What determines an ecosystem's intrinsic resilience and vulnerability to natural and anthropogenic forcing?
2. How do ecosystems respond to natural and anthropogenic forcing, and how might they change in the future?
3. How do human activities affect coastal ecosystems and how are societies affected by changes in these ecosystems?

The responses of the Working Group to the additional questions posed by Science Board are:

- What is the progress with the expected contribution to FUTURE?
  - Good progress,
  - Habitat-stressor relationships and potential indicators have been identified,
  - Outline of the report has been developed,
  - About 6 months to get a draft together.

- What is the gap/obstacles in making progress?
  - Lack of full representation from all countries,
  - Data exchange,
  - Overuse of the same experts for similar surveys.

- What will be the necessary actions to overcome the gaps?
  - Members might need to be engaged by correspondence through written materials,
  - Bring to the Technical Committee on Data Exchange (TCODE),
  - Similar surveys – but there is no clearing house.
- What kind of coordination is needed with other expert groups?
  - Section on *Human Dimensions of Marine Systems*,
  - Advisory Panel on *Marine Birds and Mammals*,
  - Section on *Ecology of Harmful Algal Blooms in the North Pacific*,
  - WG 21 on *Non-indigenous Aquatic Species* (*e.g.*, Manila clams).
- How well do you communicate with Committees/FUTURE APs on FUTURE matters?
  - Currently report annually with the Committees and FUTURE APs and welcome the opportunity to have additional communication.

b) Report on participation and presentation by WG 28 in NOWPAP Workshop

Purpose of this workshop was to discuss Marine Protected Areas and biodiversity issues in the East Asian Seas region. Goals included developing common language around these topics, and developing marine ecosystem indicators. See PICES Press July 2013 article for a discussion of the meeting and of the WG 28 presentation by Dr. Kulik: http://www.pices.int/publications/pices_press/volume21/v21-n2/pp_28-29_NOWPAP-Wsh.pdf, and also the meeting report on WG28 web page:
http://www.pices.int/members/working_groups/materials/WG-28-2013-Report-from-NOWPAP-MPA-Workshop.pdf

The HELCOM (Baltic Marine Environment Protection Commission – Helsinki Commission) presentation by Dr. Maria Laamanen is of interest to WG 28; see their website for their multi-layered core indicators report (www.HELCOM.fi). One conclusion is that the main interactions among pressures are not additive.

In discussion, it was suggested that Chapter 3 of the WG 28 report might include a summary of main indicator webpages and compare/contrast indicators among ecosystems. For example, which indicators are common in a majority of lists produced by various organisations, and which are ‘unique’ to specific locations? Many indicators are status indicators, but WG 28 is looking for ecosystem response to multiple stressors; can we identify the dominant driver/stressor that is causing changes in an indicator from the observed ecosystem response? In addition, can WG 28 identify candidate early-warning indicators? See also websites for the health of the Salish Sea ecosystem (www2.epa.gov/salish-sea), Baltic Sea (www.HELCOM.fi), and www.oceantippingpoints.org.

Dr. Vladimir Kulik mentioned that another meeting on marine ecosystem indicators was held in early October in Russia. The interest here was to develop ecosystem indicators to assist decisions on Total Allowable Catches because often there is insufficient information to develop Virtual Population Analyses and other traditional stock assessments, but there is information on hydrological conditions and populations, *i.e*., the use of ecosystem indicators to assist with fisheries management.

c) Report on participation and presentation by WG 28 to the 2013 Inter-sessional Science Board meeting, and at the ICES/PICES workshop on "Climate Change Effects on Marine Ecosystems" (SICCME)

These meetings took place in St. Petersburg, Russia, May 20–24, 2013; WG 28 was represented by Dr. Takahashi. For details on the workshop and presentation, please see the web site: http://www.pices.int/publications/presentations/2013-S-CCME-Wsh/2013-SCCME-wsh-agenda.aspx.
In discussion, it was noted that the vulnerability definitions adopted by the IPCC and expressed by Allison *et al*. (2009, *Fish and Fisheries* 10, 173–196), in which the vulnerability of a national economy (or any ecosystem) can be expressed as a function of exposure to pressures, sensitivity to those pressures, and the capacity to adapt to those pressures, may have some applicability to the work of WG 28, in particular at sub-national levels.

d) Report on additional WG 28 session proposals

At the FUTURE Open Science Meeting in Hawaii, April 14–18, 2014, WG 28 is supporting one scientific session and one workshop (*WG 28 Endnote 5*). The WG is also supporting a topic session at the 2014 PICES Annual Meeting in Yeosu, Korea (*WG 28 Endnote 6*).

e) WG 28-sponsored topic session at PICES-2013

WG 28 co-sponsored one topic session (S8) at this PICES Annual Meeting, titled "*Ecosystem indicators to characterise ecosystem responses to multiple stressors in North Pacific marine ecosystems*". Details of this session can be found in the Session Summaries section of the 2013 Annual Report at http://www.pices.int/publications/annual_reports/Ann_Rpt_13/2013-Session-Summaries.pdf.

f) Report on project MEcoPAM

The project "Sustainability of **M**arine **Eco**system **P**roduction under Multiple stressors and **A**doptive **M**anagement" (MEcoPAM) focuses on the impact of multi-stressors on the sustainability of marine ecosystem production in China. It is a project under IMBER.

The sustainability of marine ecosystem production is impacted by multi-stressors, such as physical processes, eutrophication, over-fishing and aquaculture. The objectives of the MEcoPAM project are to identify and characterize the interactions of marine biogeochemical cycles and marine ecosystems, and to understand the response of typical marine ecosystem production to multi-stressors, thereby improving our knowledge of the impact of multi-stressors on the sustainability of marine ecosystem production. The research areas include several unique sub-ecosystems in the Bohai Sea, Yellow Sea, and East China Sea (*e.g.*, the hypoxia zone off the Changjiang Estuary, and aquaculture sites in the Shandong Peninsula). The major scientific questions to be addressed are:

- What is the impact of multi-stressors on biogeochemical cycles in coastal ecosystems (*e.g.*, hydrodynamic control of biogenic element cycles, coupling mechanism of primary production with biogeochemical processes)?
- How does ecosystem functioning in the hypoxia zone of the East China Sea respond to multi-stressors (*e.g.*, the role of metabolism and redox processes on element cycles, impact of hypoxia on the function and structure of marine ecosystem, impact of open ocean and atmosphere)?
- What are the adaptive strategies of coastal aquaculture ecosystems to deal with multi-stressors (*e.g.*, the supporting role of main biogeochemical processes in food production and food web trophodynamics of major biological functional groups, adaptive strategies to fishery management)?

In addition to field observations of the physical, chemical and biological properties of ecosystems in East China Sea, Changjiang Estuary and the coastal area of the Shandong Peninsula, historical data analysis, numerical modelling and microcosm experiments will be undertaken.

The program is structured around five sub-projects: (1) Biogeochemical Dynamics of Marine Ecosystems; (2) Nutrient Cycles and Response to Multi-stressors; (3) Hydrodynamic Response to Multi-stressors and its Impact on the Supply of Nutrients; (4) Microbial Loop and Coupling with Biogeochemical Cycles; and (5) Feedback Mechanisms of Ecosystem Structure and Function to Climate Change and Human Activities.

The project is scheduled for completion in 2015. The project web site is at http://www.imber.info/index.php/Science/National-Network/CHINA/MEcoPAM-project-website.

AGENDA ITEM 3

Progress on Terms of Reference, and brief country reports of activities of interest to WG 28

Canada

Dr. Perry reported that an ecological risk assessment framework has been developed and a detailed case study application has been developed and reviewed – the report is in preparation. Indicators for the Salish Sea ecosystem (Strait of Georgia and Juan de Fuca Strait in Canada, and Puget Sound in the U.S.) have been updated and published (http://www2.epa.gov/salish-sea).

Japan

Dr. Takahashi stated that discussions have been ongoing with China regarding relevant work in the East China Sea. Work has also been ongoing to develop coupled pelagic-benthic biogeochemical models for the Mikawa Bay estuary (*e.g.*, see presentation on "*The pelagic and benthic coupled biogeochemical cycle model study for Mikawa Bay estuary*" in Session S8 by Dr. Kisaburo Nakata: S8-9005).

Korea

Dr. Jaebong Lee informed the WG that a primary ecosystem assessment framework is IFRAME; a current major goal is to identify reference points and conduct risk analyses. Korea has a new *Fishery Act*, but so far no methods for ecosystem-based management. IFRAME may be applicable to aquaculture as well to calculate total allowable aquaculture (TAA) and to assess the carrying capacity and risks of aquaculture to the ecosystem. This is a 3-year project. The project will start at the end of this year or early next year.

Russia

Dr. Kulik said that in Russia, damage to ecosystems is not part of the science program; therefore, there is difficulty in obtaining data. For example, estimates of the total biomass of targeted species can vary considerably because of the use of different base data (spring or fall surveys which target different life stages or species) and different geostatistical techniques (*e.g.*, GAMS, kriging, or other techniques). As a consequence, indicators show promise in providing alternative methods. Several indicators developed by IndiSeas have been explored, although there were issues with FAO designations of over- and moderately exploited species. General additive mixed models have been used to incorporate environmental indicators. Which values are included or excluded from indicators can affect indicator values/outputs. How data are selected or grouped also affects the results. In Russia, there is pressure from Industry on Science to lower the total allowable catch (TAC) because they have to catch 50% of TAC for the TAC to exist the next year. This could be viewed as precautionary since the TAC may not really reflect population status.

United States (Martone)

Dr. Rebecca Martone announced that significant efforts are being directed towards a Marine Monitoring Enterprise and a project on ocean tipping points: www.oceantippingpoints.org. This project is characterizing nonlinear responses in ecosystems, with the goal of developing early warning indicators and how these may be incorporated in oceans management. An example of an early warning indicator is the coefficient of variation, and how it may change as the system approaches a regime shift (*e.g.*, Lindegren *et al*., 2012, *PLoS One* 7(7), e38410). Case study locations for this project include Hawaii, and Haida Gwaii in Canada.

AGENDA ITEM 4

Report draft chapter outlines

Draft outlines for the chapters of the WG 28 final report were presented and discussed. These form the basis for focused work for the next year. The updated chapter outlines (revised from those developed last year in Hiroshima) are presented in *WG 28 Endnote 7*.

It is anticipated that about 50% of the report will consist of a literature review, 30% the application of existing methods to data and information from the PICES region, and 20% of new analyses. The goal now is to create drafts of each of the core chapters, for presentation and discussion at the FUTURE Open Science Meeting in April and subsequently (expecting that not all members of WG 28 will be able to attend this meeting). The objective of these first drafts is to take stock of what we have in hand, and to understand where the gaps remain. These gaps will then become the focus for directed efforts in the remaining two years of the WG.

In discussion of the revised outline for Chapter 2, one gap that was suggested was whether the report should include a summary from each PICES member country of relevant work, using a common template – this is something to consider. There was also discussion about how best to include the open ocean/high seas areas. Some of this may rely on existing assessments. It may also be useful to identify limitations of existing approaches, *e.g.*, the Halpern model for regional level applications; what is important to capture at small spatial scales. We need to be clear that we are not planning on a comprehensive and exhaustive review of all stressors everywhere in the North Pacific. Instead, we could identify what can apply to areas not covered in our report, and their limitations; we need to focus on areas for which we have expertise. A relevant recent publication was noted (Knights *et al*., 2013, *Ecological Applications* 23(4), 755–765) which conducted a network analysis on stressors.

In discussion of Chapter 3, it was noted there needs to be interaction between this chapter and the case studies, *i.e*., perhaps including the trial of some of the indicators proposed in Chapter 3.

Chapter 4 should then take the recommendations from Chapters 2 and 3 to utilize and apply in case studies. It was also noted the terminology should be “indicators of ecosystem responses to multiple stressors” (not “indicators of multiple stressors”). It would be useful to include early warning indicators from the literature (*e.g.*, tipping points) where possible, although it was recognized this is a new and emerging field. Reference points could also be included in Chapter 3: at least their importance should be discussed. They could be included in the Conclusions chapter under future work.

End of March 2014 was recommended as the due date for rough first drafts of Chapter 2 and 3, for circulation amongst WG members, to help prepare for the presentations at the FUTURE OSM, and to help identify remaining gaps which may need to be filled prior to completion of the report.

In broad discussion on the draft report outline, it was noted by Dr. Takafumi Yoshida (NOWPAP representative) that WG 28 appears to be focused on fisheries. Dr. Perry indicated that this WG does not have to be focused only on fisheries and, in fact, should include non-fisheries activities as well. It needs to be stated in the introduction that fisheries is just one example of an activity that may stress a marine ecosystem. Dr. Martone added that cumulative impacts work done to date elsewhere has included fishing, climate, land-based impacts (pollution and sedimentation); for some systems, land-based stressors are correlated with responses.

AGENDA ITEM 5
Interactions with other PICES groups

This item was largely covered by the discussions and responses of WG 28 to the questions posed by Science Board (see Agenda Item 2).

AGENDA ITEM 6
Plans for primary publications resulting from the WG 28 report

This item was deferred.

AGENDA ITEM 7
Other business

It was noted that the FUTURE OSM could be useful for informal discussions amongst WG members who are able to participate, as to the evolving chapter drafts. It was suggested that a good venue for a future meeting of the WG would be in China, as a way to engage Chinese representatives on the draft report.

The meeting adjourned at 18:00 h, with the next full meeting of the WG scheduled for the PICES 2014 Annual Meeting in Yeosu, Korea.

WG 28 Endnote 1

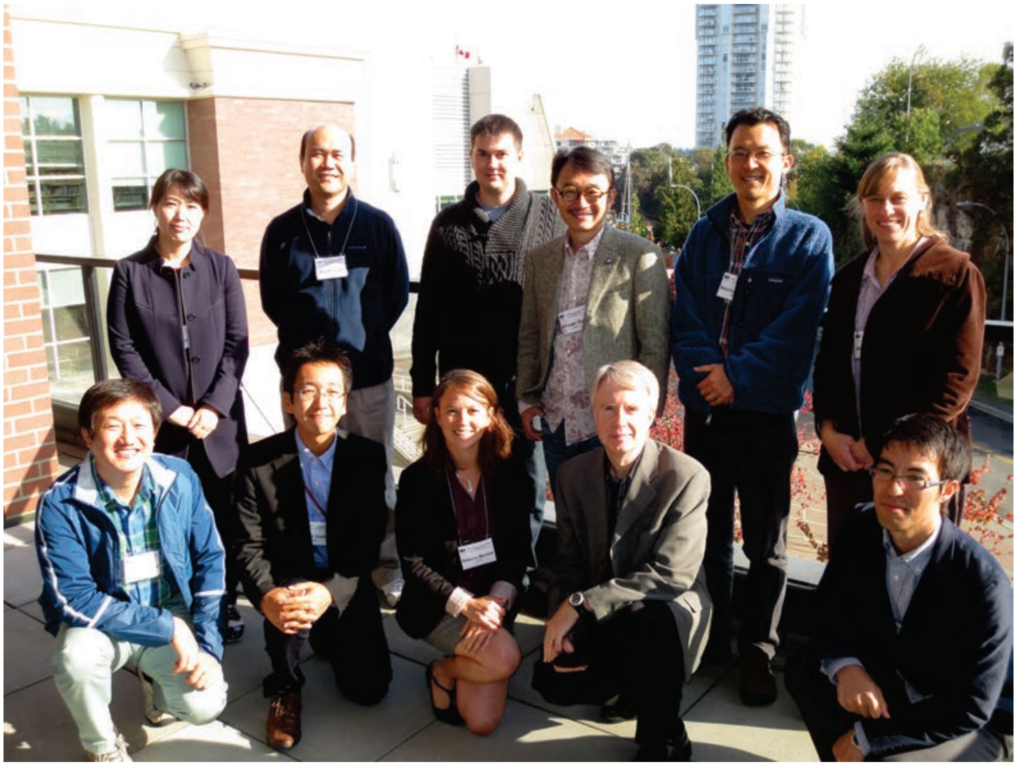
WG 28 participation list

Members

- Jennifer L. Boldt (Canada)
- Sachihiko Itoh (Japan)
- Vladimir V. Kulik (Russia)
- Jaebong Lee (Korea)
- Rebecca Martone (USA)
- Ian Perry (Canada, Co-Chair)
- Motomitsu Takahashi (Japan, Co-Chair)
- Naoki Yoshie (Japan)

Observers

- Karin Baba (Japan)
- Sunkil Lee (Korea)
- Vadim Navrotsky (Russia)
- Hiroaki Saito (Japan)
- Jeong Hee Shim (Korea)
- Sinjae Yoo (PICES)
- Takafumi Yoshida (NOWPAP)



WG 28 meeting participants at PICES-2013 in Nanaimo, Canada. Left to right, back: Jeong Hee Shim, Sunkil Lee, Vladimir Kulik, Hiroaki Saito, Motomitsu Takahashi, Jennifer Boldt. Left to right, front: Jaebong Lee, Naoki Yoshie, Rebecca Martone, Ian Perry, Sachihiko Itoh.

WG 28 Endnote 2

WG 28 meeting agenda

1. Welcome, Introduction and sign-in (all) – including introductions of new Working Group members (co-chairs; see *WG 28 Endnote 3* for list of WG members)
2. Review of activities during the 2nd year of WG 28
    a) General review of Terms of Reference (see Appendix 3) plus discussion of expectations for the Working Group by PICES, and what we expect to be able to deliver (all)
    b) Report on participation and presentation by WG 28 in NOWPAP Workshop (Kulik); [see PICES Press July 2013 article: http://www.pices.int/publications/pices_press/volume21/v21-n2/pp_28-29_NOWPAP-Wsh.pdf, also meeting report on WG28 web page: http://www.pices.int/members/working_groups/materials/WG-28-2013-Report-from-NOWPAP-MPA-Workshop.pdf.
    c) Report on participation and presentation by WG28 to PICES Inter-sessional Science Board meeting, and at ICES/PICES workshop on Climate Change Effects on Marine Ecosystems (SICCME) (Takahashi)
    d) Report on additional WG 28 session proposals, at 2014 PICES FUTURE Open Science Meeting (Perry), and submitted for 2014 PICES Annual Meeting (Martone/Samhouri)
    e) Brief outline of WG 28-convened session at 2013 Annual Meeting later in the week (Session S8, titled "Ecosystem indicators to characterize ecosystem responses to multiple stressors in North Pacific marine ecosystems")
    f) Report on the project MEcoPAM, which focuses on the impact of multi-stressors on the sustainability of marine ecosystem production in China (discussion led by Takahashi, with input from Chinese WG members)
    g) Other related WG28 activities?
3. Review of progress on Terms of Reference

    General discussion of how far we have progressed in addressing our ToR – which have we covered, which have we still to do? To include brief reports from each country of activities of importance to WG 28.
4. Presentations on outlines for each of the draft report chapters, and plans for moving these ahead.

    Lead authors for the various chapters in our draft report outline are requested to present and lead a discussion of their proposed chapter outline, *i.e.*, contents, contributors and task assignments, timelines. Additional contributors (in particular among new WG members or those not able to participate in Hiroshima) are welcome:
    a) Chapter 2 "Frameworks linking pressures to impacts and changes in North Pacific marine ecosystems", and "Multiple pressures on North Pacific marine ecosystems" (discussion leads: Perry, Takahashi)
    b) Chapter 3 "Ecosystem indicators" and "Indicators for ecosystem responses to multiple pressures" [discussion leads: Boldt, Samhouri, Itoh, Yoshie, Chung, others (?)]
    c) Chapter 4 "Case study examples":

        Inland seas, *e.g.*, Salish Sea (Strait of Georgia; Puget Sound), Seto Inland Sea (discussion leads: Samhouri, Perry, Takahashi)

        High latitude seas, *e.g.*, possibly Sea of Okhotsk, Bering Sea (discussion leads: Kullik, Zador, Lukyanova)

   - d) Re-look at proposed report chapter outline – are any topics missing (*e.g.*, reference points/tipping points – or could that be added to Chapter 3)?
   - e) Conclusions and recommendations – can we begin to identify any of these now? (discussion leads: co-chairs)

5. Discussion of interactions with other PICES groups (co-chairs)
   - a) Relationships between WG28 and other Working Groups and Committees
   - b) Contributions to FUTURE
6. Discussion of plans for primary publications resulting from the WG 28 report (Samhouri)
7. Any other business

18:00 End

WG 28 Endnote 3

WG 28 members as of September 2013

Dr. Jennifer L. Boldt (Canada)
Dr. Ian Perry (Canada, WG 28 Co-Chairman)
Prof. Min Chao (China)
Dr. Baisong Chen (China)
Dr. Honghui Huang (China)
Dr. Chaolun Li (China)
Prof. Cuihua Wang (China)
Dr. Heng Zhang (China)
Dr. Shigeru Itakura (Japan)
Dr. Sachihiko Itoh (Japan)
Dr. Motomitsu Takahashi (Japan, WG 28 Co-Chairman)
Dr. Naoki Yoshie (Japan)
Prof. Ik Kyo Chung (Korea)
Dr. Jaebong Lee (Korea)
Prof. Chang-Ik Zhang (Korea)
Dr. Vladimir V. Kulik (Russia)
Dr. Olga N. Lukyanova (Russia)
Dr. Rebecca G. Martone (USA)
Dr. Jameal F. Samhouri (USA)
Dr. Stephani G. Zador (USA)

WG 28 Endnote 4

Terms of Reference

1. Identify and characterize the spatial (and temporal) extent of critical stressors in North Pacific ecosystems both coastal and offshore and identify locations where multiple stressors interact. Identify trends in these stressors if possible.
2. Review and identify categories of indicators needed to document status and trends of ecosystem change at the most appropriate spatial scale (e.g., coastal, regional, basin).
3. Using criteria agreed to at the 2011 PICES FUTURE Inter-sessional Workshop in Honolulu, determine the most appropriate weighting for indicators used for:
   - a. documenting status and trends
   - b. documenting extent of critical stressors
   - c. assessing ecosystem impacts/change

4. Review existing frameworks to link stressors to impacts/change, assessing their applicability to North Pacific ecosystems and identify the most appropriate for application to North Pacific ecosystems.
5. Determine if ecosystem indicators provide a mechanistic understanding of how ecosystems respond to multiple stressors and evaluate the potential to identify vulnerable ecosystem components.
6. For 1-2 case studies, identify and characterize how ecosystems respond to multiple stressors using indicators identified above. Are responses to stressors simply linear or are changes non-linear such that small additional stressors result in much larger ecosystem responses? Do different parts of the ecosystem respond differently (e.g., trophic level responses)? How do stressors interact?
7. Publish a final report summarizing results with special attention to FUTURE needs. This WG will focus primarily on delivery of FUTURE Questions 3 and 1 (outlined below).

Linkages to the FUTURE Science Plan:

1. What determines an ecosystem's intrinsic resilience and vulnerability to natural and anthropogenic forcing?
2. How do ecosystems respond to natural and anthropogenic forcing, and how might they change in the future?
3. How do human activities affect coastal ecosystems and how are societies affected by changes in these ecosystems?

WG 28 Endnote 5

WG 28-sponsored session at the FUTURE Open Science Meeting, Hawaii, April 2014

Identifying multiple pressures and system responses in North Pacific marine ecosystems

Co-convenors: Vladimir Kulik (Russia), Rebecca Martone (USA), Ian Perry (Canada), Jameal Samhouri (USA), Motomitsu Takahashi (Japan)

Coastal and offshore marine ecosystems of the North Pacific are impacted by increasing temperature, changing iron supply, harmful algal bloom events, invasive species, hypoxia/eutrophication and ocean acidification. These multiple pressures can act synergistically to change ecosystem structure, function and dynamics in unexpected ways that differ from single pressure responses. It is also likely that pressures and responses will vary geographically. A key objective of the FUTURE program is to identify and characterize these pressures in order to facilitate comparative studies of North Pacific ecosystem responses to multiple stressors and how these systems might change in the future. This session has two primary objectives: 1) to identify key stressors and pressures on North Pacific marine ecosystems, and to compare how these stressors/pressures may differ in importance in different systems and how they may be changing in time; and 2) to identify ecosystem responses to these multiple stressors and pressures, including gaining an understanding of how natural and human perturbations may cascade through ecosystems, and whether there may be amplifiers or buffers which modify the effects of perturbations on marine systems. Papers using conceptual, model-based, observation-based, or experimental-based approaches are welcome, as well as papers which evaluate approaches to linking pressures to ecosystem changes, such as pathways of effects or driver-pressure-state-impact-response models. The overall goal of this session is to obtain an overview of the pressures being experienced by North Pacific marine ecosystems, how these pressures may be changing with time, variation in these pressures (both singly and in combination) among regions, and the combined effects of pressures, both now and in the future, on the marine ecosystems of the North Pacific.

WG 28-sponsored workshop at the FUTURE Open Science Meeting, Hawaii, April 2014

Bridging the divide between models and decision-making: The role of uncertainty in the uptake of forecasts by decision makers

Convenors: Harold Batchelder (USA), Kai Chan (Canada), Edward Gregr (Canada), Shin-ichi Ito (Japan), Vladimir Kulik (Russia), Naesun Park (Korea), Ian Perry (Canada), Jameal Samhouri (USA), Motomitsu Takahashi (Japan)

Uncertainty is a key theme of the FUTURE program. Scientific uncertainty extends beyond the outputs of oceanographic or ecosystem models and has significant consequences on human dimensions ranging from public and stakeholder perception to tactical and strategic decision making by managers and policy makers. The workshop will consider uncertainty along the entire path from data, through model design and implementation to communication and uptake of results by decision makers. Such end-to-end consideration of uncertainty is critical to improve the uptake of oceanographic model results by stakeholders and decision makers in all PICES member countries, particularly as the modeling community moves towards end-to-end models, and faces the challenges of managing multiple stressors. This workshop will thus bridge two central themes of the FUTURE Open Science Meeting: quantification and measurement of uncertainty in observations and projects, and communication and engagement in the development and dissemination of FUTURE products.

The workshop will be centered on two themes. The first of them concerns input data, model structure, and parameterization, and will focus on how sources of uncertainty can be articulated and presented on a technical level. This theme challenges the modeling community to explain the credibility of their results, articulate their assumptions, and generally expose sources of uncertainty. Models of any topic including stock assessment, ecosystem dynamics, and cumulative effects are welcome. The second theme will consider decision analysis and decision making, including psychological insights into how people perceive, understand, and incorporate complex information into decision-making. Discussions will focus on:

(1) how FUTURE can best articulate uncertainty assessments, and develop a communication strategy to broaden the engagement of the public, communities, decision makers and other stakeholders in the results emerging from FUTURE; and (2) how FUTURE products can link to coastal communities, with an emphasis on how and to what degree these products are relevant to the communities whose decisions they presume to affect. This includes the fundamental challenge of how to scale FUTURE scientific outputs with impacts on human dimensions, generally considered at more local extents. This theme in particular will consider approaches to communicate the value of FUTURE products beyond the natural science community. Potential topics of additional discussion include outreach to other disciplines (e.g., psychologists and anthropologists) with the intent of developing more insightful and applicable inter-disciplinary outputs and strategies for presenting FUTURE products to the broader, international stakeholder community. From this workshop, we plan a primary publication outlining how FUTURE products can be effectively communicated to the intended audiences.

WG 28 Endnote 6

Proposal for a 1-day Topic Session on “*Tipping points: defining reference points for ecological indicators of multiple stressors in coastal and marine ecosystem*” at PICES-2014

Co-sponsors: ICES, IMBER

Co-Convenors: Rebecca G. Martone (USA), Ian Perry (Canada), Jameal Samhouri (USA), Motomitsu Takahashi (Japan), Maciej Tomczak (Poland), Chang Ik Zhang (Korea)

Many coastal and marine ecosystems, ranging from reefs to estuaries to pelagic systems, are exposed to multiple stressors, which can lead to rapid changes with significant, long-term consequences that are often difficult to reverse. Changes in ocean climate, the abundance of key species, nutrients, and other factors drive these shifts, which affect ocean food webs, habitats, and ecosystem functions and people's livelihoods and well-being. Determining indicators of ecological changes due to multiple stressors and defining reference points for those indicators are key steps for managers to avoid ecological degradation and loss of keys goods and services. Setting ecological reference points in ecological systems presents a challenge to resource managers because (a) reference points are often difficult to determine due to the complexity of natural systems, including the presence of thresholds, tipping points, and non-linearities; (b) the paucity of theoretical modeling and empirical understanding needed to address these complexities, identify ecological thresholds and develop early warning indicators means that managers must make decisions based on high levels of uncertainty; and, (c) many institutional and governance structures do not allow managers the necessary flexibility to take up this information and react within relevant timeframes. This session will address these pressing challenges, and explore promising approaches to tackling them with the goal of catalyzing new research and management innovation. In particular, we invite presentations that (i) define the conceptual basis for reference points and management objectives surrounding reference points; (ii) use theoretical, modeling and observational approaches to identify potential reference points for indicators of changes in marine ecosystems; (iii) incorporate risk and sources of error (measurement, model, process) in such analyses; (iv) discuss how reference points may be used in helping to manage marine ecosystems, specifically in relation to the decision-making process related to evaluating and deciding on acceptable levels of risk. These discussions will be guided by the FUTURE science themes, with special attention to examining climate and anthropogenic drivers of ecological change, and identifying early warning indicators to enable forecasting to avoid crossing ecological thresholds. The outcomes will contribute to the work of PICES Working Group 28 on Development of ecosystem indicators to characterize ecosystem responses to multiple stressors.

WG 28 Endnote 7

Updated and revised (draft) outlines for each chapter of WG 28 final report

(revised from the version originally developed at the WG 28 meeting at PICES-2012 in Hiroshima)

General Outline

Chapter 1. Introduction (Co-Chairs: Takahashi/Perry)
- Background to the WG
- ToR/Objectives
- Brief overview of the issue of multiple activities/stressors on marine ecosystems

  - *e.g.*, use of the phrase “activities/stressors (or “pressures”) to indicate both natural and anthropogenic pressures, and that not all of these are always “bad” for the ecosystem. Define what is a “bad” ecosystem? – *e.g.*, different objectives for ecosystem states, what is “bad” varies for fishers *vs* conservationists. Perhaps recommend the broader concept of retaining the natural resilience of ecosystems?
  - Include definitions for “stressors”. Note the issue that information to construct indicators is often available at multiple but different time and space scales, *etc*.
  - Brief literature review of problems of multiple and cumulative stressors in marine systems – *e.g.*, the norm, but difficult to assess more than 2–3 stressors at one time
    - presentation by Dr. Coté in Session S8 later in this PICES meeting provides an excellent overview and access to key literature.
    - include reference to climate change and fishing issues (*e.g.*, age structures are truncated and this can create problems with resilience to climate change).
    - two general types of approaches:
      - mesocosm experiments,
      - whole ecosystem studies and statistical methods.
- Organization and guide to report contents

Chapter 2. Multiple stressors on North Pacific marine ecosystems (Perry, Takahashi, Samhouri, Zhang, Lee, Martone, others welcome!)

- Frameworks linking pressures to impacts and changes in North Pacific marine ecosystems (*e.g.*, PICES Session S10 at 2012 Annual Meeting in Hiroshima)
  - brief review of potential frameworks that could be used to link activities and stressors to ecosystem responses,
  - assessment of their applicability to North Pacific marine ecosystems,
  - recommendations for applications.
  - *e.g.*,
    - Pathways of Effects
    - Driver-Pressure-States-Impact-Response models,
    - simulation and other analytical modeling approaches, *e.g.*, Ecopath with Ecosim,
    - probabilistic (Bayesian) networks,
    - Integrated Ecosystem Analyses,
    - IFRAME, INVEST,
    - others?
- Multiple pressures on North Pacific marine ecosystems
  - identification of the spatial (and temporal, where possible) extent of important activities and stressors in North Pacific marine ecosystems,
  - identify habitats and general locations (if possible) where multiple stressors overlap,
  - identify trends in these activities/stressors if possible,
  - use existing literature as a starting point, but also build on own analyses.
- Sub-sections of this chapter for each PICES country, preferably using a common approach (???), plus a synthesis section. Or perhaps these might be included in the case studies?

Chapter 3 Ecosystem Indicators for multiple stressors (Boldt, Samhouri, Itoh, Yoshie, Chung, Martone, others?)

A. Chapter Introduction
  - Identify need to include indicators of multiple stressors when evaluating the state of marine ecosystems.
  - Purposes of chapter:
    - review existing indicators,
    - review potential sources of data available from national and international programs,
    - indicator-selection criteria, and
    - approaches for evaluating indicators.

B. Review of indicators in literature
  - General definition of indicators
  - General categories of indicators:
    - Human, biological (including trophodynamics), environmental, socio-economic-political,
    - State and trend,
    - Fulton (2003): strong, intermediate, and weak indicators.
  - Examples of indicators:
    - PICES Scientific Report No. 37:
      - Relative biomass, *e.g.*, top predators,
      - Biomass ratios, *e.g.*, Piscivore:planktivore,
      - Habitat-forming taxa, *e.g.*, proportional area covered by epifauna,
      - Community size spectra slopes,
      - Taxonomic diversity (richness),
      - Total fishery removals,
      - Maximum (or mean) length of species in catch,
      - Size-at-maturity,
      - Trophic level or trophic spectrum of the catch,
      - Biophysical characteristics, *e.g.*, temperature, chlorophyll a.
    - IndiSeas1 (focused on effects of fishing):
      - Mean length,
      - Trophic level of landed catch,
      - Proportion under/ moderately exploited species,
      - Proportion predatory fish,
      - Mean life span,
      - 1/CV biomass,
      - Biomass of surveyed species,
      - 1/landings/biomass.
    - IndiSeas2 (in addition to IndiSeas1 indicators; expanded to include effects of environment and indicators of human dimensions)
    - Environmental indicators: SST, Chl-*a*, global and regional climate
    - Human dimensions indicators:
      - Effectiveness, efficiency and fairness of fisheries management and quality of governance,
      - Contribution of fisheries to food provision, economic and social well being,
      - Well being and resilience of fisher communities.
    - Biodiversity indicators:
      - Mean intrinsic vulnerability index of fish catch,

        - Trophic level of the community,
        - Mixed trophic index (TL ≥ 3.25),
        - Proportion of exploited species with declining biomass,
        - Relative abundance of flagship species,
        - Discards/landings.

C. Indicator Selection Criteria
- Rice and Rochet (2005) 8-step process for selecting a suite of ecosystem indicators:
    - Step 1 determine user needs,
    - Step 2 develop list of candidate indicators,
    - Step 3 determine screening criteria,
    - Step 4 score candidate indicators against screening criteria,
    - Step 5 summarise scoring results,
    - Step 6 decide how many indicators are needed,
    - Step 7 make final selection,
    - Step 8 report on chosen suite of indicators.
- PICES 2011 FUTURE workshop criteria (each criterion should be weighted for relevance to end user identified):
    - available regularly and in a timely manner,
    - available as a time series,
    - statistical properties are understood and provided,
    - related to attribute either empirically or theoretically,
    - specific to attribute,
    - spatial and temporal scales of indicator appropriate to attribute,
    - responsive (sensitive to perturbation),
    - relevant to objective,
    - understandable by target audience,
    - provides a basis for comparison between ecosystems.

D. Indicators of ecosystem responses to multiple stressors
- Approaches:
    - Halpern *et al*. (2007, 2008, 2009), Teck *et al*. (2010) – cumulative impact scores,
    - Samhouri and Levin (2012).
    - IndiSeas2 exploring approaches to integrating/combining indicators (Shin *et al*., 2012):
        - scoring approach to aggregate all indicators into a single indicator,
        - multidimensional approach,
        - multi-criteria decision analysis.
    - Ban:
        - Data-based: Meta-analysis,
        - Expert-based elicitation,
        - Combined above, spatial: Regional mapping, GIS approaches,
        - Experimental,
        - Model-based.
    - Evaluation of indicators to identify vulnerable ecosystem components
        - despite pros and cons of each approach there is a need to use multiple approaches (expert elicitation, model-based simulation, and empirical analysis) to identify and evaluate critical multiple stressors of North Pacific marine ecosystems and indicators to assess their impacts.

Chapter 4. Case Studies

- Coastal systems (using Strait of Georgia, Canada, Puget Sound (US), Seto Inland Sea (Japan) *e.g.*, Perry *et al*. S8 presentation (but at the moment development of Indicators is lacking)
- Possibly: Sea of Okhotsk, Bering Sea (?Lukyanova, Kullik, Zador?)

Chapter 5. Conclusions and recommendations (drafted by Co-Chairs but developed by all WG 28 members)

Appendices

1. Terms of Reference
2. Membership
3. Reports of sessions held by WG 28

etc.

2014 FUTURE Open Science Meeting
April 15–18, 2014, Kohala Coast, Big Island, Hawaii, USA

Session 1
Identifying multiple pressures and system responses in North Pacific marine ecosystems

Convenors:
Vladimir Kulik (Russia)
Rebecca Martone (USA)
Ian Perry (Canada)
Jameal Samhouri (USA)
Motomitsu Takahashi (Japan)

Invited Speaker
Isabelle Rombouts (Université de Lille, France)

Coastal and offshore marine ecosystems of the North Pacific are impacted by increasing temperature, changing iron supply, harmful algal bloom events, invasive species, hypoxia/eutrophication and ocean acidification. These multiple pressures can act synergistically to change ecosystem structure, function and dynamics in unexpected ways that differ from single pressure responses. It is also likely that pressures and responses will vary geographically. A key objective of the FUTURE program is to identify and characterize these pressures in order to facilitate comparative studies of North Pacific ecosystem responses to multiple stressors and how these systems might change in the future.

This session has two primary objectives: 1) to identify key stressors and pressures on North Pacific marine ecosystems, and to compare how these stressors/pressures may differ in importance in different systems and how they may be changing in time; and 2) to identify ecosystem responses to these multiple stressors and pressures, including gaining an understanding of how natural and human perturbations may cascade through ecosystems, and whether there may be amplifiers or buffers which modify the effects of perturbations on marine systems. Papers using conceptual, model-based, observation-based, or experimental-based approaches are welcome, as well as papers which evaluate approaches to linking pressures to ecosystem changes, such as pathways of effects or driver-pressure-state-impact-response models. The overall goal of this session is to obtain an overview of the pressures being experienced by North Pacific marine ecosystems, how these pressures may be changing with time, variation in these pressures (both singly and in combination) among regions, and the combined effects of pressures, both now and in the future, on the marine ecosystems of the North Pacific.

List of presentations

Jameal Samhouri, A.O. Shelton, B. Feist, G. Williams, K. Bartz, M. Sheer and P. Levin
How much city is too much city? Diversity and ecosystem functions along an urban gradient in Puget Sound

R. Ian Perry, Motomitsu Takahashi, Jameal Samhouri, Chang-Ik Zhang, Rebecca Martone, Jennifer Boldt, Baisong Chen and Stephani Zador
Multiple interacting natural pressures and human activities in North Pacific marine ecosystems

Jennifer Boldt, Ik Kyo Chung, Sachihiko Itoh, Rebecca Martone, Ian Perry, Jameal Samhouri and Naoki Yoshie
Development of ecosystem indicators to characterize ecosystem responses to multiple stressors

Stephani Zador and Heather Renner
Red flags or red herrings revisited: Using ecosystem indicators to track ecosystem status in the Gulf of Alaska

Cathryn Clarke Murray, Selina Agbayani and Natalie Ban
Current and future cumulative effects of human activities on the Northeast Pacific with climate change and industrial development

Rebecca Martone, Erin T.H. Crockett, Allison Thompson and Kai M.A. Chan
Linking pathways of effects to assess cumulative impacts on ecosystem services: Modeling effects of nutrient run-off on shellfish aquaculture in British Columbia, Canada

Sukgeun Jung
Fishing vs. climate change: An example of filefish (*Thamnaconus modestus*) in the northern East China Sea

Jeffrey Polovina and Phoebe Woodworth-Jefcoats
Projected responses of the central North Pacific subtropical ecosystem to future pressures of fishing and climate change

Gen Del Raye and Kevin Weng
Challenges for peak aerobic metabolism in the future oceans: The effect of multiple climate variables on exercise performance in a model teleost fish

Motomitsu Takahashi, Sachihiko Itoh, Naoki Yoshie, Kazuhiko Mochida, Masakazu Hori, Shigeru Itakura and Mingyuan Zhu
Ecosystem responses to anthropogenic activities and natural stressors among inland, shelf and oceanic waters in the western North Pacific

Nam-Il Won, Min-Gyu Ji, Young-Teck Hur and Jin-Hyeog Park
Freshwater input as multiple stressors on coastal ecosystems under a changing ocean: Implication of possible mitigation effect

Vladimir Kulik
Multiplicative effect of SST variation during spawning period and 1 year after on the catches of walleye pollock 5 years later in the waters off the northeastern part of Sakhalin Island

Workshop 2

Bridging the divide between models and decision-making: The role of uncertainty in the uptake of forecasts by decision makers

Convenors:
Harold Batchelder (USA)
Kai Chan (Canada)
Edward Gregr (Canada)
Shin-ichi Ito (Japan)
Vladimir Kulik (Russia)
Naesun Park (Korea)
Ian Perry (Canada)
Jameal Samhouri (USA)
Motomitsu Takahashi (Japan)

Invited Speakers:
Georgina Gibson (International Arctic Research Center, University of Alaska Fairbanks, USA)
Lee Failing (Compass Resource Management Ltd., Canada)

Uncertainty is a key theme of the FUTURE program. Scientific uncertainty extends beyond the outputs of oceanographic or ecosystem models and has significant consequences on human dimensions ranging from public and stakeholder perception to tactical and strategic decision making by managers and policy makers. The workshop will consider uncertainty along the entire path from data, through model design and implementation to communication and uptake of results by decision makers. Such end-to-end consideration of uncertainty is critical to improve the uptake of oceanographic model results by stakeholders and decision makers in all PICES member countries, particularly as the modeling community moves towards end-to-end models, and faces the challenges of managing multiple stressors. This workshop will thus bridge two central themes of the FUTURE Open Science Meeting: quantification and measurement of uncertainty in observations and projects, and communication and engagement in the development and dissemination of FUTURE products.

The workshop will be centered on two themes. The first of them concerns input data, model structure, and parameterization, and will focus on how sources of uncertainty can be articulated and presented on a technical level. This theme challenges the modeling community to explain the credibility of their results, articulate their assumptions, and generally expose sources of uncertainty. Models of any topic including stock assessment, ecosystem dynamics, and cumulative effects are welcome.

The second theme will consider decision analysis and decision making, including psychological insights into how people perceive, understand, and incorporate complex information into decision-making. Discussions will focus on: (1) how FUTURE can best articulate uncertainty assessments, and develop a communication strategy to broaden the engagement of the public, communities, decision makers and other stakeholders in the results emerging from FUTURE; and (2) how FUTURE products can link to coastal communities, with an emphasis on how and to what degree these products are relevant to the communities whose decisions they presume to affect. This includes the fundamental challenge of how to scale FUTURE scientific outputs with impacts on human dimensions, generally considered at more local extents. This theme in particular will consider approaches to communicate the value of FUTURE products beyond the natural science community. Potential topics of additional discussion include outreach to other disciplines (*e.g.*, psychologists and anthropologists) with the intent of developing more insightful and applicable inter-disciplinary outputs and strategies for presenting FUTURE products to the broader, international stakeholder community.

List of presentations

Edward J. Gregr and Kai M.A. Chan
Uncertainty from observations to decision-making: What we know, what we assume, and what matters

Georgina A. Gibson (Invited)
Ecosystem modeling predictions – How reliable are they?

William T. Peterson
Modelers: Know thy fish

Shin-ichi Ito, Takeshi Okunishi, Michio J. Kishi and Muyin Wang
Uncertainty of fish growth projection caused by uncertainty of physical forcing

Rowenna Gryba and Edward J. Gregr
Evaluation of predictive habitat suitability: Using contemporary sightings and prey data to assess model assumptions

Kai M.A. Chan and Edward J. Gregr
The problem isn’t uncertainty, but its monotypic treatment

Lee Failing (Invited)
How decision science can improve the relevance of oceanographic research to managers and stakeholders

PICES-2014

October 16–26, 2014, Yeosu, Korea

Excerpted from:

Summary of Scientific Sessions and Workshops at PICES-2014

BIO/MEQ Topic Session (S3)

Tipping points: defining reference points for ecological indicators of multiple stressors in coastal and marine ecosystem

Co-sponsored by the International Council for the Exploration of the Sea (ICES) and Integrated Marine Biogeochemistry and Ecosystem Research (IMBER)

Co-Convenors: *Rebecca G. Martone (USA), Ian Perry (Canada), Jameal Samhouri (USA), Motomitsu Takahashi (Japan), Maciej Tomczak (Poland / ICES), Chang Ik Zhang (Korea)*

Invited Speakers:
Phil Levin (NNOAANW Fisheries Science Center, USA)
Tetsuo Yanagi (Research Institute for Applied Mechanics, Kyushu University, Japan)

Background

Many coastal and marine ecosystems, ranging from reefs to estuaries to pelagic systems, are exposed to multiple stressors, which can lead to rapid changes with significant, long-term consequences that are often difficult to reverse. Changes in ocean climate, the abundance of key species, nutrients, and other factors drive these shifts, which affect ocean food webs, habitats, and ecosystem functions and people's livelihoods and well-being. Determining indicators of ecological changes due to multiple stressors and defining reference points for those indicators are key steps for managers to avoid ecological degradation and loss of keys goods and services. Setting ecological reference points in ecological systems presents a challenge to resource managers because (a) reference points are often difficult to determine due to the complexity of natural systems, including the presence of thresholds, tipping points, and non-linearities; (b) the paucity of theoretical modeling and empirical understanding needed to address these complexities, identify ecological thresholds and develop early warning indicators means that managers must make decisions based on high levels of uncertainty; and (c) many institutional and governance structures do not allow managers the necessary flexibility to take up this information and react within relevant timeframes.

The aim of this session was to address these pressing challenges, and explore promising approaches to tackling them with the goal of catalyzing new research and management innovation. In particular, the convenors sought presentations that (i) define the conceptual basis for reference points and management objectives surrounding reference points; (ii) use theoretical, modeling and observational approaches to identify potential reference points for indicators of changes in marine ecosystems; (iii) incorporate risk and sources of error (measurement, model, process) in such analyses; (iv) discuss how reference points may be used in helping to manage marine ecosystems, specifically in relation to the decision-making process related to evaluating and deciding on acceptable levels of risk. Discussions were guided by the FUTURE science themes, with special attention to examining climate and anthropogenic drivers of ecological change, and identifying early warning indicators to enable forecasting to avoid crossing ecological thresholds. The outcomes are expected to contribute to the work of PICES Working Group 28 on *Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors.*

Summary of presentations

The session provided a very interesting overview of how tipping points pertain to marine species and ecosystems. It was well-attended and there was a great diversity of presentations, featuring many different geographies and at many different scales – from ecosystem-wide changes in response to tipping points to threshold responses of individual animals and fisheries stocks.

In his Invited Presentation, Dr. Phillip Levin addressed the important topic of how to respond to regime shifts in social-ecological systems. He focused on the importance of integrated ecosystem assessments (IEAs), and how they can be applied to counteract regime shifts. He suggested that the first question to answer as part of an IEA is whether the existing regime is desired, and then further broke this question down into 3 parts. First, do people see the world the same way? Dr. Levin illustrated that people do not necessarily view the world the same way using a folk taxonomy example, and suggested that regime shifts are likely not to be perceived the same way either. Second, Dr. Levin posed the question: does anyone care if a regime shifts? Using the example of regime shifts from kelp forests to sea urchin barrens and back again, he illustrated how different groups of people are likely to have different preferences for each regime. The third question Dr. Levin addressed focused on defining the target regime. Via the lens of eelgrass restoration, Dr. Levin described a novel approach for determining public preferences for different ecosystem configurations. Overall, he argued that portfolios of indicators need to be accompanied by portfolios of reference points that reflect people's preferences for alternative ecosystem configurations.

Dr. Jake Rice asserted that the one thing managers should avoid is to make a tipping point a target. This argument stems from the fact that rapid changes in the ecosystem happen near tipping points, and those changes may not be desirable. However, Dr. Rice showed that identifying tipping points is analytically challenging. Nonetheless, he made a strong case for managers to: avoid tipping points with high probability, emphasize that objective even more so than an objective of achieving targets, and avoid optimizing along a single ecosystem dimension (*e.g.*, a single fishery).

Dr. Rebecca Martone provided an overview of a multi-institutional collaborative project called "Ocean Tipping Points." The project includes scientists and lawyers from universities, government agencies, and NGOs and consists of synthesis and application components. The synthesis component includes compilation of a global database of marine ecosystem shifts (n > 100 studies, few from the western Pacific), a meta-analysis of nonlinear relationships in pelagic systems, a law review that demonstrated that regulations incorporating thresholds yield better environmental outcomes, and a management review of 50 case studies of current management contexts showing that explicit use of tipping points in management yields improved environmental outcomes. The application components focus on coral reefs in Hawaii, USA, and the herring food web in Haida Gwaii, BC, Canada.

Dr. Maciej Tomczak described an impressive body of work showing that overexploitation, changes in climate, and nutrient loading combined to cause a shift from a cod-dominated to a sprat-dominated

Baltic ecosystem. Dr. Tomczak defined this phenomenon as a regime shift, *i.e*., a food web reorganization and redirection of energy flow pathways. He used a network indicator called Redundancy to suggest that resilience has declined in the Baltic over time, in response to an overall forcing index (inclusive of changes in climate, fishing, *etc*.).

Dr. Takahashi and colleagues presented the results from an expert judgment survey to determine relative risks of coastal and marine habitats in the Eastern, Central and Western Regions of the Seto Inland Sea. Results indicate regional variation within the Seto Inland Sea to a suite of stressors. Coastal engineering and development affects strongly all ecosystems across the regions. Commercial activities, including fishing, have stronger impacts in the eastern waters. Nutrient input and HABs have higher risk in the central and eastern areas. Dr. Takahashi presented spatially explicit temporal data that corroborate many of the outcomes from the expert judgment survey. For example, tidal flats and seagrass beds have decreased in areas of the Seto Inland Sea. Stressor-specific risk scores indicate regional variability linked to population density and geographical features in the Seto Inland Sea. Future comparisons with results from global models and other regional models will help identify gaps and biases in expert judgement. These results can help identify priorities for research and management of cumulative impacts to ecosystems at regional spatial scales.

Dr. Ian Perry presented work in the Salish Sea examining the drivers of change acting on the Strait of Georgia in the Salish Sea, British Columbia. Using redundancy analysis, Dr. Perry identified regime-like transitions of the Strait of Georgia since 1970. Dr. Perry then presented an examination of potential predictors for typical system behaviours prior to significant shifts in the system, including variance, autocorrelation at lag-1, and conditional heteroskedasticity. Standard deviation and the autocorrelation are not correlated with the regime shifts and thus do not act as good predictors. Interestingly, conditional heteroskedasticity of SST and North Pacific Gyre Oscillation within the moving window of 37 months was well-correlated with the regime shift and possibly could be used as an early warning indicator. Dr. Perry described some of the challenges associated with choosing which indicators, which predictors for early warnings of regime shifts, choice of time period (*e.g*., moving windows), and how to identify significance. Early warning indicators appear promising, but the real world is more messy than simulated data. Several indicators are likely necessary, particularly lower trophic level biological variables, and combining these in a probability approach might be good way forward.

Dr. Bill Sydeman focused on the importance of understanding how changes in community structure relate to changes in ecosystem functions and processes, with emphasis on tipping points of mid-trophic level invertebrates and fishes and meso-predators. Meso-predators may serve as indicators of variability in ecosystem function as they may be the most responsive to the forage fish community variability. Dr. Sydeman showed that there are many non-linear responses of ecosystems to changes in mid trophic level (MTL) fish, (*e.g*., changes in breeding success of seabirds) and that shapes of the relationships can be used to determine which indicators might be more sensitive to ecosystem changes. The global model for seabird breeding success indicates a threshold that around the mean long-term trend. Dr. Sydeman then explored whether there is variability in the threshold numerical response between forage fish abundance and seabirds, either among predator species, prey species or the parameter examined. Interestingly, among some predator and prey species the threshold holds but for other species there are different relationships, but despite this variation North Pacific seabird threshold range is similar to the global model. Furthermore, the threshold tends to hold for different parameters; however, there is high uncertainty associated with this because of data limitations. Ultimately, predator-prey threshold relationships may provide insight to ecosystem state shifts. Future work on population-level responses, multi-species predator–prey numerical responses, and how differences in mean abundance or life history characteristics (*e.g.*, diet specialization) might affect the threshold, will be useful to understand threshold responses in ecosystem indicators.

Dr. Wen Yu presented on the effects of acute gamma radiation on the survival and physiological indices of the Chinese black sleeper. Existing studies from UNSCEAR (2008) indicate that fish are the most sensitive species based on LD_{50} reference points but few focus on data from marine fish and there are no data in China. By examining the Chinese black sleeper, Dr. Yu's study fills important gaps in our understanding of the response of marine species to radiation, particularly as it may be more susceptible to pollution and is economically important. Dr. Yu presented the results of a dose-response experiment that examined 5 irradiated groups and a control groups, with 60 individuals per group. Preliminary results indicate that with the 3 higher levels of irradiation, 100% mortality occurred within a few days, while the lowest level of radiation was similar to the controls. The calculated LD_{50} was 7.1 (6.3–7.9) Gy, which is lower than the 10–25 Gy summarized from UNSCEAR. Future research will include additional experiments to confirm these results, along with research on other local species and tests of the effects of chronic radiation.

Mr. Kyung-Su Kim described his research on the combined effects of elevated CO_2 and temperature on the physiological conditions of olive flounder larvae, *Paralichthys olivaceus*. Using a MFC controller and mixing chambers Mr. Kim described the experimental settings, including 3 different CO_2 concentrations, based on current day 2100 mild and strong emissions based on IPCC predictions and 2 temperatures, optimum and high temperature. Both total length and wet weight increased with CO_2 at lower temperatures, but variable responses occurred when CO_2 was combined higher temperatures. Skeleton malformation occurred more frequently with higher CO_2 conditions, and bone density decreased with increasing CO_2 conditions. Results from histomorphology did not show any malformation in tissues under higher CO_2 conditions. Dr. Kim's study illustrated that CO_2 and temperature have variable interactive effects on growth (positive) and bone density (negative), suggest that these types of studies are necessary to tease apart the multiple effects of stressors on condition, which may have implications for population dynamics and ecosystems.

For his invited presentation Dr. Tetsuo Yanagi described eutrophic and oligotrophic processes in the Seto Inland Sea and their relation to the Satoumi concept. Eutrophication (TN:TP) in recent years has decreased in the Seto Inland Sea and fish stocks have also seen similar declines, suggesting regime shifts related to changes in productivity driven by nutrient inputs. Dr. Yanagi explored models of phytoplankton population dynamics using relationships with different strengths of non-linearity for a variety of parameters. The relation between fish catch and nutrient concentration is non linear and there is hysteresis due to sediment pollution. Oligotrophic conditions may lead to changes in stratification and ability of fish to eat sinking phytoplankton, leading to hypoxia and possibly a new regime. Dr. Yanagi then suggested that there is a possibility to move from oligotrophic conditions back to eutrophic conditions with higher productivity, which is the preferred state, and introduced the Satoumi concept. The Satoumi concept developed by Dr. Yanagi supports the idea that coastal seas can have high biodiversity and productivity under human interactions, where both over and under- use can lead to low biodiversity and productivity. For example, decreases of eelgrass beds in the Seto Inland Sea led to decrease of fish catch by set nets, which in turn led local fishermen to create eelgrass beds. Now both eelgrass beds and fish catches by set nets are increasing. Currently Dr. Yanagi has a new project supported by the Ministry of the Environment to develop a coastal management method to realize the sustainable coastal sea, in which physical, biological, social sciences, and governance will support integrated, community-based management, to realize clean, rich and prosperous seas.

Dr. Kazumi Wakita presented research on the diversity of perceptions and utility of marine ecosystem services. With an online survey of 1100 residents of Japan, Dr. Wakita examined people's perceptions of different ecosystem services and the utility or satisfaction experienced by different people could be used as a basis for decision making. In addition, she explored the how utility that residents derive from marine ecosystem services affect their behavioural intentions for marine conservation, assuming that where there is higher the perceived indispensability, the greater the utility, and the higher the indispensability the greater its influence on enhancing behavioural intensions for marine conservation. Using factor analysis and structural equation modeling to determine the causal relationships between perceived value and their intensions of behaviour for conservation of marine biodiversity, Dr. Wakita uncovered 3 hidden factors including (1) Essential Benefits, including food, life satisfaction, health, *etc*.; (2) Indirect Benefits, which was primarily composed of provisioning services and regulating services; and (3) Cultural Benefits. Dr. Wakita found that cultural benefits were most important in driving behavioural intentions for marine conservation. Essential benefits also contributed to behaviour assessments, whereas indirect benefits were not significant. Essential benefits had highest indispensability, followed by indirect benefits, while cultural benefits scored lower on indispensability. These results indicate that indispensability does not correlate with conservation behaviors. Focusing on the landlocked Nagano residents, Dr. Wakita also performed factor analysis to examine the scarcity principle. The same 3 factors were identified, but their contents were different. Perception of the marine ecosystem could vary reflecting scarcity of the services in their place of residents, which will be different for different communities. Dr. Wakita's talk emphasizes the need for more attention for cultural aspects of marine ecosystem services.

Dr. Christopher Aura assessed the magnitude and interrelationships of seasonal phytoplankton bloom occurrence at the Japanese scallop farming area of Okhotsk Sea, Hokkaido Japan. To define tipping points, Dr. Aura and colleagues defined different bloom types, including the spring bloom, ice bloom, and open water bloom, using time series data sources including chl-*a*, sea ice, surface wind stress. By identifying the mechanism of bloom occurrence, Dr. Aura was able to identify that a decline of wind stress leads to increased ice edge blooming and decreased open water bloom variability. In addition, using PCA and Pearson correlation matrices, he found that there are distinct relationships between scallop landings, sea ice cover, and bloom variability. Where there is a strong negative relationship between sea ice days and open water bloom, open water blooms are positively correlated with scallop landings. Thus, tipping points can be described by wind stress and solar radiation.

Dr. Jameal Samhouri and colleagues explore what has happened once a tipping point has been crossed, where multiple pressures shift systems over ecological thresholds and lead to different ecosystem states. Dr. Samhouri described how examining systems that have crossed tipping points may help guide the recovery of ecosystems, specifically working toward the development of theory to reassemble marine systems. Dr. Samhouri examined what types of ecosystem reassembly strategies are currently in use, what strategies are likely to be the most effective using a theoretical model, and finally, determined if and where the most effective strategies that have been identified from models are being used. Dr. Samhouri identified three main reassembly strategies, where lower trophic levels recover first, higher trophic levels recover first, or simultaneous recovery occurs. Using a theoretical toy model of a generalist predator and multiple prey species, Dr. Samhouri asked whether who goes first matters in terms of ecosystem reassembly, specifically examining these three strategies. Simultaneous recovery (to equilibrium) of both predator and prey is fastest while predator first is the slowest, but predator first is the most direct in terms of amplification volume, without noisy transient dynamics. From the literature, the least common strategy is where highest trophic level recovery first, suggesting that the most effective strategies, specifically simultaneous reassembly and lower trophic level first, are the most common. Additional future work examining stochastic dynamics and multiple trophic levels in the system may help identify how regimes shift and the possibility of priority effects under more realistic scenarios.

Dr. Kulik presented work examining potential reference points for mean trophic level of macrofauna in the Sea of Okhotsk. Trophic level, a common indicator of fisheries status, can be determined by the stable isotope ratio of nitrogen, but this depends both on seasonal delivery of nitrogen with spring blooms and on the age of the consumer. To address this variability, Dr. Kulik used an adjusted mean weighted average trophic level (muTL) of every catch, using information on weight at length from fishery data and stable isotope ratio information from data of species in the benthic-pelagic zone. Using a trophic level of 67 fish, 6 squid and 5 decapod species and 148 species from Fishbase, Dr. Kulik and colleagues estimated muTL from 9926 trawls in pelagic waters from 1984–2013 and from 6321 bottom trawls from 1977–2010. Dr. Kulik examined spatial and temporal variation of muTL using Generalized Additive Models with splines for coordinates, horizon of trawling, years and months. Dr. Kulik's results indicate that there is deviation from the global mean of muTL in pelagic waters over time in the Sea of Okhotsk, and during the period of 2003–2013, he estimated that the linear rate of increase in muTL of catches was 0.007 per year. Spatial variation also occurs in muTL, with deeper pelagic waters showing lower than average muTL in the pelagic fisheries, but for bottom trawls, the deeper pelagic waters demonstrate higher than average muTL. This research illustrates the need to understand spatial and temporal variation in reference points of indicators in order to understand ecosystem shifts.

Dr. Yusheng Zhang and colleagues described the fate and potential impacts from radionuclides in the NW Pacific following the Fukushima Nuclear Disaster (FND). Transfer of radionuclides can occur from water to fish through the food web and directly through contact with water. On a series of cruises beginning in June 2011, Dr. Zhang and colleagues collected tissue samples from 3 species – squid, saury, and dolphin fish. They used these samples to analyze radionuclide concentrations of ^{134}Cs, ^{137}Cs, and ^{110m}Ag, using the gamma spectrometry method. All radionuclides were detected in all 3 collected species of marine animals, including ^{134}Cs and ^{110m}Ag, which are important indicators of nuclear accident pollution and are not usually seen. Squid showed higher concentrations than saury and dolphin fish, though radionuclide contents varied among tissue types. Dr. Zhang also developed spatial maps of exposure, indicating where the nuclide samples were found and their magnitudes, and examined temporal patterns in radionuclide concentrations in tissues. Concentrations of most radionuclides in squid peaked in November 2011, and dropped precipitously, except for ^{90}Sr, which showed a very different temporal pattern. Dolphin fish radionuclide concentrations also exhibited declines over time. Dr. Zhang indicated that though radionuclide concentrations in marine animals increased following FND, they were lower than the limit reference point for seafood safety.

Dr. Hyeong-gi Kim presented work regarding thermal influence on nematodes, the most numerous metazoans worldwide and a potentially informative indicator group because of their abundance, occurrence in a wide range of habitats, habitat specificity, and a broad range of feeding types and generation times. Dr. Kim focused on the effects of thermal discharge from nuclear power plants on nematode communities in Gori coastal waters of the southern East Sea / Sea of Japan. The nematode community consisted of 6 dominant species, but a much larger number of species were extremely rare. Most nematodes were non-selective deposit feeders, and sediment type was a dominant factor determining nematode community composition. Interestingly, bottom temperature was not significantly correlated with the abundance of most nematodes.

Mr. Delvan Neville from Oregon State University discussed reference points in the context of radioecology. In this field, reference points are referred to as Derived Consideration Reference Level. Mr. Neville determined distribution of radionucleotides in the bodies of several Northern California Current marine species including *Thunnus aluluna* (albacore tuna). Concentrations were generally low, such that only a 10,000-fold increase in ^{137}Cs would exceed safe limits. Pink shrimp and several other species exhibited much larger responses than those seen in tuna.

Some overall comments:

- Tipping points are an integrative concept for social-ecological systems and pertain to many issues of strong interest to PICES, including climatic shifts, changes in top predator abundances, ecosystem responses to multiple pressures, and more.
- However, a clear definition is challenged by this same feature. It seemed that the implicit and most general definition that emerged in S3 focused on the existence of a nonlinear change in a dynamical system. Defined this way, tipping points can occur in individual animals in response to environmental challenges (*e.g.*, radiation, CO_2), to harvested fish stocks because of spawner–recruit relationships, and to entire food webs and ecological communities because of nonlinear predator–prey and competitive interactions.
- Early warning indicators of tipping points may be difficult to identify and anticipating or forecasting tipping points may not be possible. However, retrospective analysis and modeling can illustrate general lessons and rules of thumb, as well as help identify potential trajectories of recovery and guide management actions.
- Tipping points are inherent to social-ecological systems, but do not in and of themselves tell us anything about objectives and targets. Rather, knowledge of tipping points can help guide decisions about objectives and targets.
- While desired states of the social ecological system are important to consider for decision making, it is the biophysical system that defines what states are possible. Thus while it is important to define desired states within the tipping points framework, it is important to manage expectations about what is possible to achieve.

We are seeing an increasing amount of integration of social-ecological effects within ecosystem PICES activities across the North Pacific. This is a good sign for the FUTURE program.

List of papers

Oral presentations

Marine ecosystem regime shifts: Challenges and opportunities for Ecosystem-Based Management (Invited)
Phil Levin

Tipping points and decision-making: Why they matter, why they are hard, and practical things to do
Jake Rice

Embedding the science of tipping points into ocean management
Rebecca Martone, Carrie Kappel, Courtney Scarborough, Mary Hunsicker, Ben Halpern, Kimberly Selkoe, Phil Levin, Jameal F. Samhouri, Crow White, Ashley Erickson, Ryan Kelly, Lindley Mease, Margaret Caldwell, Larry Crowder and Rod Fujita

Ecological network indicators of ecosystem status and change in the Baltic Sea
Maciej T. Tomczak, Johanna J. Heymans, Johanna Yletyinen, Susa Niiranen, Saskia A. Otto and Thorsten Blenckner

Regional variations in ecosystem responses to anthropogenic activities and natural stressors in the Seto Inland Sea
Motomitsu Takahashi, Sachihiko Itoh, Naoki Yoshie and Kazuhiko Mochida

Potential early warning indicators of marine ecosystem changes in coastal British Columbia, Canada
R. Ian Perry

Seabird indicators and "tipping points" in North Pacific marine ecosystems
William J. Sydeman, Sarah Ann Thompson, Julie A. Thayer, Marisol Garcia-Reyes, Heather Renner, John F. Piatt, Stephanie Zador and Yutaka Watanuki

The effects of acute gamma irradiation on the survival and the physiological and biochemical indexes of Chinese black sleeper, *Bostrichthys sinensis*
Wen Yu, Tao Yu, Yusheng Zhang and Feng Lin

The combined effects of elevated CO_2 and temperature on the physiological condition of the olive flounder larvae *Paralichthys olivaceus*
Kyung-Su Kim, JeongHee Shim and Suam Kim

Eutrophication and oligotrophication processes in the Seto Inland Sea and their relationships to the Satoumi concept (Invited)
Tetsuo Yanagi

Diversity of perceptions and utility of marine ecosystem services
Kazumi Wakita, Zhonghua Shen, Taro Oishi, Nobuyuki Yagi, Hisashi Kurokura and Ken Furuya

Assessment of the magnitude and interrelationship of seasonal phytoplankton bloom occurrence at the Japanese scallop (*Mizuhopecten yessoensis*) farming area of Okhotsk Sea, Hokkaido, Japan
Christopher Mulanda Aura, Sei-Ichi Saitoh, Yang Liu and Toru Hirawake

Ordered re-assembly of marine ecosystems
Jameal F. Samhouri, Adrian C. Stier and Phil Levin

Potential reference points for mean trophic level of macrofauna in the Sea of Okhotsk
Konstantin M. Gorbatenko, Vladimir V. Kulik and Artem E. Lazshentsev

The bioconcentration of artificial radionuclides by marine animals after the Fukushima nuclear accident in the Northwest Pacific
Wu Men, Jianhua He, Wen Yu, Fenfen Wang, Wuhui Lin and Yusheng Zhang

Seasonal and spatial variations in nematode assemblages affected by thermal influence of a nuclear power plant in Korea (East Sea, Pacific Ocean)
Hyeong-gi Kim, Hyun soo Rho and Chul-woong Oh

Characterization of absorbed dose from natural and anthropogenic radionuclides for the purpose of establishing reference points within the marine environment
Delvan R. Neville and Kathryn A. Higley

Poster presentations

DNA damage (Comet Assay) as biomarker of Cd exposure in bivalve mollusks *Modiolus kurilensi* and *Corbicula japonica*
Valentina V. Slobodskova, Sergey P. Kukla, Viktor P. Chelomin and Elena V. Zhuravel

Sulfonamide antibiotics in the Northern yellow Sea are related to resistant bacteria: Implications for antibiotic resistance genes
Guangshui Na, Hui Gao, Ruijin Li, Jinqiu Du, Ziwei Yao and Chuanlin Huo

Growth rate comparison of Pacific oyster, *Crassostrea gigas*, reared in situ in a high-CO_2 mesocosm environment
JeongHee Shim, Hakbin Hwang, Jae-Hyun Lim, Sang-Jun Lee and Jung-no Kwon

Valuation of ecosystem diversity maintenance service in marine protected areas: Shandong case
Shang Chen, Shengjie Tu, Tao Xia, Zhengxiang Gao and Tao Zhang

Report of Working Group 28 on *Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors*

WG 28 met from 9:00 to 18:00 h on October 17 and 18, 2014 in Yeosu, Korea, under the chairmanship of Drs. Motomitsu Takahashi (Japan) and Ian Perry (Canada). The meeting objective was to review activities during the 3rd year (2013–2014) of WG 28, plan for activities during the 4th year (2014–2015), and discuss the contents of the final report. Note that reports from previous WG 28 meetings and sponsored sessions are available on the WG 28 web page.

Meeting participants and agenda are listed in *WG 28* ***Endnote 1***. The agenda for this meeting is presented in *WG 28* ***Endnote 2***.

AGENDA ITEM 2
Review of activities during the 3rd year of WG 28

a) Review of Terms of Reference:

The Terms of Reference for WG 28 were reviewed and discussed. It was recognized they are very challenging and ambitious. WG 28 is making progress on addressing them, but may not be able to fully respond to all questions. It was also noted that there are expectations from PICES, FUTURE, and NOWPAP to provide a list of indicators as an output of the WG, and to recommend a set of indicators to the next version of the North Pacific Ecosystem Status Report.

b and c) Report on WG 28-sponsored sessions at the PICES FUTURE Open Science Meeting

WG 28 sponsored a Theme Session (S1) on "*Identifying multiple pressures and system responses in North Pacific marine ecosystems*" and co-sponsored a workshop (W2) on "*Bridging the divide between models and decision-making: The role of uncertainty in the uptake of forecasts by decision makers*" at the FUTURE Open Science Meeting held April 15–18, 2014, on Kohala Coast, Hawaii. See PICES Press Vol. 22, No. 2, 2014, http://www.pices.int/publications/pices_press/volume22/v22-n2/pp_09-10_S1_Perry.pdf and http://www.pices.int/publications/pices_press/volume22/v22-n2/article_pp_24-27_W2_Gregr.pdf.

d) Report on WG 28-sponsored session at PICES-2014

WG 28 co-sponsored a BIO/MEQ Topic Session (S3) on "*Tipping points: defining reference points for ecological indicators of multiple stressors in coastal and marine ecosystem*" at PICES-2014 with ICES and IMBER. Co-Convenors were Rebecca G. Martone (PICES/USA), Ian Perry (PICES/Canada), Jameal Samhouri (PICES/USA), Motomitsu Takahashi (PICES/Japan), Maciej Tomczak (ICES/Poland), Chang-Ik Zhang (PICES/Korea). A summary of the Topic Session can be found in the Session Summaries of the 2014 Annual Report.

e) Other related WG 28 activities (including country reports)

Country reports were presented under Agenda Item 3.

AGENDA ITEM 3
Progress on Terms of Reference, and brief country reports of activities of interest to WG 28

Canada (Ian Perry)

Dr. Perry described work undertaken by the Puget Sound Science Panel to develop a process for identifying pressures on this ecosystem. This approach is systematic, expert-based, and includes an evaluation of the potential impact of stressors on endpoints. The process is described in Puget Sound Partnership Technical Report 2014-02 (Labiosa *et al*.).

China

No report.

Japan (Motomitsu Takahashi)

Dr. Takahashi described his work on understanding ecosystem responses to activities and stressors among inland (Seto Sea), shelf (Yellow Sea and East China Sea), and oceanic waters (Kuroshio/Oyashio) in the western North Pacific, using a comparative study based on expert elicitation. Presentation of his results were made in Topic Session S3.

Korea (Chang-Ik Zhang)

The ecosystem approach to fisheries management approach being developed in Korea uses the IFRAME approach (Zhang *et al*. 2011. *ICES J. Mar. Sci.*). It is not revolutionary, but rather is an evolutionary approach. It is capable of being applied with available information, is precautionary and environmentally sound, and is relatively simple and pragmatic to use. The second tier of this approach is underway to develop management objectives, indicators and reference points, and nested risk indices and management status indices. Examples of management objectives and indicators include: sustainability, habitat quality, socio-economy, and biodiversity.

Russia (Olga Lukyanova)

Dr. Lukyanova described work being conducted in Peter the Great Bay, which has the highest pressure from human activities of eastern Russian marine systems. Pressures being investigated include pollution, fisheries, *etc*. The approach used both expert elicitation and data driven methods. Dr. Kulik described issues with the exchange of data among institutes in Russia. In the past, they could only calculate the effects of stressors for individual regions within Russia. Recently, however, approval has been granted to share metadata among institutes.

United States (Jameal Samhouri)

Dr. Samhouri described activities (Integrated Ecosystem Assessments) by NOAA, and noted that a national meeting is being planned to consider issues of reference points, vulnerability, and stationarity over time. Regional studies are being conducted in Puget Sound and in the California Current System. In Alaska, an expert survey is ongoing to identify ecosystem indicators for the Gulf of Alaska, which would include the effects of climate change.

NOWPAP (Alexander Tkalin)

Dr. Tkalin described the Northwest Pacific Action Plan (NOWPAP). NOWPAP is interested in the outcomes of WG 28, as a potential user of the recommendations and materials provided. Dr. Tkalin noted that UNEP (United Nations Environment Programme) is also working on a toolbox of indicators, as is HELCOM (the Helsinki Commission) in the Baltic. NOWPAP is focused on 5 broad themes: biodiversity, eutrophication, pollution, marine litter, invasive species. Dr. Tkalin noted that fishing is not one of NOWPAP's foci.

AGENDA ITEMS 4 AND 5

Report draft chapter outlines

The working draft report's chapter outline is present in *WG 28 Endnote 3*.

Chapter 2 Multiple stressors on North Pacific marine ecosystems

Suggested items to include are:

- Comparing global GIS-based stressor maps with more detailed regional maps: do the global; maps represent the regional maps?
- The INVEST approach helps to structure and illustrate trade-offs. Note, however, that INVEST is more correctly a suite of tools rather than a framework *per se*. For WG 28, the more useful tools might be those relating to habitat risk assessment and sensitivity.
- Some frameworks require an Objective, *e.g*., DPSIR. Therefore, Objectives need to be assigned in order for these frameworks to be applied, which is often done by a small group of indicator developers. It would be helpful to include a table which identifies those frameworks which require objectives, *etc*. (*i.e*., which have specific requirements for data, objectives, *etc*.). Frameworks also need to be applied at the appropriate scales.

Chapter 3 Ecosystem Indicators for multiple stressors in the North Pacific

Dr. Boldt and colleagues were congratulated on their publication arising in part from work to prepare this chapter (Boldt, J., Martone, R., Samhouri, J., Perry, R.I., Itoh, S., Chung, I.K., Takahashi, M., Yoshie, N. 2014. Developing ecosystem indicators for responses to multiple stressors. *Oceanography* 27(4): 116–133).

The stacked bar chart figure in this publication is a great demonstration of the different processes (and indicators) across a number of areas. It will also be useful to compare the similarities and differences among these indicators sets. Some of the outcomes from preparing this paper included a recognition that one general list of indicators for multiple stressors is likely not currently possible (and maybe never). There are two obvious approaches: 1) ecosystem specific, for example, in which a general set might be applied to many systems, and 2) a core set of general indicators supplemented by additional indicators specific to a particular system. The latter was considered as a 'toolbox' approach and was preferred by the WG. It was noted that the EU Marine Strategy Framework Directive included 11 descriptors with 57 indicators. Also noted was the general problem of a lack of objectives and how best to define "Good Environmental Status". The WG suggested it would be useful to include a list of potential indicators, matched against whether they were available to populate these indicators.

The approach taken in Japan is quite different. It uses a hierarchical medical chart analogy, and includes the smoothness of materials cycling (*e.g.*, see the presentation by Dr. Kisaburo Nakataat, http://www.pices.int/publications/presentations/PICES-2013/2013-S8/Day1-S8-1645-Nakata.pdf (BIO/FIS/MEQ/TCODE/FUTURE Topic Session (S8) on "*Ecosystem indicators to characterize ecosystem responses to multiple stressors in North Pacific marine ecosystems*" at PICES-2013 (Nanaimo, Canada). This approach also provides a framework for local people to conduct their own analyses.

Suggestions for additional information in Chapter 3 included:

- Western Pacific examples of programs/approaches to identifying indicators of multiple stressors and ecosystems assessments (*e.g.*, Itoh's list from Japan);
- A recommended list of indicators of responses to multiple stressors;
- Tables of data availability for indicators and pressures (mostly complete);
- Final summary with references to other chapters in the WG 28 report.

Much of Day 2 of the meeting involved extensive discussions on what indicators, and sets of indicators, should be recommended for application in PICES areas. It was agreed that the European Union Marine Strategy Framework Directive (EU-MSFD) indicators can serve as a reasonable starting point from which to build on or subtract from when applying to PICES areas. An important question to ask is whether any of these indicators might lead to mis-interpretation of results if multiple interacting stressors are present – *i.e.*, Are single indicators enough to capture status and trends in marine ecosystems, or might they lead to incorrect interpretations if multiple stressors are in fact present? The Crain *et al*. (2008) study might be useful as an initial guide to how various stressors may interact, additively or negatively. *WG 28 Endnote 4* presents the WG 28's initial assessment of indicators suggested by the EU-MSFD for application to the North Pacific.

The meeting adjourned at 15:00 h on 18 October 2014.

WG 28 Endnote 1

WG 28 participation list

Members	Observers
Jennifer L. Boldt (Canada)	Phil Levin (USA)
Kazuhiko Mochida (Japan)	Alexander Tkalin (NOWPAP coordinator)
Sachihiko Itoh (Japan)	Sang Chul Yoon (NFRDI, Korea)
Vladimir V. Kulik (Russia)	Xiaodong Zhong (NOWPAP Secretariat)
Jaebong Lee (Korea)	
Olga Lukyanova (Russia)	
Rebecca Martone (USA)	
Ian Perry (Canada, Co-Chair)	
Jameal Samhouri (USA)	
Motomitsu Takahashi (Japan, Co-Chair)	
Naoki Yoshie (Japan)	
Stephanie Zador (USA)	
Chang-Ik Zhang (Korea)	

WG 28 meeting participants at PICES-2014 in Yeosu, Korea. Left to right: Sang Chul Yoon, Jaebong Lee, Naoki Yoshie, Xiaodong Zhong, Kazuhiko Mochida, Motomitsu Takahashi, Ian Perry, Jameal Samhouri, Chang-Ik Zhang, Vladimir Kulik, Jennifer Boldt, Sachihiko Itoh, Stephani Zador, Rebecca Martone.

WG 28 Endnote 2

WG 28 meeting agenda

1. Welcome, Introduction and sign-in (all)
2. Review of activities during the 3rd year of WG 28
    a) General review of Terms of Reference plus discussion of expectations for the Working Group by PICES, and what we expect to be able to deliver (all)
    b) Report on WG 28-sponsored Theme Session at the PICES FUTURE Open Science Meeting in Hawaii, April 2014 (Perry);
    c) Report on Workshop (W2) at the PICES FUTURE Open Science Meeting in Hawaii, April 2014
    d) Report on WG 28-sponsored Topic Session at PICES-2014 FUTURE Open Science Meeting (Martone/Samhouri)
    e) Other related WG 28 activities (including country reports)
3. Review of progress on Terms of Reference, and brief country reports of activities of interest to WG 28
    General discussion of how far we have progressed in addressing our ToR – which have we covered, which have we still to do? To include brief reports from each country of activities of importance to WG 28.

4. Presentations on progress on each of the draft report chapters, and plans for moving these ahead (see Appendix 4 for draft report outline and lead authors, as discussed at our meeting in Nanaimo, 2013)
    a) *Chapter 2* "Frameworks linking pressures to impacts and changes in North Pacific marine ecosystems", and "Multiple pressures on North Pacific marine ecosystems" (discussion leads: Perry, Takahashi)
    b) *Chapter 3* "Ecosystem indicators" and "Indicators for ecosystem responses to multiple pressures" - to include presentation/discussion of article accepted for publication in *Oceanography* [discussion leads: Boldt, Samhouri, Itoh, Yoshie, Chung, others (?)]
    c) *Chapter 4* "Case study examples":
        - Inland seas, *e.g.*, Salish Sea (Strait of Georgia; Puget Sound), Seto Inland Sea (discussion leads: Samhouri, Perry, Takahashi)
        - High latitude seas, *e.g.*, possibly Sea of Okhotsk, Bering Sea (discussion leads: Kullik, Zador, Lukyanova)

5. Discussions of report outline, continued
    d) Re-look at proposed report chapter outline – Are any topics missing (*e.g.*, reference points/tipping points – or could that be added to Chapter 3)?
    e) Conclusions and recommendations – can we begin to identify any of these now? (discussion leads: co-chairs). To include discussion of possible specific indicators to recommend to PICES for inclusion in the next North Pacific Ecosystems report.

6. Discussion of interactions with other PICES groups (co-chairs)
    a) Relationships between WG28 and other Working Groups and Committees
    b) Contributions to FUTURE

7. Discussion of plans for primary publications resulting from the WG28 report (Samhouri)

8. Any other business

18:00 End

NOTE: WG 28 has available a second day (Saturday, October 18, 2014, 0900–1800) for its business meeting if needed for work on the various chapters, etc. At present the agenda for day 2 is unscheduled.

WG 28 Endnote 3

Updated and revised (draft) outlines for each chapter of WG 28 final report

(revised from the version originally developed at the WG 28 meeting at PICES-2012, Hiroshima)

<u>General Outline</u>

Chapter 1. Introduction (Co-Chairs: Takahashi/Perry)

- Background to the WG
- ToR/Objectives
- Brief overview of the issue of multiple activities/stressors on marine ecosystems
    - *e.g.*, use of the phrase "activities/stressors (or "pressures") to indicate both natural and anthropogenic pressures, and that not all of these are always "bad" for the ecosystem. Define what is a "bad" ecosystem? – *e.g.*, different objectives for ecosystem states, what is "bad" varies for fishers *vs* conservationists. Perhaps recommend the broader concept of retaining the natural resilience of ecosystems?

  - Include definitions for “stressors”. Note the issue that information to construct indicators is often available at multiple but different time and space scales, *etc*.
  - Brief literature review of problems of multiple and cumulative stressors in marine systems – *e.g*., the norm, but difficult to assess more than 2–3 stressors at one time
    - presentation by Dr. Coté in Session S8 later in this PICES meeting provides an excellent overview and access to key literature.
    - include reference to climate change and fishing issues (*e.g*., age structures are truncated and this can create problems with resilience to climate change).
    - two general types of approaches:
      - mesocosm experiments,
      - whole ecosystem studies and statistical methods.
- Organization and guide to report contents

Chapter 2. Multiple stressors on North Pacific marine ecosystems (Perry, Takahashi, Samhouri, Zhang, Lee, Martone, others welcome!)

- Frameworks linking pressures to impacts and changes in North Pacific marine ecosystems (*e.g*., PICES Session S10 at 2012 Annual Meeting in Hiroshima)
  - brief review of potential frameworks that could be used to link activities and stressors to ecosystem responses,
  - assessment of their applicability to North Pacific marine ecosystems,
  - recommendations for applications.
  - *e.g*.,
    - Pathways of Effects
    - Driver-Pressure-States-Impact-Response models,
    - simulation and other analytical modeling approaches, *e.g*., Ecopath with Ecosim,
    - probabilistic (Bayesian) networks,
    - Integrated Ecosystem Analyses,
    - IFRAME, INVEST,
    - others?
- Multiple pressures on North Pacific marine ecosystems
  - identification of the spatial (and temporal, where possible) extent of important activities and stressors in North Pacific marine ecosystems,
  - identify habitats and general locations (if possible) where multiple stressors overlap,
  - identify trends in these activities/stressors if possible,
  - use existing literature as a starting point, but also build on own analyses.
- Sub-sections of this chapter for each PICES country, preferably using a common approach (???), plus a synthesis section. Or perhaps these might be included in the case studies?

Chapter 3 Ecosystem Indicators for multiple stressors (Boldt, Samhouri, Itoh, Yoshie, Chung, Martone, others?)

A. Chapter introduction

  - Identify need to include indicators of multiple stressors when evaluating the state of marine ecosystems.
  - Purposes of chapter:
    - review existing indicators,
    - review potential sources of data available from national and international programs,
    - indicator-selection criteria, and
    - approaches for evaluating indicators.

B. Review of indicators in literature
- General definition of indicators
- General categories of indicators:
  - Human, biological (including trophodynamics), environmental, socio-economic-political,
  - State and trend,
  - Fulton (2003): strong, intermediate, and weak indicators.
- Examples of indicators:
  - PICES Scientific Report No. 37:
    - Relative biomass, *e.g.*, top predators,
    - Biomass ratios, *e.g*., Piscivore:planktivore,
    - Habitat-forming taxa, *e.g*., proportional area covered by epifauna,
    - Community size spectra slopes,
    - Taxonomic diversity (richness),
    - Total fishery removals,
    - Maximum (or mean) length of species in catch,
    - Size-at-maturity,
    - Trophic level or trophic spectrum of the catch,
    - Biophysical characteristics, *e.g*., temperature, chlorophyll a.
  - IndiSeas1 (focused on effects of fishing):
    - Mean length,
    - Trophic level of landed catch,
    - Proportion under/ moderately exploited species,
    - Proportion predatory fish,
    - Mean life span,
    - 1/CV biomass,
    - Biomass of surveyed species,
    - 1/landings/biomass.
  - IndiSeas2 (in addition to IndiSeas1 indicators; expanded to include effects of environment and indicators of human dimensions)
  - Environmental indicators: SST, Chl-*a*, global and regional climate
  - Human dimensions indicators:
    - Effectiveness, efficiency and fairness of fisheries management and quality of governance,
    - Contribution of fisheries to food provision, economic and social well being,
    - Well being and resilience of fisher communities.
  - Biodiversity indicators:
    - Mean intrinsic vulnerability index of fish catch,
    - Trophic level of the community,
    - Mixed trophic index ($TL \geq 3.25$),
    - Proportion of exploited species with declining biomass,
    - Relative abundance of flagship species,
    - Discards/landings.

C. Indicator selection criteria
- Rice and Rochet (2005) 8-step process for selecting a suite of ecosystem indicators:
  - Step 1 determine user needs,
  - Step 2 develop list of candidate indicators,
  - Step 3 determine screening criteria,
  - Step 4 score candidate indicators against screening criteria,

    - Step 5 summarise scoring results,
    - Step 6 decide how many indicators are needed,
    - Step 7 make final selection,
    - Step 8 report on chosen suite of indicators.
  - PICES 2011 FUTURE workshop criteria (each criterion should be weighted for relevance to end user identified):
    - available regularly and in a timely manner,
    - available as a time series,
    - statistical properties are understood and provided,
    - related to attribute either empirically or theoretically,
    - specific to attribute,
    - spatial and temporal scales of indicator appropriate to attribute,
    - responsive (sensitive to perturbation),
    - relevant to objective,
    - understandable by target audience,
    - provides a basis for comparison between ecosystems.

D. Indicators of ecosystem responses to multiple stressors
  - Approaches:
    - Halpern *et al*. (2007, 2008, 2009), Teck *et al*. (2010) – cumulative impact scores,
    - Samhouri and Levin (2012).
    - IndiSeas2 exploring approaches to integrating/combining indicators (Shin *et al*., 2012):
      - scoring approach to aggregate all indicators into a single indicator,
      - multidimensional approach,
      - multi-criteria decision analysis.
    - Ban:
      - Data-based: Meta-analysis,
      - Expert-based elicitation,
      - Combined above, spatial: Regional mapping, GIS approaches,
      - Experimental,
      - Model-based.
    - Evaluation of indicators to identify vulnerable ecosystem components
      - despite pros and cons of each approach there is a need to use multiple approaches (expert elicitation, model-based simulation, and empirical analysis) to identify and evaluate critical multiple stressors of North Pacific marine ecosystems and indicators to assess their impacts.

Chapter 4. Case Studies

- Coastal systems (using Strait of Georgia, Canada, Puget Sound (US), Seto Inland Sea (Japan) *e.g*., Perry *et al*. S8 presentation (but at the moment development of Indicators is lacking)
- Possibly: Sea of Okhotsk, Bering Sea (Lukyanova, Kullik, Zador?)

Chapter 5. Conclusions and recommendations (drafted by Co-Chairs but developed by all WG 28 members)

Appendices

1. Terms of Reference
2. Membership
3. Reports of sessions held by WG 28

WG 28 Endnote 4

Initial discussion list of potential indicators*

Indicator	Type	Could non-additive interactions between fishing and nutrients complicate interpretation of this indicator? (could be positive or negative reaction; could be antagonistic or synergistic)
1.1.1. Distributional range	State	yes
1.1.2. Distributional pattern within the latter	State	no
1.1.3. Area covered by the species (for sessile/benthic species)	State	yes
1.2.1. Population abundance and/or biomass	State	yes
1.3.1. Population demographic characteristics	State	no
1.3.2. Population genetic structure	State	no
1.4.1. Distributional range	State	no
1.4.2. Distributional pattern	State	no
1.5.1. Habitat area	State	no
1.5.2. Habitat volume, where relevant	State	no
1.6.1. Condition of the typical species and communities	State	yes
1.6.2. Relative abundance and/or biomass, as appropriate	State	yes
1.6.3. Physical, hydrological and chemical conditions	State	yes
1.7.1. Composition and relative proportions of ecosystem components (habitats, species)	State	yes
3.2.1. Spawning Stock Biomass (SSB)	State	yes
3.2.2. Biomass indices	State	yes
3.3.1. Proportion of fish larger than the mean size of first sexual maturation	State	yes
3.3.2. Mean maximum length across all species found in research vessel surveys	State	yes
3.3.3. 95% percentile of the fish length distribution observed in research vessel surveys	State	yes
3.3.4. Size at first sexual maturation	State	yes
4.1.1. Performance of key predator species using their production per unit biomass	State	yes
4.2.1. Large fish (by weight)	State	yes
4.3.1. Abundance trends of functionally important selected groups/species	State	?
5.1.1. Nutrients concentration in the water column	State	no
5.1.2. Nutrient ratios (silica, nitrogen and phosphorus)	State	no
6.1.1. Type, abundance, biomass and areal extent of relevant biogenic substrate	State	yes
6.1.2. Extent of the seabed significantly affected by human activities for the different substrate types	State	yes
6.2.1 Presence of particularly sensitive and/or tolerant species*	State	yes

6.2.2. Multi-metric indices assessing benthic community condition and functionality, such as	State	yes
6.2.3. Proportion of biomass or number of individuals in the macrobenthos above specified length/size	State	yes
6.2.4. Parameters describing the characteristics of the size spectrum of the benthic community	State	yes

*derived from the European Union’s Marine Strategy Framework Directive, the type of indicator they represent, and WG 28’s initial assessment of whether interactions among multiple stressors may lead to incorrect interpretations

Appendix 5

PICES Press Articles Related to WG 28

Workshop on Marine Biodiversity Conservation and Marine Protected Areas in the Northwest Pacific

by Vladimir Kulik

Fig. 1 The participants of the NOWPAP/NEASPEC workshop on "Marine biodiversity conservation and marine protected areas in the Northwest Pacific", March 13–14, 2013, in Toyama, Japan. The photo was provided by the Special Monitoring and Coastal Environmental Assessment Regional Activity Centre (CEARAC) of NOWPAP.

The beautiful city of Toyama, Japan, 300 km northeast of Tokyo, was the setting on March 13–14, 2013, for a workshop on "*Marine biodiversity conservation and marine protected areas in the Northwest Pacific*". The workshop was convened by NOWPAP (Action Plan for the Protection, Management and Development of the Marine and Coastal Environment of the Northwest Pacific Region; part of the Regional Seas Program of the United Nations Environment Program; http://www.nowpap.org/) and NEASPEC (North-east Asian Sub-program for Environmental Cooperation; http://www.neaspec.org/). The objectives of the workshop were: (1) to share information on methodologies for marine environment assessment and the current status of Marine Protected Areas (MPAs) in member states of NOWPAP, and (2) to discuss the programs and operations of the proposed North-east Asian MPA network. PICES was invited to participate in this workshop, and was represented by Dr. Vladimir Kulik, a member of the PICES Working Group 28 on *Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors*. In addition to PICES, other participants at the workshop included experts from all NOWPAP member states (Japan, People's Republic of China, Republic of Korea and the Russian Federation) and from international organizations such as the Helsinki Commission (HELCOM; http://www.helcom.fi/) and the IOC Sub-Commission for the Western Pacific (IOC/WESTPAC; http://www.unescobkk.org/westpac). In total, more than 20 people attended the workshop (Fig. 1).

The motivation for the workshop was responsibilities to contribute to marine biodiversity conservation and sustainable use of marine ecosystem services in the NOWPAP region. The meeting had presentations and shared information on details of MPAs in the region, including definition, categories and monitoring/management status in each member state of NOWPAP. An information sheet was developed and will be finalized based on additional information provided after the workshop. The meeting discussed the similarities and differences in the definitions of MPAs among the member states and recognized the usefulness of such information for future considerations to improve the management of MPAs. Information was also shared on the challenges of maintaining and managing MPAs, as well as future plans to design and expand these areas, including the possible application of the Ecologically or Biologically Significant Sea Area (EBSA) concept developed by the United Nations (UN) Convention on Biological Diversity (CBD; http://www.cbd.int) and other organizations.

The meeting learned about ongoing related activities for assessing the marine environment being conducted by PICES, HELCOM and IOC/WESTPAC, which were recognized as being useful for the conservation of marine biodiversity in the NOWPAP region. The necessity of Ecological Quality Objectives for the NOWPAP region was stressed as a basis for setting targets for assessment and appropriate management. Collaborations among the NOWPAP member states and other regional organizations such as PICES towards the conservation of marine biodiversity were acknowledged as being crucial. Of special interest to PICES was a presentation by Dr. Maria Laamanenof (HELCOM) on "*Comprehensive ecosystem assessment for marine biodiversity conservation*". She noted that they have reached the 10 % target set by the UN CBD for a regional network of MPAs in the Baltic Sea. However, the present network may not be entirely ecologically coherent if adequacy, representativity, replication and connectivity are the primary criteria used for its assessment. The most important problems they have encountered in evaluating the effectiveness of this network of MPAs are nonlinearities and thresholds in the ecosystem recovery process. Therefore, reaching some of the targets did not lead to convergence with other targets from the same domain. As a result, widely used simplifications in the models of ecosystem assessment such as linearity and additivity must be reconsidered. HELCOM member states are in the process of summarizing their achievements in assessing the progress towards reaching HELCOM objectives for a healthy Baltic Sea, which are available at http://www.helcom.fi/BSAP_assessment/en_GB/main.

At its conclusion, the NOWPAP/NEASPEC workshop recommended the following:

- The regional monitoring centre for NOWPAP to assess the availability of data and to consider the collection of metadata and the development of assessment tools based on the available data for marine biodiversity conservation in the NOWPAP region;
- Recognizing that the indicators employed by HELCOM and those being studied by PICES are useful references for the NOWPAP region, to consider the availability of data and different conditions in the marine environment in the NOWPAP region when selecting indicators;
- Strengthen collaboration with relevant partners, for example, PICES, HELCOM and IOC/WESTPAC, when conducting the above tasks.

Fig. 2 PICES WG 28 presentation at the NOWPAP/NEASPEC workshop.

The full meeting report, with details from each NOWPAP member state, and all presentations (including that given by the author of this article (Fig. 2) on behalf of PICES WG 28) are available on the workshop website at http://www.cearac-project.org/NOWPAP_NEASPEC_Workshop/NOWPAP_NEASPEC_Joint_Workshop.htm.

Dr. Vladimir Kulik (vladimir.kulik@tinro-center.ru) is the Leading Research Scientist at the Regional Data Center of the Pacific Research Institute of Fisheries and Oceanography (TINRO-Centre) in Vladivostok, Russia. His research focuses on the fluctuation of abundance of species which are caught by pelagic and bottom trawls with 1 cm mesh during scientific surveys in the Russian part of the Northwestern Pacific Ocean since 1979. Within PICES, Vladimir is a member of the Technical Committee on Monitoring, the Working Group on Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors (WG 28), and the FUTURE Advisory Panel on Anthropogenic Influences on Coastal Ecosystems.

OSM Session on "*Identifying multiple pressures and system responses in North Pacific marine ecosystems*"

by Ian Perry

Marine ecosystems of the North Pacific, both coastal and offshore, are impacted by multiple pressures, such as increased temperature, change in iron supply, harmful algal bloom events, invasive species, hypoxia/eutrophication and ocean acidification. These multiple pressures can act synergistically to change ecosystem structure, function and dynamics in unexpected ways that differ from single pressure responses. It is also likely that pressures and responses will vary geographically. A key objective of the PICES FUTURE science program is the identification and characterization of these pressures to facilitate comparative studies of North Pacific ecosystem responses to multiple stressors and how these systems might change in the future. This session had two primary objectives: 1) identify key stressors and pressures on North Pacific marine ecosystems, including comparisons as to how these stressors/pressures may differ in importance in different systems and how they may be changing in time; and 2) identify ecosystem responses to these multiple stressors and pressures. Objective 2 includes understanding how natural and human perturbations may cascade through ecosystems, and whether there may be amplifiers or buffers which modify the effects of perturbations on marine systems. The overall goal of this session was to contribute to the work of PICES Working Group 28 on *Developing Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors* and to obtain an overview of the pressures being experienced by North Pacific marine ecosystems and their impacts on the marine ecosystems of the North Pacific.

In total, 15 papers were presented in session S1, plus one by Isabelle Rombouts in a plenary session (Fig. 1). All presentations demonstrated that multiple stressors are common, and that single stressors are rare (*e.g.*, Fig. 2). Literature analyses of multiple stressors usually list between 25 to 50 multiple stressors (Working Group 28 has been working with an integrated list of about 20 stressors for its comparative studies). Several presentations by Working Group 28 members (Takahashi *et al*., Martone *et al*., Kulik, Samhouri *et al*., Zador and Renner, Perry *et al*.) provided descriptions of multiple stressors in North Pacific marine ecosystems. The presentation by Perry *et al*. concluded that the scientific community is beginning to understand issues of sensitivity and exposure of habitats to multiple stressors (Fig. 3), but there is also consensus that a lot of questions remain. Early analyses from Working Group 28 suggest that there are more stressors, and greater impacts, in coastal than offshore areas. However, comparative studies also suggest there may be a shorter list of important stressors at regional scales. In analysis of scenarios of cumulative impacts along the coast of British Columbia, Canada, Clarke-Murray *et al*. found climate change impacts overwhelmed all other stressors.

Fig. 1 Plenary speaker, Dr. Isabelle Rombouts addressing the audience.

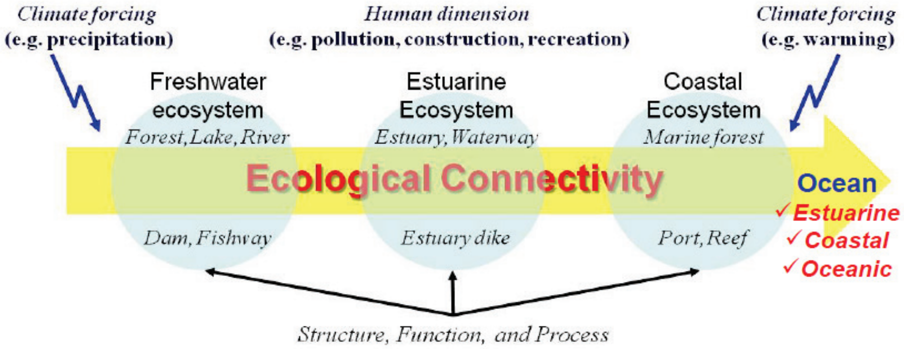


Fig. 2 Example of multiple and cumulative stressors along an ecological gradient from freshwater to marine systems. From Won et al.

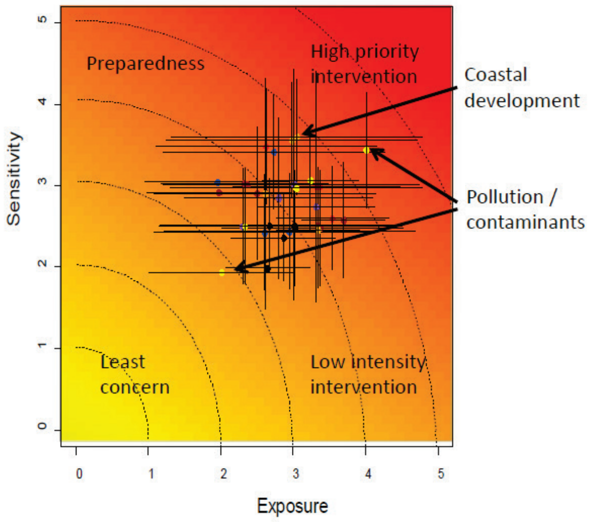


Fig. 3 Example of a risk plot (Exposure by Sensitivity) of multiple stressors (20 stressors by 22 habitats) for the Strait of Georgia, Canada. Color coding represents degrees of inferred relative risk. Horizontal and vertical bars represent uncertainties derived across multiple experts. From Perry et al.

Several presentations discussed options for developing ecosystem indicators to characterise ecosystem responses to multiple stressors. Boldt *et al*. outlined a number of requirements for such indicators. These include the need to define strategic goals and ecological or management objectives for these indicators, and the need for a suite of integrative indicators that would cover key components and gradients at the appropriate spatial scales. It was also recognised that mechanistic approaches can give insights into how pressures are likely to interact and how impacts may become observable. The synthesis of indicator status across multiple trophic levels may reveal broad-scale changes in the environment that may have important biological and management implications. For example, upper trophic level organisms such as seabirds and halibut may serve as integrative indicators that can provide near-real time cues of environmental state (Zador and Renner presentation).

Multiple stressors might interact in additive, synergistic, or antagonistic ways. An analysis of interaction type from 171 studies that manipulated 2 or more stressors found that 26% identified additive interactions, which are most commonly used in model studies of stressor interactions, but that 36% and 38% of the studies identified synergistic or antagonistic interactions, respectively (Crain *et al*. 2008, Ecology Letters). Examples presented during this session included the paper by Jung, who concluded that intensive fishing activities by Korean trawlers could have aggravated the potential resilience of the filefish stock, causing it to collapse when the climate changed; and the paper by Polovina and Woodworth-Jefcoats, who concluded that top-down responses in the Central North Pacific ecosystem means that fishing and potentially bottom-up climate impacts are likely to have stronger negative impacts on the larger fishes than on smaller fishes, causing the ecosystem size structure to shift towards smaller sizes. Their study, based on two ecosystem models, indicated that impacts from bottom-up stressors could range from moderate (–20%) to severe (–60%) depending on changes in phytoplankton. Del Raye and Weng identified a need for physiological models that use aerobic scope for activity to understand interactions between temperature and O_2 at discrete $p\mathrm{CO}_2$.

Based on the presentations and discussions, the session reached the following conclusions:

- Ecosystem responses to multiple stressors are non-uniform: a suite of indicators is best to capture a diversity of ecosystem responses.
- Because a diversity of ecosystem responses is expected, it is essential to clarify which types of ecosystem changes matter to a pre-specified group of people.
- Interactions between multiple stressors more often appear to be non-additive (synergistic or antagonistic); there is the need to understand how predicted ecosystem responses vary with different assumptions about interactions between stressors (noting, however, that there is no substitute for data).
- Climate and fishing provide good examples of how interactions between stressors can act non-additively in some cases and additively in others to change the dynamics of exploited fish populations.

Different approaches may be needed for situations with different degrees of complexity. For example, data-driven evaluations are obviously to be preferred for situations where data are available (in space, time, and types of variables). Expert opinion may be necessary when the focus is on broad spatial scales, although care should be taken to verify these opinions with data or other experts when possible.

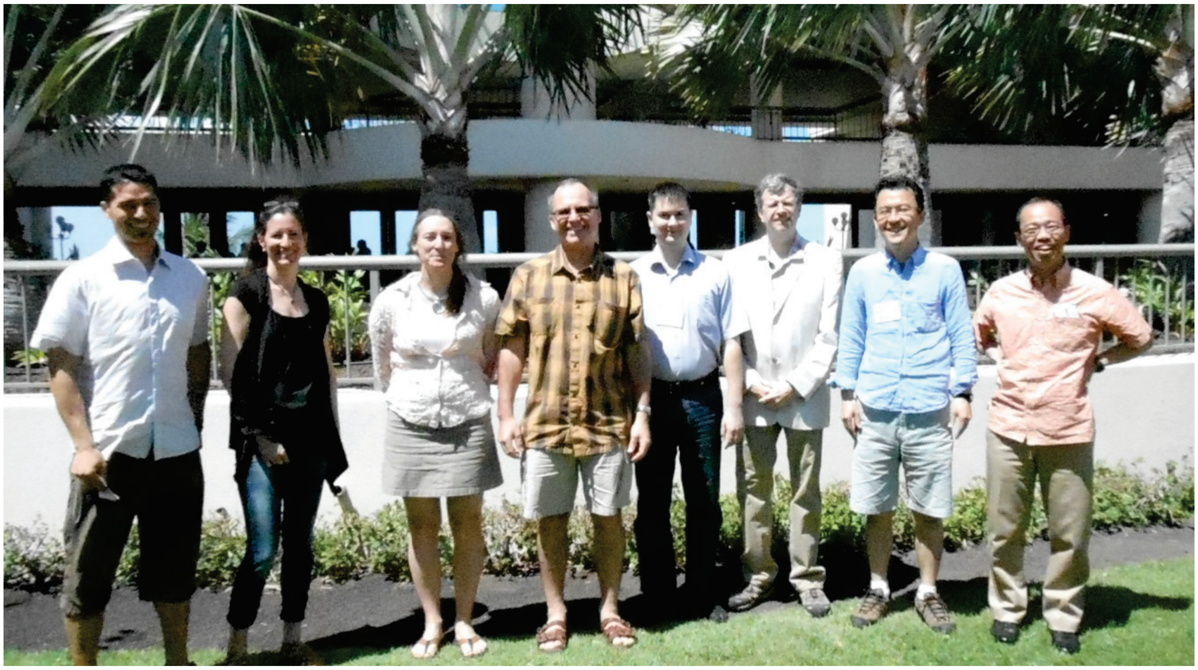
Acknowledgements

I would like to thank the other S1 co-convenors, Vladimir Kulik, Rebecca Martone, Jameal Samhouri and Motomitsu Takahashi for their contributions in organizing and chairing this session.

Dr. Ian Perry (Ian.Perry@dfo-mpo.gc.ca) is a research scientist with Fisheries and Oceans Canada at the Pacific Biological Station in Nanaimo, British Columbia. His research includes the structure and function of marine ecosystems and the development of ecosystem approaches to management of these systems.

OSM Workshop on "*Bridging the divide between models and decision-making: The role of uncertainty in the uptake of forecasts by decision makers*"

by Edward J. Gregr



Convenors and invited speakers (left to right): Kai M.A. Chan (Canada), Lee Failing (invited speaker, Compass Resource Management Ltd., Canada), Georgina A. Gibson (invited speaker, International Arctic Research Center, University of Alaska Fairbanks), Edward J. Gregr (Canada), Vladimir Kulik (Russia), Hal Batchelder (PICES Secretariat), Motomitsu Takahashi (Japan), Shin-ichi Ito (Japan), Missing: Naesun Park (Korea), Ian Perry (Canada), Jameal Samhouri (USA).

The FUTURE science program recognizes the need to more directly address uncertainty in products such as ocean climate forecasts, and to improve how the knowledge produced by PICES is disseminated. In a series of presentations and discussions, our workshop (W2), held April 14, 2014, examined both the nature of uncertainty in model systems, and how uncertainties can be included in the decision making process. The workshop was well attended, with broad representation from PICES member countries. We identified a number of opportunities for the PICES community to improve how uncertainty is characterized, and to highlight several advantages that would emerge from tailoring model outputs, including uncertainties, for diverse audiences.

Understanding uncertainty

The first step in addressing uncertainty is to understand its source. Gregr and Chan (in review) consider three classes (Data, Scope, and Process) of uncertainty based on the assumptions necessary at various steps in the model design process. Assumptions about data relate to uncertainties about things such as sampling bias, representativeness, and the overall relevance of the data to the study under consideration. Decisions about model scope (*e.g.*, specification of spatial, temporal, and compositional extents) are central to model design and contain uncertainties about model boundaries and resolution, among other things. Once model data and scope are defined, decisions and assumptions about process must be made, for example, which ecosystem components interact and the nature of these interactions, some of which are also uncertain.

For the purposes of communication and decision-making, Gregr and Chan added two additional classes of assumptions, Communication and Relevance (Table 1). Assumptions around communication obscure uncertainties related to things such as language and disciplinary epistemology. Perhaps most importantly, the relevance of ecosystem model results to decision-making is often assumed to be quite high by model developers. However, this is far from certain, and evidence suggests that it is often quite low (Failing, this workshop). This class of assumptions thus relates to uncertainties about indicator selection and the context relevance. In many cases, comprehensive treatments of model uncertainties are not necessarily desirable (or tractable). However, Gregr and Chan argue that a more explicit recognition and discussion of model assumptions is necessary for improving our understanding and communication of model results, and the associated uncertainties.

Table 1 Assumption classes and the associated types of uncertainty.

Assumption class	Uncertainty
Data	Observational
Scope	Design uncertainty
Structure	
Process	Parameter estimation Natural variation Inherent randomness
Communication	Ambiguity Under-specification Vagueness
Relevance	Context dependence Relativism

Representing uncertainty

Several presentations illustrated methods for examining model uncertainties. Invited speaker, Georgina Gibson (USA), discussed the role of assumptions in the development of lower trophic level (LTL) ecosystem models. Describing how the complexity of model structure and parameterization can increase quickly, she emphasized the associated need for assumptions to manage this. She demonstrated how to use sensitivity analysis to identify critical parameters, but noted that the large computational demands limit the extent to which it can be applied. Gibson and Spitz (2011) used a one-dimensional lower trophic level model to examine a suite of 135 biological and 8 environmental factors, and ranked these factors according to their influence on model outputs. Although the approach identified parameters deserving closer scrutiny, similar analysis has not been applied to 2- or 3-dimensional models because of the computational limitations, leaving important parameters untested.

Exploring the parameter uncertainties in such simulation models is typically handled using established Monte Carlo methods. However, knowing the range over which to sample parameters is critical to such efforts. Unfortunately, such ranges (which are necessary to parameterize theoretical, mechanistic models) are not always known, and thus represent important design assumptions. Similarly, initial or starting conditions for models may be unknown, which can have a significant effect on the trajectory of model predictions (Gibson and Spitz 2011).

Rowenna Gryba (Canada) examined assumptions about the relevance and utility of data, and how this influences the evaluation of habitat suitability in models of North Pacific Right whales. Standard cross-validation approaches to evaluating models of habitat suitability are sensitive to potential biases in the data. Analytical methods typically assume unbiased data, but analyses often contain implicit, potentially false assumptions about the relevance or suitability of such data, which may contain geographic or seasonal sampling biases. Gryba also considered conceptual assumptions implicit in such models, where, for example, it is often assumed that mammal sightings are correlated with high prey concentrations. She showed how this conceptual assumption is testable using independent data on prey distributions, thus providing insights into the uncertainty associated with this key habitat modeling assumption.

The challenge of coupling models was discussed by Shin-Ichi Ito (Japan), who presented the results of a fisheries production model for Pacific saury forced using sea surface temperature predictions from 12 different global climate models developed by the Intergovernmental Panel on Climate Change (IPCC). While a number of correlations were found, uncertainty in fish growth projections were dominated by uncertainties in the physical forcing. This emphasizes the need for appropriate scaling methods when moving from global to regional study areas. Ito suggested that to effectively couple models across scales, more attention needs to be paid to key processes at the interfaces. For example, zooplankton dynamics play a key role in saury abundance. Thus, it is critical to appropriately capture the relationships between physics and zooplankton, and between zooplankton and higher trophic levels (HTLs). Given that HTLs typically respond to multiple drivers operating at different scales (*e.g*., Palacios *et al*. 2013), a better understanding is needed about how HTLs respond to short-term forecasts.

The need to understand such processes and their interactions was nicely illustrated by Bill Peterson (USA), who showed how the correlation between the Pacific Decadal Oscillation (PDO) and Chinook salmon ocean survival, which had shown a robust negative correlation for 15 years, suddenly failed dramatically in 2011. The causal relationship appears mediated by copepods, which provide an index of the lipid richness at the base of the food chain. This 'lipid rich copepod index' is, in turn, correlated with Chinook survival. However, the decoupling of the relationship highlights new uncertainties about the scale and process of the presumed mechanism. Once again, this emphasizes the need to understand the process, though even so, surprises should be expected. For HTL models in particular, the need to transition from correlative to mechanistic model frameworks is increasingly relevant (Palacios *et al*. 2013).

Decision making and communication

Lee Failing (Canada), our second invited speaker, provided an important perspective on the role of research and uncertainty in decision making. Failing noted that while many frameworks exist to support integrated management, the process of actually making decisions and managing the risks arising from uncertainty are rarely emphasized. Rather, the decision-making components are often presented as *post-hoc* interactions with the principal science represented in prominent detail (*e.g.*, Figure 1). Treating decision-making as an afterthought introduces many implicit and likely false assumptions about the role of science in the decision-making process. Such perspectives are grounded in the information deficit model of science communication, an approach that is increasingly understood to be false (see http://en.wikipedia.org/wiki/Information_deficit_model). Only a small portion of science as currently practiced is typically salient to decision makers. To improve the relevance of science to policy and decision making, Failing emphasized the transformative power that comes from "making the decision" the goal of the scientific effort and analysis. This leads to immediate identification of what is important, and informs where science could best contribute to the process. The salience of such contributions would be greatest if they helped inform the trade-offs faced by decision-makers and their stakeholders.

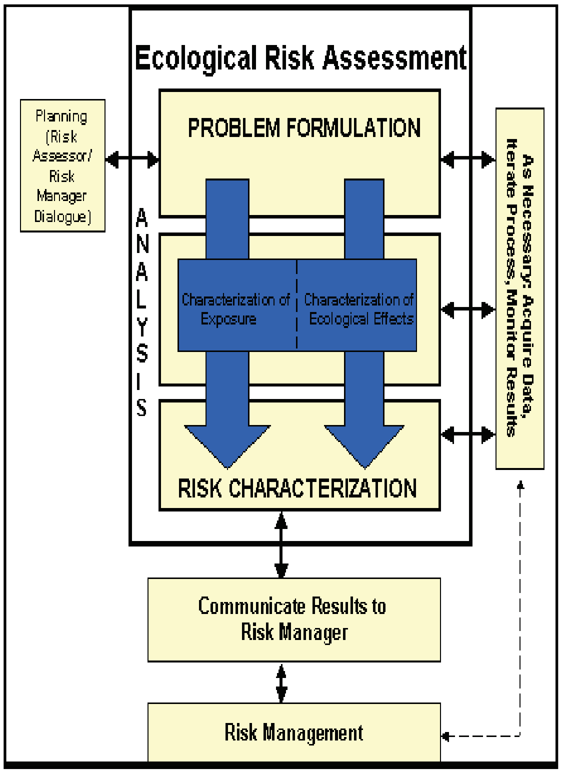


Fig. 1 Example risk assessment framework emphasizing (red oval, added) the implied post-hoc role for the decision making process.

This leads to the question of science communication, and Kai Chan (Canada) argued that this is as much a question of targeting as it is of understanding the science and the inherent uncertainties. Through various examples, Chan emphasized the need to focus on the complete decision scenario to identify what really matters and, equally important, what is at risk. From the perspective of the FUTURE program, this means identifying relevant metrics and understanding the distribution of inputs and outputs. It also means being explicit about unquantified assumptions to help understand the associated risk. And perhaps most importantly, it means recognizing that there is no single audience or stakeholder, but rather a diversity of interests for whom different metrics and presentation methods may be required. Targeting – identifying what matters, and how it is best measured, for each decision scenario – will be key to effectively communicating FUTURE products beyond the PICES scientific community.

Challenges and opportunities

In addition to the presentations, we devoted considerable time to discussion, including a joint session with the participants of workshop W3 on "*Climate change and ecosystem-based management of living marine resources: appraising and advancing key modeling tools*". The joint session acknowledged that the fundamental challenge for the modeling community is to identify what resonates with decision makers. Given the diversity of management and policy decisions that are regularly made, this emphasizes the need to develop communication strategies that can adapt effectively to diverse audiences. Decision makers would like to reduce risk and reduce surprises. This would presumably simplify the trade-offs inherent in policy and management decisions.

The role of reliable ecosystem forecasts in reducing risk and producing fewer surprises is recognized, although the risk of such forecasts being wrong and surprising decision makers will need to be carefully managed. Integrating data from regional Ocean Observing Systems, focusing on short-term forecasts, and predicting the responses of HTLs are essential components of such ecosystem forecast systems. The increasing risks faced by decision makers due to climate uncertainty provide an opportunity to advocate for ocean climate forecast services at regional scales, emphasizing that their utility for managing risk is as high as traditional short-term weather forecasts.

Uncertainties related to closure terms (*i.e.*, the parameters required to represent aspects not included in the model), model structure, and the downscaling of global models will continue to present challenges to the development of such short-term forecasts. Ensemble modeling is increasingly providing an opportunity to address the cumulative uncertainty in highly complex models, allowing the assessment of robustness (Knutti and Sedláček 2013). To demonstrate their relevance, a key performance challenge for such short-term forecasts is to achieve not only statistical accuracy, but to reasonably predict the phase (*i.e.*, timing) of climatic events. This will be best approached through regional models, which have already met with some success, such as the prediction of hypoxia events (Siedlecki *et al.* 2014). Accurate predictions of phase changes is critical (although emphatically not sufficient) for forecasting the HTL indicators important for many stakeholder groups.

Other opportunities are emerging due to the consequences of a changing ocean. As ecosystem boundaries shift, baselines on which stock assessment data are based will begin to expose the assumption of spatial stationarity. This provides an opportunity for fisheries scientists to reconsider how the science underpinning management decisions is conducted, and perhaps refocus it more directly on the decision and the risks to stocks in a more unpredictable ocean. This is particularly salient in light of recent research suggesting ocean conditions play a much stronger role in recruitment than previously believed (Szuwalski *et al*. 2014), re-enforcing the need for reliable ocean forecast systems.

The take-home message for FUTURE from the workshop is that broader uptake of our knowledge products will require clearly articulating the decision context to which they contribute. The extent to which we can explicitly inform the risks in the choices facing managers and policy makers will influence the uptake of our science into decision making. Casting our uncertainties as risks, and targeting these results at the appropriate audiences, will further increase our contribution to evidence-based decision making. Finally, by considering how we can contribute to decisions that will be made in the future, the ocean science community has an opportunity to move from a reactive, crisis-management role to proactive leadership where best available science provides timely, salient, and sound advice to support ocean management decisions.

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