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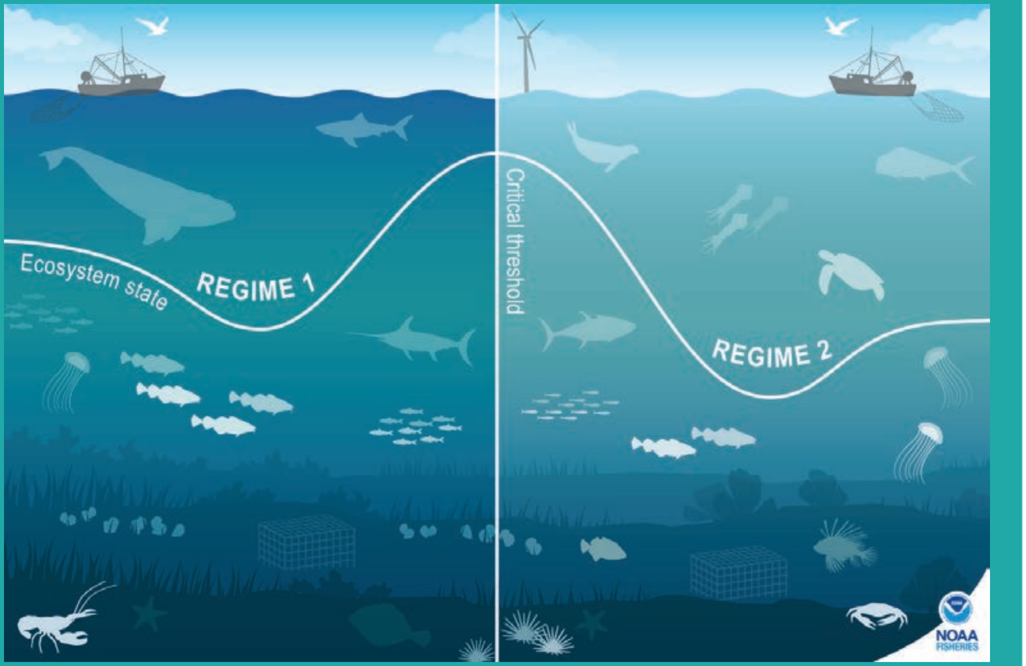

Report of Working Group 36 on Common Ecosystem Reference Points across PICES Member Countries

NORTH PACIFIC MARINE SCIENCE ORGANIZATION

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Report of Working Group 36 on Common Ecosystem Reference Points across PICES Member Countries

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Front cover:
A conceptual figure of a regime shift in ocean ecosystems. Credit: NOAA Fisheries.

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Acknowledgements

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Executive Summary

Overview

PICES Working Group (WG 36) on *Common Ecosystem Reference Points* was established in 2016 under PICES's integrative science program **F**orecasting and **U**nderstanding **T**rends, **U**ncertainty and **R**esponses of North Pacific Marine **E**cosystems (FUTURE). FUTURE was organized around three research themes, each with several objectives[1]. WG 36 addressed FUTURE's research theme questions #1: "What determines an ecosystem's intrinsic resilience and vulnerability to natural and anthropogenic forcing?" and #2: "How do ecosystems respond to natural and anthropogenic forcing, and how might they change in the future?". Analyses and results for Terms of Reference (TOR) 4 and 6 addressed several of FUTURE's objectives, particularly Objective 1.4: "How might changes in ecosystem structure and function affect an ecosystem's resilience or vulnerability to natural and anthropogenic forcing." In addition, results from analyses helped to address FUTURE's Objectives 1.2, 1.5, 2.1, 2.2, 2.3, 2.4 and 2.6 (see Appendix 5).

Strong nonlinearities in marine ecosystems indicate the existence of thresholds beyond which small changes in pressure variables can cause large responses in other ecosystem components. Better knowledge of where thresholds occur can advance our ability to anticipate future conditions and critically inform what management actions can maximize ecological, social or economic benefits. Moreover, thresholds common across analogous systems can be used to develop robust sets of reference points to prevent ecosystems from shifting into undesirable states.

WG 36's TORs were to:

1. Outline each country's mission, goals, and governmental science plans that point to the establishment of reference points across PICES member nations, and identify those that are comparable.
2. Summarize 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. This would build upon indicators identified *via* WG 19 (Ecosystem-based Management Science and its Application to the North Pacific, WG 28 (Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors), HD (Human Dimensions Committee) and WG 35 (Third North Pacific Ecosystem Status Report (NPESR3)); determine a subset (or not) of ecosystems and indicators that would be the focus of WG activities.
3. Summarize and select previous methods for determining thresholds (both non-linear and societal limits) in ecosystem indicators. This would include statistical and objective-based approaches.

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[1] https://meetings.pices.int/Members/Scientific-Programs/FUTURE#objectives

4. Determine shapes or functional forms of driver–response relationships from available datasets, and quantify thresholds to identify potential ecosystem reference points.
5. Identify ecosystem components that respond earliest to changes in biophysical drivers and could potentially serve as leading indicators of loss of resilience and ecosystem change.
6. Develop a "heuristic model" to examine drivers (climate forcing, fishing) and ecosystem response using selected ecosystem reference points for member countries.
7. Publish a final report

WG 36 conducted the following activities to address their TORs (see Appendices 6 and 7 for more details):

1. Convened a Topic Session: S3, Below and beyond maximum sustainable yield: Ecosystem reference points. PICES Annual Meeting, September 22–October 1, 2017, Vladivostok, Russia.
2. Convened a workshop: W11, Quantifying thresholds in driver–response relationships to identify reference points. PICES/ICES/IOC/FAO 4th Symposium on "*Effects of climate change on the world's oceans*", June 2–3, 2018, Washington, DC.
3. Published an article in PICES Press Summer Issue 2018, Vol. 26, No. 2, ECCWO-4 Workshop on "Quantifying thresholds in driver-response relationships to identify reference points".
4. Convened a workshop: W5, Identifying common reference points and leading indicators of ecosystem change. PICES Annual Meeting, October 25–November 4, 2018, Yokohama, Japan.
5. Convened a Topic Session: S6, Identifying thresholds and potential leading indicators of ecosystem change: The role of ecosystem indicators in ecosystem-based management. PICES Annual Meeting, October 16–27, 2019, Victoria, BC, Canada.
6. Convened a workshop: W13, Common ecosystem reference points. PICES Annual Meeting, October 16–27, 2019, Victoria, BC, Canada.
7. Convened annual and inter-sessional business meetings each year, 2017–2020, and published four reports summarizing WG 36 activities and progress: 2020, 2019, 2018, 2017.
8. Completed analyses outlined in this report.
9. Published two manuscripts (Boldt *et al*., 2021; Hunsicker *et al*., 2022).

Main findings and conclusions by TOR

TOR 1

Reference points are commonly used for single-species fisheries management across multiple PICES member countries. However, there is increasing attention on the development and implementation of ecosystem-level reference points (ELRPs) in marine resource management. To address TOR 1, WG 36 summarized if and how PICES member countries are incorporating ELRPs in their management and science plans.

The main findings for TOR 1 included:

1. All PICES member countries are required to use single-species reference points in fisheries management.
2. PICES member countries point to the establishment of ELRPs in their science and management plans; however, they are not yet commonly required across the member countries.
3. Most PICES member countries point to the inclusion of ecosystem information in government science and management plans.
4. A few PICES member countries include the establishment of ELRPs as an important priority in government science and management plans.

TOR 2

WG 36 summarized previous efforts that identified data availability for marine systems within North Pacific ecosystems, fish stocks, and fishing communities and determined a subset of ecosystems and indicators to focus on WG 36 activities.

The main findings for TOR 2 included:

5. WG 36 members selected indicators from a toolbox of recommended indicators for each region of study.
6. Many of the recommended core indicators were selected in all ecosystems to reflect environmental and human pressures and ecosystem responses; however, not all core indicators could be examined (because, for example, data were not available or to maximize the length of the time series examined). Some PICES member countries had different priorities for their recommended core indicators that influenced their data collection and sharing protocols.
7. In addition to core indicators, some additional, ecosystem-specific indicators were included.
8. For analyses, a data-based approach was used (time series of data to calculate indicators) and indicators were selected to address ecosystem-based management objectives, where possible.

TOR 3

Over the past few decades, there have been many advancements in statistical methods for detecting thresholds in time series data (Andersen *et al.*, 2009). WG 36 summarized methods used to quantify nonlinearities and thresholds in pressure–response relationships in marine ecosystems with an emphasis on those methodologies used for case studies presented in TOR 4.

The main findings for TOR 3 included:

9. We provided an overview of a suite of quantitative methods that are more commonly used to detect thresholds in pressure–response relationships in marine ecosystems, as well as methods to detect thresholds in single time series and common trends in multivariate time series.
10. All of the methods reviewed had advantages and drawbacks. For example, some could handle multiple pressures and multiple responses, but were not easily interpretable while others were easily interpretable, but required long time series and could not handle missing data.

11. There are additional advanced statistical methods for threshold detection that we did not review because either (1) to the best of our knowledge there were no existing applications to marine ecosystems, or (2) the methodology (*e.g.*, R code) was not easily accessible.
12. To address TOR 4, we selected Generalized Additive Models with derivative analysis, Gradient Forest Analysis, and Dynamic Factor Analysis for our working group activities. These analyses were selected because (1) the methods have been thoroughly vetted by ecologists and fisheries scientists, (2) several members of our working group (Appendix 2) had prior knowledge of and experience working with these methods, and (3) as part of a workshop, we built reproducible R code associated with the analyses, which are well documented and readily available for our working group and other PICES needs.

TOR 4

WG 36 developed several regional case studies to determine the shapes or functional forms of pressure–response relationships and to quantify thresholds to identify potential ecosystem reference points.

The main findings for TOR 4 included:

13. We characterized key pressure–response relationships and examined evidence of ecosystem thresholds in the pressure–response relationships. We used Dynamic Factor Analyses to identify common trends, Gradient Forest Analyses to identify important pressures on ecosystem responses and thresholds, and general additive models to examine nonlinearities in pressure–response relationships.
14. Where significant single pressure–response relationships were found, over 50% were linear and less than 10% were nonlinear. The nonlinear relationships may provide leading indicators with thresholds.
15. Dimension-reducing analyses, such as Dynamic Factor Analysis, can simplify a suite of indicators to a few important trends. For example, for most of the case studies the pressures and ecosystem responses loaded on single trends. This was especially true for those models based on a small number of time series, *e.g.*, less than 10 (Japan), and those that demonstrated strong coherence among the time series (U.S.A.). In some cases, correlations among Dynamic Factor Analysis trends could be used to provide evidence of structural or functional relationships between pressures and responses (*e.g.*, Korea). Future analyses could be aimed at combining human pressures, environmental pressures, and ecosystem responses within the same model to evaluate potential associations among the time series.
16. A case study off the west coast of Vancouver Island, Canada, applied both Gradient Forest and Generalized Additive Model analyses to environmental and biological time series. The Gradient Forest Analysis identified similar nonlinearities as the single pressure–response Generalized Additive Models, and additional nonlinearities. These findings support the use of a multi-model approach to detect nonlinearities and thresholds in marine ecosystems.
17. Top pressures include both basin- and regional-scale environmental pressures. Human pressures were not identified as important in the west coast of Vancouver Island or U.S. case studies. However, human pressures were important in the Samhouri *et al.* (2017) U.S. study, especially in the Gradient Forest Analysis.

18. Identification of pressure–response relationships likely depends on the length of the time series, frequency of measurements (seasonal *vs* annual), spatial scale of indicators analyzed, as well as the ecosystem being examined. A recent update of the Samhouri *et al*. (2017) analyses using a longer time series resulted in the identification of fewer nonlinearities (M. Hunsicker *et al*., unpublished).
19. Future studies could take into account more proximate pressures of ecological responses. For example, changes in predator abundances could be evaluated with respect to prey abundance and condition rather than using environmental pressures as a proxy. The potential for nonstationarity in pressure–response relationships also deserves consideration in future efforts to quantify nonlinearities and threshold locations in those relationships.

TOR 5

The development and testing of methodological approaches for detecting early warning signs of loss of resilience and ecosystem change has been the focus of myriad research efforts over the past few decades.

The main findings for TOR 5 included:

20. While the pursuit of effective leading indicators or early detection of ecosystem change is ongoing, there are management-relevant indicators that have already been derived from significant pressure–response relationships (both linear and nonlinear), including anthropogenic and environmental pressures.
21. The characteristics that define reliable leading indicators of ecosystem change will depend on the ecosystem process and time scale of interest.
22. Indicators investigated to date depend on time series availability of the data.
23. Results may change with the length of time series or spatial scale of the data. Simulation studies, sensitivity analyses, and the use of ecosystem models could help address this challenge.
24. There is a potential for nonstationarity in pressure–response relationships which could change the usefulness of leading indicators, as well as forecasting abilities. This highlights the importance of monitoring and developing a process-based understanding of pressure–response relationships.

TOR 6

Heuristic models can be a useful tool for increasing the understanding of complex relationships between pressures and ecosystem responses and how they might inform management actions or outcomes. Such models are simplified representations of ecosystem structure and functioning and are constructed based on hypotheses about the causal relationships among several variables.

The main findings for TOR 6 included:

25. The outcome of our analyses from TOR 4 precluded us from developing heuristic models for all ecosystems examined. For example, (1) single pressure–response relationships were not examined in all ecosystems, (2) of those where single pressure–response relationships were examined, a small number resulted in defined thresholds, and (3) the identified pressure–response relationships with defined thresholds did not always have clear links to management actions.
26. We provided two examples of heuristic models, for coastal waters off the U.S. west coast and waters around the Korean Peninsula, to illustrate how such models could be constructed and how they might be useful for making management decisions.

Recommendations for future research related to TOR 6

As environmental, human and ecological time series lengthen and become more readily available, continued efforts to examine pressure–response relationships will enable the development of similar types of heuristic models. Those relationships that may have clear links to management actions should be prioritized. These efforts would help support the development of heuristic models, regardless if the identified relationships are linear or nonlinear. In addition, this information could be used to develop and inform other models (*e.g.*, qualitative or quantitative network models) and to assess ecosystem linkages and dynamics. For example, qualitative networks models are a useful tool for conducting dynamic simulations of conceptual or heuristic models and evaluating how perturbations might affect different components of an ecosystem as well as management strategies (Harvey *et al*., 2016; Sobocinski *et al*., 2018; Forget *et al*., 2020). They are also well suited for data-poor systems where precise quantitative relationships among different stressors and ecological components are unknown (Reum *et al*., 2015). All of these modeling approaches may serve as valuable tools for supporting ecosystem-based approaches to the management of marine resources in PICES member countries.

Literature cited

Andersen, T., Carstensen, J., Hernández-García, E. and Duarte, C.M. 2009. Ecological thresholds and regime shifts: approaches to identification. *Trends in Ecology and Evolution* **24**: 49–57, doi: 10.1016/j.tree.2008.07.014.

Boldt, J.L., Fu, C., Hazen, E., Hunsicker, M., Perry, R.I. and Xiujuan, S. 2021. Quantifying ecosystem responses to environmental and human pressures on the west coast of Vancouver Island. *Ecological Indicators* **132**: 108232, https://doi.org/10.1016/j.ecolind.2021.108232.

Forget, N.L., Duplisea, D.E., Sardenne, F., and McKindsey, C.W. 2020. Using qualitative network models to assess the influence of mussel culture on ecosystem dynamics. *Ecological Modelling* **430**:109070, https://doi.org/10.1016/j.ecolmodel.2020.109070.

Harvey, C.J., Reum, J., Poe, M., William, G.D. and Kim, S. 2016. Using conceptual models and qualitative network models to advance integrative assessments of marine ecosystems. *Coastal Management* **44**: 486–503, https://doi.org/10.1080/08920753.2016.1208881.

Hunsicker, M.E., Ward, E.J., Litzow, M.A., Anderson, S.C., Harvey, C.J., Field, J.C., Gao, J., Melin, S., Thompson, A.R. and Warzybok, P. 2022. Tracking and forecasting community responses to climate perturbations in the California Current Ecosystem. *PLOS Climate* **1**: e0000014, https://doi.org/10.1371/journal.pclm.0000014.

Reum, J.C.P., McDonald, P. S., Ferriss, B.E., Farrell, D.M., Harvey, C.J. and Levin, P.S. 2015. Qualitative network models in support of ecosystem approaches to bivalve aquaculture. *ICES Journal of Marine Science* **72**: 2278–2288, https://doi.org/10.1093/icesjms/fsv119.

Samhouri, J.F., Andrews, K.F., Fay, G., Harvey, C.J., Hazen, E.L., Hennessey, S.M., Holsman, K., Hunsicker, M.E., Large, S.I., Marshall, K.N., Stier, A.C., Tam, J.C., and Zador, S.G. 2017. Defining ecosystem thresholds for human activities and environmental pressures in the California Current. *Ecosphere* **8**: e01860, https://doi.org/10.1002/ecs2.1860.

Sobocinski, K.L., Greene, C.M. and Schmidt, M.W. 2018. Using a qualitative model to explore the impacts of ecosystem and anthropogenic drivers upon declining marine survival in Pacific salmon. *Environmental Conservation* **45**: 278–290, https://doi.org/10.1017/S0376892918000073.

1 Introduction

Projected impacts of climate change and anthropogenic drivers in ocean ecosystems create uncertainty in ecological responses and can cause major shifts in ecosystem states or regimes (Biggs *et al*., 2018; Heinze *et al*., 2021; Fig. 1.1). These shifts can occur gradually and continuously along a gradient of environmental and anthropogenic pressures (Hillebrand, *et al*., 2020). Alternatively, they can be dramatic and abrupt, such as when single populations, species interactions, or whole ecosystems cross a tipping point and rapidly change or reorganize (Selkoe *et al*., 2015; Heinze *et al*., 2020; Turner *et al*., 2020). Restoring a system from an altered state to its original state may be difficult or even impossible once a critical threshold is crossed because the pathway to recovery of an ecosystem may be different from the pathway leading to the state change (Suding and Hobbs, 2009; Selkoe *et al*., 2015).

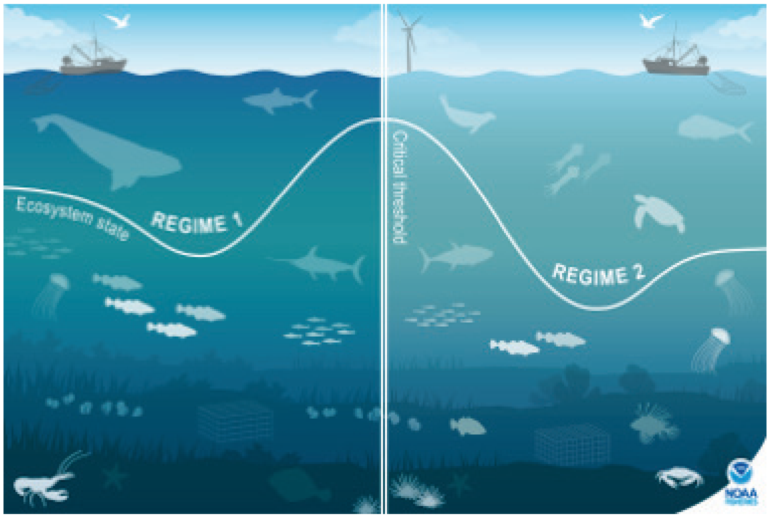

Fig. 1.1 Conceptual figure of a regime shift in ocean ecosystems. Credit: NOAA Fisheries.

Large and abrupt changes in marine populations or ecosystem functioning potentially result in losses of valuable ecosystem benefits, which can have important consequences for coastal communities and economies. Therefore, there is much interest among scientists, resource managers, and stakeholders in anticipating these changes before they occur. Identifying and monitoring indicators of resilience, species or system traits that might provide advanced warning of tipping points may be useful for avoiding or mitigating ecosystem shifts (Scheffer *et al*., 2015; Selkoe *et al*., 2015; Mahli *et al*., 2020). Identifying strong nonlinearities and thresholds in relationships between environmental and anthropogenic pressures and ecosystem indicators can also be valuable for identifying targets or reference points for triggering management actions to prevent or mitigate the impacts of such shifts (Fig. 1.2, Samhouri *et al*., 2010, 2011; Large *et al*., 2013). Over the past two decades, multiple research efforts have been aimed at detecting ecological thresholds that could help determine ecosystem-level reference points for managing natural resources. However, more research is needed to detect robust, management-relevant thresholds in North Pacific Ocean ecosystems and beyond. Pathways for the uptake of ecosystem-level reference points in the management process also need to be identified.

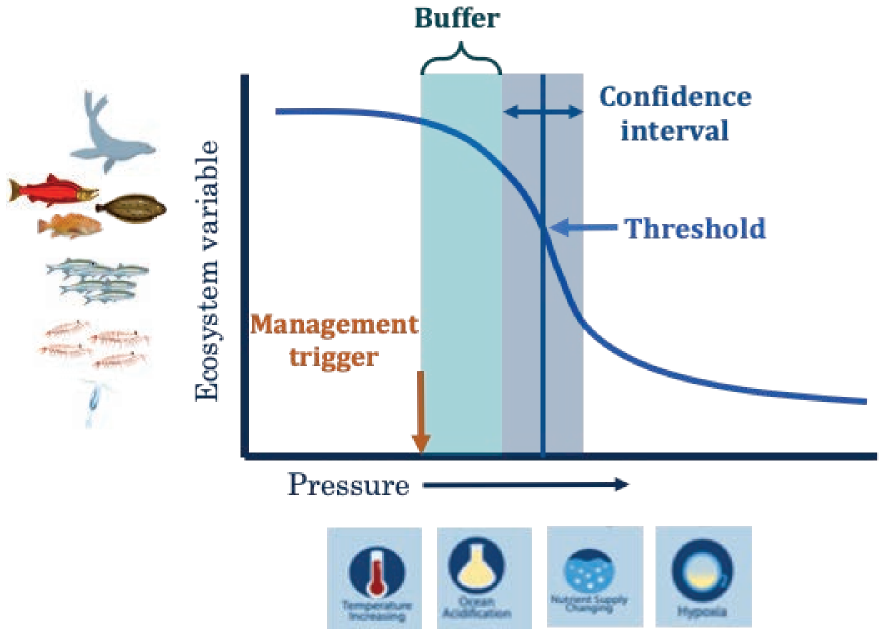

Fig. 1.2 Conceptual figure showing nonlinearity and a defined threshold in the response of an ecosystem variable to an environmental pressure. It also denotes a target or reference point for triggering management action. Here, and throughout the report, we define nonlinear relationships as those pressure–response relationships 'having one or more curves or points of rapid change' and thresholds are defined as a 'relatively rapid change from one ecological condition to another' as per Selkoe *et al*. (2015).

1.1 Guide to the report

Here, we present the efforts of WG 36 to address six TORs (Appendix 1) and to contribute to the broader efforts of identifying ecosystem-level reference points for the management of marine resources in PICES member countries and elsewhere. For TOR 1, we identified if and how PICES member countries are incorporating ecosystem-level reference points in their management and science plans. For TORs 2 and 4, we developed country-specific case studies and (1) identified the status and trends of key climate and biological variables in member country coastal ecosystems, (2) characterized key pressure–response relationships using those variables, and (3) determined whether there was evidence of ecosystem thresholds in the pressure–response relationships examined. For TOR 3, we summarized methods used to quantify nonlinearities and thresholds in pressure–response relationships in marine ecosystems with an emphasis on the methodologies that we selected for the member country case studies. For TOR 5, we provided a discussion on leading indicators of ecosystem change and the challenges associated with identifying reliable indicators. Finally, for TOR 6, we reviewed the value of developing heuristic pressure–response models using thresholds or reference points for making management decisions.

For country-specific case studies, we refer to the study systems according to PICES biogeographic regions (Fig. 1.3): Canada, waters on the west coast of Vancouver Island that fall within the northern area of Region 11; China, waters on the east coast of Mainland China in the northern area of Region 20; Japan, waters around the Shiretoko Peninsula, Hokkaido, in Regions 17 and 18; Korea, waters around the Korean Peninsula in Regions 19, 20, and 21; Russia, Exclusive Economic Zone of Russia in Region 19; U.S.A., waters off the U.S. west coast (California, Oregon, Washington) that fall within the southern area of Region 11.

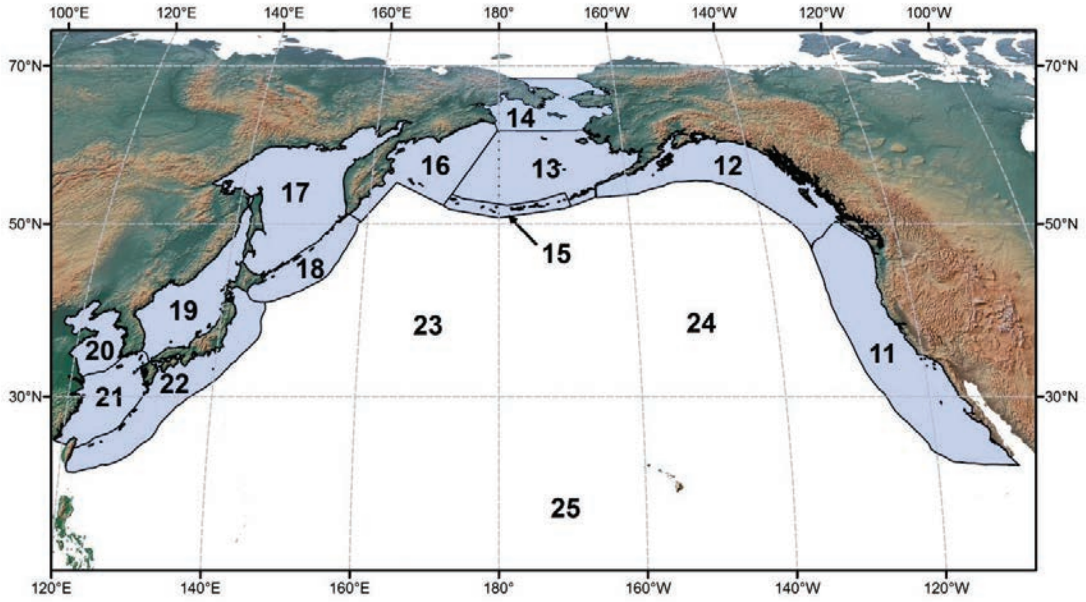

Fig. 1.3 Biogeographic regions of the PICES Convention Area.[2] Study systems for WG 36 country-specific case studies include PICES Regions 11 and 17–20.

1.2 Literature cited

Biggs, R., Peterson, G.D. and Rocha, J.C. 2018. The Regime Shifts Database: a framework for analyzing regime shifts in social-ecological systems. *Ecology and Society* **23**: 9, https://doi.org/10.5751/ES-10264-230309.

Heinze, C., Blenckner, T., Martins, H., Rusiecka, D., Döscher, R., Gehlen, M., Gruber, N., Holland, E., Hov, Ø., Joos, F., Matthews, J.B.R., Rødven, R. and Wilson, S. 2021. The quiet crossing of ocean tipping points. *Proceedings of the National Academy of Sciences of the United States of America* **118**: e2008478118, https://doi.org/10.1073/pnas.2008478118.

Hillebrand, H., Donohue, I., Harpole, W.S., Hodapp, D., Kucera, M., Lewandowska, A.M., Merder, J., Montoya, J.M. and Freund, J.A. 2020. Thresholds for ecological responses to global change do not emerge from empirical data. *Nature Ecology and Evolution*, **4**: 1502–1509, https://doi.org/10.1038/s41559-020-1256-9.

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[2] The use of numbered biogeographic regions in the PICES Convention Area used in the following sections follows the terminology for numbered areas named in accordance with Decision 2016/s/11(vii) adopted by PICES Governing Council.

Large, S.I., Fay, G., Friedland, K.D. and Link, J.S. 2013. Defining trends and thresholds in responses of ecological indicators to fishing and environmental pressures. *ICES Journal of Marine Science* **70**: 755–767, https://doi.org/10.1093/icesjms/fst067.

Malhi, Y., Franklin, J., Seddon, N., Solan, M., Turner, M.G., Field, C.B. and Knowlton, N. 2020. Climate change and ecosystems: threats, opportunities and solutions. *Philosophical Transactions of the Royal Society B* **375**: 20190104, https://doi.org/10.1098/rstb.2019.0104.

Samhouri, J.F., Levin, P.S. and Ainsworth, C.H. 2010. Identifying thresholds for ecosystem-based management. *PloS ONE* **5**: e8907–e8907, https://doi.org/10.1371/journal.pone.0008907.

Samhouri, J.F., Levin, P.S., James, C.A., Kershner, J. and Williams, G. 2011. Using existing scientific capacity to set targets for ecosystem-based management: A Puget Sound case study. *Marine Policy* **35**: 508–518, https://doi.org/10.1016/j.marpol.2010.12.002.

Selkoe, K.A., Blenckner, T., Caldwell, M.R., Crowder, L.B., Erickson, A.L., Essington, T.E., Estes, J.A., Fujita, R.M., Halpern, B.S., Hunsicker, M.E., Kappel, C.V., Kelly, R.P., Kittinger, J.N., Levin, P.S., Lynham, J.M., Mach, M.E., Martone, R.G., Mease, L.A., Salomon, A.K., Samhouri, J.F., Scarborough, C., Stier, A.C., White, C. and Zedler, J. 2015. Principles for managing marine ecosystems prone to tipping points. *Ecosystem Health and Sustainability* **1**: 1–18, https://doi.org/10.1890/EHS14-0024.1.

Scheffer, M., Carpenter, S.R., Dakos, V. and van Nes, E.H. 2015. Generic indicators of ecological resilience: Inferring the chance of a critical transition. *Annual Review of Ecology, Evolution, and Systematics* **46**: 145–167, https://doi.org/10.1146/annurev-ecolsys-112414-054242.

Suding, K.N. and Hobbs, R.J. 2009. Threshold models in restoration and conservation: a developing framework. *Trends in Ecology and Evolution* **24**: 271–279, https://doi.org/10.1016/j.tree.2008.11.012.

Turner, M.G., Calder, W.J., Cumming, G.S., Hughes, T.P., Jentsch, A., LaDeau, S.L., Lenton, T.M., Shuman, B.N., Turetsky, M.R., Ratajczak, Z., Williams, J.W., Williams, A.P. and Carpenter, S.R. 2020. Climate change, ecosystems and abrupt change: science priorities. *Philosophical Transactions of the Royal Society B* **375**: 20190105, https://doi.org/10.1098/rstb.2019.0105.

2 Mission, Goals, and Governmental Science Plans that Point to the Establishment of Ecosystem Reference Points across PICES Member Countries

2.1 Introduction

Reference points are commonly used for single-species fisheries management across multiple PICES member countries. For example, Maximum Sustainable Yield (MSY), the maximum catch that can be continuously removed without causing long-term stock depletion, has been used for decades as a target, and more recently, as a limit on fishing mortality and biomass removal. However, it has become widely recognized that inclusion of broader ecosystem information is necessary to sustainably manage marine resources, particularly in a variable climate. In turn, there is increasing attention on the development and implementation of ecosystem-level reference points (ELRPs) in marine resource management.

In 2015 PICES established a Study Group on *Common Ecosystem Reference Points across PICES Member Countries* (SG-CERP), which led to the formation of Working Group 36 to support the need for ELRPs in North Pacific Ocean ecosystems. The first Terms of Reference (TORs) for the WG was to identify if and how PICES member countries are incorporating ELRPs in their management and science plans. Here, we provide summaries of the current status of ELRPs in marine resource management in Canada (Fisheries and Ocean Canada, Federal), China (Bureau of Fisheries, Federal), Japan (Fisheries Agency, Federal), Korea (Ministry of Oceans and Fisheries, Federal), Russia (The Pacific branch (TINRO) of the Russian Federal Research Institute of Fisheries and Oceanography (VNIRO)), and the United States (NOAA Fisheries, Federal).

2.2 Country-specific summaries

2.2.1 Canada

Mission

Fisheries and Oceans Canada (DFO) has the lead federal role in managing Canada’s fisheries and safeguarding its waters. DFO works toward the following three strategic outcomes: Economically Prosperous Maritime Sectors and Fisheries, Sustainable Aquatic Ecosystems, Safe and Secure Waters (https://www.dfo-mpo.gc.ca/about-notre-sujet/mandate-mandat-eng.htm), DFO’s vision is to advance sustainable aquatic ecosystems and support safe and secure Canadian waters while fostering economic prosperity across maritime sectors and fisheries. The Department supports strong economic growth in Canada’s marine and fisheries sectors by supporting exports and advancing safe maritime trade; supports innovation through research in expanding sectors such as aquaculture and biotechnology; and contributes to a clean and healthy environment and sustainable aquatic ecosystems through habitat protection, oceans management, and ecosystems research. DFO's work is guided by five key pieces of legislation: the *Oceans Act*; the *Fisheries Act*; the *Species at Risk Act*; the *Coastal Fisheries Protection Act*; and the *Canada Shipping Act*, 2001 (Transport Canada-led). In addition to these *Acts*, there are others, such as the *Canada National Marine Conservation Areas Act* and the *Canada Environmental Protection Act* (for a list of all *Acts*, see: https://www.dfo-mpo.gc.ca/acts-lois/regulations-reglements-eng.htm), as well as several policies that guide the management of fisheries resources in the Pacific (http://www.dfo-mpo.gc.ca/reports-rapports/regs/policies-politiques-eng.htm), including the Sustainable Fisheries Framework (SFF) which incorporates the precautionary approach (http://www.dfo-mpo.gc.ca/reports-rapports/regs/sff-cpd/overview-cadre-eng.htm). Other policies and initiatives under the SFF include the Wild Salmon Policy (http://waves-vagues.dfo-mpo.gc.ca/Library/285006.pdf), a Forage Species policy, a Sensitive Benthic Areas policy, and others that factor in ecosystem considerations and precaution, providing a more rigorous and comprehensive approach to managing Canada's fisheries.

Goals

The overarching goal of Fisheries and Oceans Canada is to protect its three oceans, coasts, waterways and fisheries and ensure that they remain healthy for future generations. The SFF provides the basis for ensuring Canadian fisheries are conducted in a manner which supports conservation and sustainable use. It incorporates existing fisheries management policies with new and evolving policies. The SFF comprises: 1) conservation and sustainable use policies that include principles of ecosystem-based fisheries management and 2) planning and monitoring tools, such as Integrated Fisheries Management Plans (IFMPs, http://www.dfo-mpo.gc.ca/fm-gp/peches-fisheries/ifmp-gmp/index-eng.htm) to monitor and assess those initiatives geared towards ensuring an environmentally sustainable fishery, and to identify areas that may need improvement. Overall, the SFF provides the foundation of an ecosystem-based and precautionary approach to fisheries management in Canada.

Government Science and Strategic Plans relevant to reference points

The SFF and some policies, such as the Wild Salmon Policy (WSP), require the establishment of 'reference points' or, in the case of the WSP, 'benchmarks' (that do not prescribe specific restrictions). The SFF applies to specific and intended targets of a commercial, recreational, or subsistence fishery, requires a harvest strategy be incorporated into respective fisheries management plans to keep the removal rate moderate when stock status is healthy, promotes rebuilding when stock status is low, ensures a low risk of serious or irreversible harm to the stock, and requires a rebuilding plan when a stock reaches low levels. A fishery decision-making framework includes: 1) reference points and stock status zones (Healthy, Cautious and Critical), 2) harvest strategy and harvest decision rules, and 3) the need to take into account uncertainty and risk when developing reference points and developing and implementing decision rules (http://www.dfo-mpo.gc.ca/reports-rapports/regs/sff-cpd/precaution-eng.htm).

Under the SFF, stock status zones are created by defining the Limit Reference Point (LRP) at the Critical: Cautious zone boundary, and an Upper Stock Reference Point (USR) at the Cautious: Healthy zone boundary and the Removal Reference for each of the three zones. LRPs are based on biological criteria through a scientific peer-reviewed process, and USRs are developed by fishery managers, based on science advice and consultations with First Nations and users. The scientific information available to define reference points may vary among stocks; therefore, different approaches must be used for calculating LRPs and defining harvest rules. A harvest rate strategy is used to manage the harvest of a stock with pre-agreed-upon harvest decision rules and management actions for each zone.

The WSP requires the identification of upper and lower benchmarks to delimit population status as well as habitat status zones (green, amber, red) (DFO, 2004). For example, a low spawner abundance may be associated with the red zone and increased management actions (DFO, 2004). Upper and lower benchmarks are also used to evaluate the status and aggregate risk rating of salmon habitat (green/low risk, amber/moderate risk, red/high risk). The identification of benchmarks is determined on a case-by-case basis with consultation with First Nations and resource users and with consideration for a variety of information. Population or habitat status relative to benchmarks and zones do not result in specific prescribed restrictions; instead, management responses vary with species, region, and causes (DFO, 2004). Full definitions of reference points and benchmarks are given in Table 2.1 at the end of the section.

Single-species reference points are required in current DFO fisheries management; however, ecosystem reference points are not commonly required. Canada's Oceans Strategy promotes an ecosystem-based approach to management (DFO, 2002), and there has been considerable research into identifying ecosystem indicators (*e.g.*, Boldt *et al.*, 2014; Bundy *et al.*, 2017), assessing the state of marine ecosystems (*e.g.*, Chandler *et al.*, 2017), identifying regime shifts in indicators (*e.g.*, Perry and Masson, 2013), and incorporating ecosystem considerations in fisheries and oceans management (*e.g.*, DFO, 2016). In 2000, DFO's National Policy Committee proposed a framework for setting ecosystem objectives that included developing a suite of objectives, indicators and reference points for the maintenance of biodiversity, productivity, and water quality within coastal ecosystems of concern (DFO, 2007). Some policies, such as the WSP and DFO's Forage Species Policy, require ecosystem benchmarks or ecosystem considerations in developing reference points. DFO's Wild Salmon Policy requires the assessment of habitats relative to benchmarks. Habitat report cards have been developed to provide a snapshot of current risks to salmon habitats in a watershed (*e.g.*, Porter *et al.*, 2013; https://salmonwatersheds.ca/document-library/?searchtype=basicandsearchall=report+card). These report cards are developed using pressure and state indicators, vulnerability indicators at different life-history stages, and upper and lower benchmarks to assign an aggregate risk rating (red/high, amber/moderate, and green/low) for salmon habitat. Another example is DFO's policy on New Fisheries for Forage Species (DFO, 2009) that requires inclusion of ecosystem considerations in developing LRPs. The policy states that LRPs "should ensure both that future recruitment of the target species is not impaired, and that food supply for predators is not depleted" and "reference points may also be set for properties such as growth rates, condition factor, or reproductive output of ecologically dependent marine predators".

2.2.2 China

Mission

Commercial fisheries within China's Exclusive Economic Zone are managed by the Ministry of Agriculture and Rural Affairs (MARA; called Ministry of Agriculture (MOA) before April 2018) of the People's Republic of China (PRC) and China Coast Guard; fisheries inside the prohibited fishing zone line for motor-trawlers are managed by the Bureau of Fisheries (BoF) functioning under MARA, and fisheries outside the prohibited fishing zone line for motor-trawlers are managed by the China Coast Guard. The mission of BoF is 'stewardship of living aquatic resources through science-based conservation, enhancement and management, and the promotion of ecological sustainability'. The mission is supported by four core mandates: 1) to ensure orderly utilization of living aquatic resources in accordance with laws and regulations (NPC, 2013; MOA, 2017) to reduce the total number and power of marine fishing vessels with engines by 20,000 and 1,500,000 kilowatts from 2015 to 2020, respectively (MOA, 2017); 2) to set the science-based total catch limit for domestic marine fisheries after 2020, which should be lower than the productivity of fishery resources in the four coastal seas surrounding China, generally no more than 10 million tons (MOA, 2017); 3) to implement catch quotas for pilot fisheries of specific species; and 4) to conserve and recover depleted fishery stocks together with rare or endangered wild aquatic species, and promote their habitat protection and restoration (NPC, 2016, 2017). These mandates are mainly derived from three laws enacted by the Standing Committee of the National People’s Congress (NPC) and recent official documents by MARA.

Goals

The overarching goal of the science and management plans by BoF functioning under MARA is to control fishing effort and set the optimal total allowable catch of marine fishery resources, while promoting the conservation and enhancement of fishery resources and protecting the broader aquatic ecosystem, including rare or endangered wild aquatic species and their habitats. This goal has been accomplished through single- or multiple-species approaches together with imperfect science-based ecosystem considerations to fisheries management (NPC 2013; MOA 2017).

Government Science and Strategic Plans relevant to reference points

Government Science and Strategic Plans are generally produced by MARA and the Ministry of Science and Technology together with the National Nature Science Foundation of China (NSFC) at the national level. Here, we describe the plans of national-level research institutes that point to the establishment and use of reference points. There are nine national fisheries research institutes throughout China, three of which carry out government Science and Strategic Plans on the seas and the others on water valleys or fishery engineering. In terms of the seas, three institutes conducting research are the Yellow Sea Fisheries Research Institute (YSFRI) located in Qingdao, East China Sea Fisheries Research Institute (ECSF) in Shanghai, and South China Sea Fisheries Research Institute (SCSFRI) in Guangzhou.

MARA of the PRC issued a ‘Notice on Further Strengthening the Management and Control of Domestic Fishing Vessels and Implementing the Total Catch Control of Marine Fishery Resources’ in January 2017. Recently, the State Council of the PRC issued ‘the fourteenth five-year plan for promoting modernization of agriculture and rural areas’ (2021, http://www.gov.cn/zhengce/content/2022-02/11/content_5673082.htm) which mandates the implementation of the Total Catch Control of Marine Fishery Resources as well as improving quota-based fisheries management and strategies of fishing moratoriums and bans. Under these documents, China’s regional fishery management plans are required to specify reference points to identify when fishery stocks are vulnerable to overfishing or are being overfished. Stock status is determined by estimating the current levels of fishing mortality, (relative) abundance, mean size and size composition of a fishery stock, and comparing these metrics with specific reference points. There are two reference points used in China’s fisheries management: annual catch limit (ACL) and total allowable catch (TAC). ACL is defined as ‘the range of sustainable catch for a species or species group within a certain area of waters’. The ACL estimates are usually set as the maximum sustainable yield (*i.e.*, MSY, the largest average yield that can be continuously taken from a stock at current status of exploitation under existing environmental conditions) of fishery stocks. Subsequently, the ACL estimates are multiplied by certain percentages to set TACs, based on the status of fishery stocks.

Single-species reference points are used for major fishery stocks with high or medium economic values. However, an overall ACL is set for all domestic marine fishery resources, since most (if not all) fisheries in China are indiscriminate and lack adequate data on catch, abundance index, and other biological characteristics to estimate current stock size and MSY using conventional assessment techniques. In this context, the China–US Stock Assessment Project is conducted under the auspices of the China Fishery Dialogue with the goal to identify data sets (*e.g*., data-limited and/or data-poor) for which specific case studies can be developed subsequently to apply the best available modeling techniques to answer questions relevant to the assessment of Chinese fisheries. A data-limited stock assessment model has been developed in China and is used for stock assessment of the specific species.

2.2.3 Japan

Mission

Commercial and recreational fisheries within Japan's Exclusive Economic Zone are managed by the Ministry of Agriculture, Forestry and Fisheries (MAFF) and more specifically, the Fisheries Agency (FA). The mission of FA is 'to stabilize and improve the life of the citizens and to develop the national economy through comprehensive and systematic implementation of the policies for fishery' (http://www.cas.go.jp/jp/seisaku/hourei/data/fba_2.pdf). The mission is supported by two core mandates: 1) maintenance of a stable supply of marine products and 2) sound development of fisheries (http://www.cas.go.jp/jp/seisaku/hourei/data/fba_2.pdf). These mandates are derived from the *Fisheries Basic Act* enacted by the National Diet of Japan.

Goals

One of the goals of the Basic Plan for Fisheries (BPF) formulated in 2017 (Japan Fisheries Agency, Ministry of Agriculture, Forestry and Fisheries of Japan, 2017), relevant to the establishment of reference points across PICES member countries, is to affectively conserve and manage fisheries resources and fishing grounds that enable those fishery resources to grow (https://warp.da.ndl.go.jp/info:ndljp/pid/11487949/www.jfa.maff.go.jp/j/policy/kihon_keikaku/attach/pdf/index-3.pdf). To achieve this goal, the BPF sets a policy to promote management of fishery resources (https://warp.da.ndl.go.jp/info:ndljp/pid/12213392/www.jfa.maff.go.jp/j/policy/kihon_keikaku/attach/pdf/index-1.pdf) both nationally and internationally. Also, the BPF sets the target self-sufficiency rate for fisheries production at 74% by 2027 (it was 67% in 2014).

2.2.4 Korea

Mission

Marine ecosystems and fisheries within the Republic of Korea's Exclusive Economic Zone are managed by the Ministry of Oceans and Fisheries (MOF), and more specifically is divided into two branches: the Office of Marine Policy (MOF Marine) addressing marine ecosystems and the Office of Fishery Policy (MOF Fisheries) addressing fisheries under MOF. The mission of MOF Marine is a 'healthy ocean, good quality of our life, and sustainable development of our nation through conservation and wise use of marine environment and ecosystem' (MOF, 2017). The mission of MOF Fisheries is 'sustainable development and economic benefit for fishermen through efficient management of fishery resources' (MOF, 2009). The MOF ecosystem mission is supported by five core objectives: 1) to reduce land-based pollution, 2) to reduce ocean-based pollution, 3) to conserve the health of the marine ecosystem, 4) to mitigate and adapt to climate change, and 5) to strengthen legal and social infrastructure (MOF, 2011). These five objectives are legally binding to the *Marine Environment Conservation Act* (MECA) of 2017. The second MOF fishery mission is supported by two fundamental managing directions: 1) to ensure ecosystem-based and efficient fishery resource management through integrative manners and restoration and 2) to conserve and recover fishery species and their habitats (MOF, 2016). These two mandates are legally binding to the *Fishery Resources Management Act* (FRMA) of 2009.

Goals

The overarching goal of MOF Marine's science and management plans is to conserve ecologically healthy marine environments and ecosystems, including all marine mammals, endangered species, and marine protected areas (MOF, 2011). The overarching goal of MOF Fisheries' science and management plans is to establish efficient fishery resources management systems through integrating measures of management, including fishery resources protected areas. By making various management plans legally binding to several laws regarding the marine environment, ecosystems, and fisheries, the management actions adopt an ecosystem-based approach to management rather than a focus on single species and/or fragmented measures.

Institution

Traditionally, MOF missions have been scientifically supported by the Korean National Institute of Fisheries Science (NIFS) and the Korea Institute of Ocean Science and Technology (KIOST). Since 2008, Korean Marine Environment Management Cooperation (KOEM) has been working to support MOF Marine in science and management perspectives. The Korea Maritime Institute (KMI) was launched in 1997 to support MOF in legislating most of the ocean-related laws and preparing legally bound management plans. NIFS, the only governmental agency in the field of marine and fishery sciences, is currently implementing an ecosystem-based approach to fisheries management (EBFM), supporting both MOF Fisheries and MOF Marine. KIOST is a more science-oriented institute that focuses on all aspects of ocean science and engineering, supporting MOF Marine. KOEM is currently supporting MOF Marine to scientifically implement several legal-binding management plans of the marine environment and ecosystems.

Government Science and Strategic Plans relevant to reference points

Both fisheries and ecosystems Strategic Science Plans are produced by MOF Fisheries and Marine, respectively. As mentioned, those science plans are based on two management plans legally binding to FRMA (MOF Fisheries) and MECA (MOF Marine).

Fisheries Science Plan – Under the FRMA, the Korean fishery management plan is required to specify measurable criteria, or reference points, to identify when fish stocks are vulnerable to overfishing or being overfished. There are two categories of reference points used in Korean fisheries management: target and limit. The target reference points are a biological benchmark used to guide a desired outcome; the limit reference points indicate a state of the fishery or ecosystem to be avoided to prevent an undesirable outcome (MOF, 2016). Based on these reference points, total allowable catches (TAC) of over 40 fishery species are determined annually in Korea. While single-species reference points are most commonly used in current national fisheries management plans, MOF Fisheries is implementing an EBFM plan with seven target areas in which a total of 26 action items are being put into effect in 2016–2020 (MOF, 2016).

Marine Ecosystems Science Plan – Under the MECA, the Korean integrated management plan of the marine environment is required to assess 'marine health' which is defined as the current and future status of the ecosystem contributing to the welfare and economy for future generations, including fisheries production, tourism, jobs, waste treatment, climate change mitigation, and coastal protection, and to specify measurable environment (water and sediment) quality criteria, or reference points, to identify when the environment is vulnerable to pollution or is polluted. However, ecosystem reference points are not presently set up or considered by MOF Marine.

2.2.5 Russia

Mission

Any kind of fisheries within the Russian Exclusive Economic Zone (EEZ) is managed by the Federal Agency for Fishery (Rosrybolovstvo), which is under the jurisdiction of the Ministry of Agriculture of the Russian Federation. Rosrybolovstvo organizes state control in the field of fishery, aquaculture and conservation of aquatic biological resources in the internal waters of the Russian Federation, except for internal sea waters. It determines the total allowable catches (TACs) of aquatic biological resources in the internal waters of the Russian Federation, including internal sea waters, as well as in the territorial sea, the continental shelf, and in the EEZ of the Russian Federation, and the Azov and Caspian seas (RFAF, 2018). The mission of Rosrybolovstvo is supported by two core mandates: 1) to ensure the productivity and sustainability of fishing using TAC limits and recommended catches and 2) to conserve and recover protected species and their habitats. The first mandate is mainly derived through Scientific Advice on values for TACs which are aggregated in the Russian Federal Research Institute of Fisheries and Oceanography (VNIRO) from the materials provided by its regional branches. The Pacific branch (TINRO) is responsible for stocks which occur in the Russian EEZ in the North Pacific. The process is regulated by Order #104 issued February 6, 2015, by Rosrybolovstvo and Orders issued by VNIRO and the Ministry of Natural Resources of Russia. In the case of recommended catch (RC), the thresholds (*e.g.*, 50% and 100% of RC usage) are monitored and if some of them are crossed then the decision will be made for each stock separately to increase the RC or to ban fishing when 100% of RC is reached. The second mandate is mainly supported by Fishing Rules, where restrictions on gears, fishing seasons and grounds, and limits on bycatch levels are embedded.

Goals

The goal of Rosrybolovstvo science and management plans is to optimize fisheries yield, prevent overfishing, and protect non-targeted species. This is accomplished using a single species approach to fisheries management. An ecosystem-based fisheries management (EBFM) was mentioned in the beginning of Order #104 but it has never been implemented for the official TAC calculation in the Far-Eastern Seas of Russia.

Government Science and Strategic Plans relevant to reference points

Both national-level and regional-level Strategic Science Plans are produced through bottom-up suggestions from the branches of VNIRO and top-down orders from Rosrybolovstvo, so they are identical in structure. To the best of our knowledge, there are no national-level and regional Science Centers plans that point to the establishment and use of ecosystem reference points. All harvest control rules (HCR) are based on the reference points from single stock assessments.

National Level – Order #104 and others require reference points to be identified when fish stocks are vulnerable to overfishing or are being overfished. Stock status is determined by estimating the current levels of fishing mortality F or harvest rate H or catch itself in the case of data-poor stocks, abundance of cohorts or of a total fish stock and comparing these metrics with specific reference points. In general, there are three categories of reference points used in Russian fisheries management: target, limit, and precautionary (or buffered). Target reference points are used in the hope of reaching maximum sustainable yield (MSY), limit reference points indicate a state of the fishery to be avoided to prevent an undesirable outcome, and precautionary reference points are buffered using their errors. In some cases, the target exploitation rate Htr may be set higher than precautionary Hpa point, when the logistic curve of the HCR is optimized during management strategy evaluation (MSE). MSE is required by Order #104 and the Risk Curves and cumulative probabilities of undesirable future states are considered for Scientific Advice.

An interest in developing reference points which incorporate ecosystem considerations, including species interactions, arose due to the requests of the Marine Stewardship Council during an audit of certification for the walleye pollock trawl fishery in the Sea of Okhotsk. Ecosystem properties, such as large fish indicators, dynamics of fish biomass, α and β diversity, average of maximum fish length in catches, mean fish weight in catches, trophic level (TL) of the catch, marine trophic index, and biomass-TL distributions have been constructed to show states and estimate trends (Kulik *et al*., unpublished data).

2.2.6 U.S.A.

Mission

Commercial and recreational fisheries within the U.S. Exclusive Economic Zone and outside of state waters are managed by the National Oceanic and Atmospheric Administration (NOAA), and more specifically the National Marine Fisheries Service (NMFS) or NOAA Fisheries. The mission of NOAA Fisheries is ‘stewardship of living marine resources through science-based conservation and management and the promotion of healthy ecosystems’ (NOAA, 2017a). The mission is supported by two core mandates: 1) to ensure the productivity and sustainability of fishing and fishing communities and 2) to conserve and recover protected species and their habitats (NOAA, 2017a, b,). These mandates are mainly derived from three laws enacted by the U.S. Congress, including the *Magnuson-Stevens Fishery Conservation and Management Act* (MSFCMA), the *Endangered Species Act*, and the *Marine Mammal Protection Act*.

Goals

The overarching goal of NOAA Fisheries’ science and management plans is to provide optimum fisheries yield while preventing overfishing and protecting the broader marine ecosystem, including marine mammals and species at risk of extinction (NOAA, 2017a). Traditionally, this has been accomplished through a single-species approach to fisheries management, with ecosystem information used sparingly as background information. However, NOAA Fisheries is currently charged with implementing an ecosystem-based approach to fisheries management (EBFM) to better integrate biological, physical, and social factors in assessments of fish stocks (NOAA, 2017b).

Government Science and Strategic Plans relevant to reference points

Both national-level and regional-level Strategic Science Plans are produced by NOAA Fisheries. Here, we describe the national-level and regional Science Centers plans that point to the establishment and use of reference points. There are six regional Science Centers. The west coast and Alaska regions are focal components of North Pacific Ocean marine ecosystems and coastal communities within PICES.

National Level – Under the MSFCMA, U.S. regional fishery management plans are required to specify reference points to identify when fish stocks are vulnerable to overfishing or are being overfished. Stock status is determined by estimating current levels of fishing mortality, abundance, and composition of a fish stock and comparing these metrics with specific reference points. Three categories of reference points are used in U.S. federal fisheries management: target, limit, and threshold (or trigger) (See Table 2.1 for full definitions of reference points.).

Single-species reference points are most commonly used in current U.S. federal fisheries management plans. However, there is increasing interest in developing reference points that incorporate ecosystem considerations, including oceanographic conditions and species interactions. To support the shift toward an EBFM, NOAA Fisheries is implementing an EBFM policy and roadmap in which two guiding principles are to 'develop and monitor ecosystem-level reference points (ERLPs)' and to 'incorporate ecosystem considerations into appropriate LMR (Living Marine Resources) assessments, control rules, and management' (NOAA, 2016a). There is growing recognition that ELRPs could be useful for detecting important dynamics, ecosystem properties or ecosystem-wide shifts that could have large impacts on many ecosystem components, including LMRs and LMR-dependent human communities. Potential examples of ELRPs include measures of ecosystem productivity, ecosystem indicator-based tipping points, and aggregate or system-level yield (NOAA, 2016a). Ecosystem properties, such as species diversity, trophic level of the catch, and biomass–size distributions could also serve as a basis for ELRPs. NOAA Fisheries is proposing to develop and track ELRPs that can be useful measures of ecosystem-level resilience and community well-being (NOAA, 2016a). To support these efforts, several recent studies have aimed to identify ecological thresholds to support the development of ELRPs for fisheries management (*e.g.*, Large *et al*., 2013; Samhouri *et al*., 2017; Tam *et al*., 2017).

In addition to EBFM, NOAA Fisheries recognizes the need for 'Climate Smart' management decisions and thus has developed a national Climate Science Strategy (CSS). A key goal of this initiative is 'to address the impacts of climate change on fisheries, their habitats, and the communities that depend upon them' (Link *et al*., 2015). To achieve this, NOAA Fisheries has outlined seven main objectives, two of which include 'identifying appropriate, climate-informed reference points for managing LMRs' and 'tracking trends in ecosystems, LMRs, and LMR-dependent human communities and providing early warning of change' (Link *et al*., 2015).

Regional Level – Strategic Science Plans, EBFM Road Map Implementation Plans, and Regional (Climate) Action Plans are developed by each of the six NOAA Fisheries Science Centers in support of EBFM and CSS, in addition to other national mandates and programs. The Alaska Science Center's Strategic Science Plan is largely focused on research activities that address the needs outlined in the national CSS. The Science plan highlights the need 'to identify and monitor thresholds in ecosystem parameters that signal the need to adjust management strategies', which could be done through Alaska's Integrated Ecosystem Assessment program (NOAA, 2017c). The Strategic Science Plans for the West Coast (NOAA, 2013a, b), Pacific Islands (NOAA, 2019a), Northeast (NOAA, 2016b), and Southeast / Gulf of Mexico (NOAA, 2016c) do not explicitly mention the establishment of ELRPs. The Pacific Islands Center's EBFM Road Map Implementation Plan includes the evaluation and tracking of ecosystem-level reference points to assess changes in ecosystem-level resilience as an ongoing action item (NOAA, 2019b), and the Northeast Center's Plan identifies research to 'establish thresholds to determine ecosystem resilience' as a dedicated area of work (NOAA, 2019c).

Each Science Center's Regional (Climate) Action Plan points to the establishment of climate-informed reference points. The Alaska Regional Action Plan specifically mentions the identification of ecosystem thresholds to climate drivers as a research priority for the Alaska Center (NOAA, 2016d). The West Coast Regional Action Plan aims to do the same through the California Current Integrated Ecosystem Assessment program and related efforts (NOAA, 2016e). In addition, the Northeast Science Center's Plan includes 'conducting research on regime shift effects on NOAA Trust Resources related to thresholds in climate-related variables' (Lovett *et al.*, 2016). The two Regional Actions Plans developed by the Southeast Science Center (Southeast U.S. and Gulf of Mexico) highlight the need for identifying thresholds (or societal preferences) in social and economic indicators that could be useful for providing early warnings about climate impacts on the fishing industry and fishing communities.

2.3 Synthesis, commonalities and differences among member countries

Our review of the mission, goals, and governmental science plans of PICES member countries reveal that consideration of ecosystem information and ELRPs in fisheries management varies across the countries. Some countries are mandated by law to implement an EBFM rather than focus on single species. In contrast, some countries do not mention the need for ecosystem information in their science and management plans, and other countries fall within this spectrum. In those member countries that are currently working towards implementing an EBFM, ecosystem information is mostly used as background information to provide context for setting fisheries catch quotas. These members point to the establishment of ELRPs in their science and management plans; however, they are not yet commonly required. Single-species reference points are required in current fisheries management for all PICES member countries.

2.4 Conclusions

- All PICES member countries are required to use single-species reference point in fisheries management.
- ELRPs are not yet commonly required across member countries.
- Most member countries point to the inclusion of ecosystem information in government science and management plans.
- A few member countries include the establishment of ELRPs as an important priority in government science and management plans.

Table 2.1 Definitions of limit, target, and threshold reference points as defined by PICES member countries.

Reference point	Definition
Target (TRP) U.S.A.	1. Benchmarks used to guide management objectives for achieving a desirable outcome (*e.g.*, optimum yield). TRPs should not be exceeded on average.[1] 2. Corresponds to a state of a fishery or a resource that is considered desirable. Management action, whether during a fishery development or a stock rebuilding process, should aim at bringing the fishery system to this level and maintaining it there. In most cases a TRP will be expressed in a desired level of output for the fishery (*e.g.*, in terms of catch) or of fishing effort or capacity, and will be reflected as an explicit management objective for the fishery.[2]
Limit (LRP) U.S.A.	1. Benchmarks used to indicate when harvests should be constrained substantially so that the stock remains within safe biological limits. The probability of exceeding limits should be low. In the National Standard Guidelines, limits are referred to as thresholds. In much of the international literature (*e.g*., United Nations Food and Agricultural Organization) thresholds are used as buffer points that signal when a limit is being approached[1] (see National Standard Guidelines).
Threshold (ThRP) U.S.A.	1. Indicates that the state of a fishery and/or a resource is approaching a TRP or an LRP, and that a certain type of action (usually agreed beforehand) needs to be taken. Fairly similar to an LRP in their utility, the specific purpose of the ThRP is to provide an early warning, reducing further the risk that the LRP or TRP is inadvertently passed due to uncertainty in the available information or inherent inertia of the management and industry systems. Adding precaution to the management setup, they might be necessary only for resources or situations involving particularly high risk.[2]
LRP Canada	Marks the boundary between the cautious and critical zones. When a fish stock level falls below this point, there is a high probability that its productivity will be so impaired that serious harm will occur. The limit reference point is established based on the best available scientific information. At this stock status level, there may also be resultant impacts to the ecosystem, associated species and a long-term loss of fishing opportunities. Several approaches for calculating the LRP are in use and may be refined over time. The units describing stock status will vary depending on the nature of the resource (groundfish, shellfish, salmonids or marine mammals). The LRP is based on biological criteria and established by Science through a peer reviewed process.
USR Canada	Marks the boundary between the healthy and cautious zones. When a fish stock level falls below this point, the removal rate at which the fish are harvested must be progressively reduced in order to avoid serious harm to the stock. The upper stock reference point (USR) is also a target reference point that is determined by productivity objectives for the stock, broader biological considerations, and social and economic objectives for the fishery. The USR, at minimum, must be set at an appropriate distance above the LRP to provide sufficient opportunity for the management system to recognize a declining stock status and sufficient time for management actions to have an effect. Secondly, the USR can be a TRP determined by productivity objectives for the stock, broader biological considerations and social and economic objectives for the fishery. In either case, the USR would be developed by fishery managers informed by consultations with the fishery and other interests, with advice and input from Science (see TRP).
TRP Canada	A TRP is a required element under UNFA and in the FAO guidance on the application of the Precautionary Approach, as well as eco-certification standards based on it, such those of the Marine Stewardship Council and may also be desirable in other situations. In practice, the threshold point below which removals must be reduced to avoid serious harm can be different than the TRP. However, it is essential that while socio-economic factors may influence the location of the USR, these factors must not diminish its minimum function in guiding management of the risk of approaching the LRP.

[1] Northeast Fisheries Science Center. 2005. The 40th Northeast Regional Stock Assessment Workshop Draft. Assessment Report. http://www.nefsc.noaa.gov/nefsc/saw/

[2] United Nations Food and Agricultural Organization. Fisheries Glossary. http://www.fao.org/fi/glossary/default.asp

2.5 Literature cited

Boldt, J.L., Martone, R., Samhouri, J., Perry, R.I., Itoh, S., Chung, I.K., Takahashi, M. and Yoshie, N. 2014. Developing ecosystem indicators for responses to multiple stressors. *Oceanography* **27**: 116–133, http://dx.doi.org/10.5670/oceanog.2014.9.

Bundy, A., Gomez, C. and Cook, A.M. 2017. Guidance framework for the selection and evaluation of ecological indicators. Canadian Technical Report of Fisheries and Aquatic Sciences 3232: xii + 212 p.

Chandler, P.C., King, S.A. and Boldt, J. (Eds.) 2017. State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2016. Canadian Technical Report of Fisheries and Aquatic Sciences 3225: 243 + vi p.

DFO (Fisheries and Oceans Canada). 2002. Canada's Oceans Strategy; Our Oceans, Our Future. Fisheries and Oceans Canada Oceans Directorate, Ottawa, Ontario. https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/264675.pdf

DFO. 2004. A policy framework for conservation of wild Pacific Salmon. Fisheries and Oceans Canada, Vancouver, B.C. https://link.edgepilot.com/s/42c26790/odpH3GeHv0e0d7fJTZivrg?u=https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/285006.pdf

DFO. 2005. A policy framework for conservation of wild Pacific Salmon. Fisheries and Oceans Canada, Vancouver, B.C. http://waves-vagues.dfo-mpo.gc.ca/Library/285006.pdf

DFO. 2006. A Harvest Strategy Compliant with the Precautionary Approach. Canadian Science Advisory Secretariat Science Advisory Report 2006/023. http://www.dfo-mpo.gc.ca/reports-rapports/regs/sff-cpd/precaution-eng.htm (accessed 28 May 2018).

DFO. 2007. A new ecosystem science framework in support of integrated management. Communications Branch, Fisheries and Oceans Canada, Ottawa, Ontario, http://publications.gc.ca/site/eng/9.689921/publication.html

DFO. 2009. Policy on new fisheries on forage species. Fisheries and Oceans Canada. http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ResDocs-DocRech/2018/2018_009-eng.pdf (accessed 28 May 2018).

DFO. 2016. Supplement to the pre-season run size forecasts for Fraser River Sockeye Salmon (*Oncorhynchus nerka*) in 2016. Canadian Science Advisory Secretariat Science Response 2016/047. http://waves-vagues.dfo-mpo.gc.ca/Library/4062254x.pdf

Large, S.I., Fay, G., Friedland, K.D. and Link, J.S. 2013. Defining trends and thresholds in responses of ecological indicators to fishing and environmental pressures. *ICES Journal of Marine Science* **70**: 755–767, https://doi.org/10.1093/icesjms/fst067.

Link, J.S., Griffis, R., and Busch. S. (Editors). 2015. NOAA Fisheries Climate Science Strategy. U.S. Dept. of Commerce, NOAA Tech. Memo. NMFS-F/SPO-155, 70 p.

Lovett, H.B., Snider, S.B., Gore, K.R. and Muñoz, R.C. (Eds.) 2016. Gulf of Mexico Regional Action Plan to Implement the NOAA Fisheries Climate Science Strategy. NOAA Technical Memorandum NMFS-SEFSC-699. 40 p. doi:10.7289/V5/TM-SEFSC-699. https://www.fisheries.noaa.gov/national/climate/climate-science-strategy-regional-action-plans#northeast

MOA (Ministry of Agriculture of the People's Republic of China). 2017. Notice on Further Strengthening the Management and Control of Domestic Fishing Vessels and Implementing the Total Catch Control of Marine Fishery Resources (in Chinese). www.moa.gov.cn/govpublic/YYJ/201701/t20170120_5460583.htm

MOF (Ministry of Oceans and Fisheries, Korea). 2009. *Fishery Resources Management Act*. https://faolex.fao.org/docs/pdf/kor108399.pdf

MOF. 2011. The 4th Integrated Marine Environment Plan of Korea for 2011–2020.

MOF. 2016. The 2nd Fishery Resources Management Plan of Korea for 2016–2020.

MOF. 2017. *Marine Environment Conservation Act*. https://elaw.klri.re.kr/eng_mobile/ganadaDetail.do?hseq=45952&type=abc&key=MARINE%20ENVIRONMENT%20MANAGEMENT%20ACT&param=M#:~:text=The%20purpose%20of%20this%20Act,such%20as%20oil%20and%20noxious

NOAA (National Oceanic and Atmospheric Administration). 2013a. Northwest Fisheries Science Center Strategic Science Plan 2013-2018. https://www.nwfsc.noaa.gov/news/features/strategic_science_plan2013/nwfsc_strategic_science_plan2013.pdf

NOAA. 2013b. Southwest Fisheries Science Center Strategic Science Plan 2013–2018. https://swfsc.noaa.gov/uploadedFiles/Home/SWFSCStratSciencePlan-2013.pdf

NOAA. 2016a. NOAA Fisheries Ecosystem-Based Fisheries Management Roadmap. https://www.st.nmfs.noaa.gov/Assets/ecosystems/ebfm/EBFM_Road_Map_final.pdf

NOAA. 2016b. Northeast Fisheries Science Center Strategic Science Plan 2016–2021.

NOAA. 2016c. Southeast Fisheries Science Center Science Plan 2016–2020.

NOAA. 2016d. Alaska Regional Action Plan for the Southeastern Bering Sea. https://www.st.nmfs.noaa.gov/Assets/ecosystems/climate/documents/raps/tech_memos/AK_Regional_Action_Plan.pdf

NOAA. 2016e. Western Regional Action Plan (WRAP), NOAA Fisheries Climate Science Strategy. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-SWFSC-565. 75 p.

NOAA. 2017a. Understanding Fisheries Management in the United States. https://www.fisheries.noaa.gov/insight/understanding-fisheries-management-united-states

NOAA. 2017b. NOAA Fisheries Priorities and Annual Guidance for 2017. https://archive.fisheries.noaa.gov/afsc/program_reviews/2017/2017_Core_Documents/NOAA%20Priorities%20and%20Annual%20Guidance%20for%20FY2017.pdf

NOAA. 2017c. Alaska Region Strategic Plan 2017–2022. https://archive.fisheries.noaa.gov/afsc/GeneralInfo/FY17StrategicSciencePlan.

NOAA. 2019a. Pacific Islands Fisheries Science Center Science Plan 2019–2023.

NOAA. 2019b. Pacific Islands Region Ecosystem-based Fisheries Management Implementation Plan 2018–2022. https://www.fisheries.noaa.gov/national/ecosystems/ecosystem-based-fishery-management-implementation-plans

NOAA. 2019c. Northeast Regional Implementation Plan of the NOAA Fisheries Ecosystem-Based Fishery Management Roadmap. https://www.fisheries.noaa.gov/national/ecosystems/ecosystem-based-fishery-management-implementation-plans

NPC (The National People's Congress of China). 2013. Fisheries Law of the People's Republic of China. http://english.agri.gov.cn/governmentaffairs/lr/fish/201305/t20130509_19610.htm (revised in December 2013).

NPC. 2016. Wild Animal Conservation Law of the People's Republic of China (revised in July 2016).

NPC. 2017. Marine Environment Protection Law of the People's Republic of China (revised in November 2017).

Perry, R.I. and Masson, D. 2013. An integrated analysis of the marine social–ecological system of the Strait of Georgia, Canada, over the past four decades, and development of a regime shift index. *Progress in Oceanography* **115**: 14–27, https://doi.org/10.1016/j.pocean.2013.05.021.

Porter, M., Casley, S., Pickard, D., Nelitz, M. and Ochoski, N. 2013. Southern Chinook Conservation Units: Habitat Indicators Report Cards. Report prepared by ESSA Technologies Ltd. for Fisheries and Oceans Canada.

RFAF (Regulations on the Federal Agency for Fishery, Russia) 2018. https://fish.gov.ru/about/polozhenie/

Samhouri, J.F., Andrews, K.F., Fay, G., Harvey, C.J., Hazen, E.L., Hennessey, S.M., Holsman, K., Hunsicker, M.E., Large, S.I., Marshall, K.N., Stier, A.C., Tam, J.C. and Zador, S.G. 2017. Defining ecosystem thresholds for human activities and environmental pressures in the California Current. *Ecosphere* **8**: e01860. 10.1002/ecs2.1860.

Tam, J.C., Link, J.S., Large, S.I., Andrews, K., Friedland, K.D., Gove, J., Hazen, E., Holsman, K., Karnauskas, M., Samhouri, J.F., Shuford, R., Tomilieri, N. and Zador S. 2017. Comparing apples to oranges: Common trends and thresholds in anthropogenic and environmental pressures across multiple marine ecosystems. *Frontiers in Marine Science* **4**: 282. Doi:10.3389/fmars.2017.00282

3 Efforts Identifying Data Availability within Specific North Pacific Ecosystems, Fish Stocks, and Fishing Communities

3.1 Introduction

WG 36 was tasked with summarizing previous efforts that identified 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. In addition, the work done by WG 36 built upon indicators identified by previous PICES expert groups, such as WG 19 (Ecosystem-based Management Science and its Application to the North Pacific), WG 28 (Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors; Appendix 3), WG 35 (Third North Pacific Ecosystem Status Report), and the Human Dimensions (HD) Committee. WG 36 reviewed previous PICES work, data inventories, and recommended indicators while consulting with WG 35 and HD regarding indicators. WG 36 then updated the data inventory for indicators within member countries and selected indicators that could be used in analyses to address its remaining Terms of Reference. The objectives for selecting these indicators were 1) to identify common indicators across PICES member countries, 2) to determine shapes or functional forms of pressure–response relationships from available datasets, 3) to quantify thresholds to identify potential ecosystem reference points, and 4) to identify ecosystem components that respond earliest to changes in biophysical drivers and could potentially serve as leading indicators of loss of resilience and ecosystem change.

3.2 Summary of PICES efforts to identify data availability and recommended indicators

In 2003–2004, a PICES Study Group on *Ecosystem-based Management Science and its Application to the North Pacific* (SG-EBM) reviewed and described existing and anticipated ecosystem-based management initiatives in PICES member countries and the scientific bases for them. This group also identified emerging scientific issues related to the implementation of ecosystem-based management. They recommended the formation of a PICES Working Group (WG 19; 2004–2009) on *Ecosystem-based Management in Science and its Application to the North Pacific*. As part of their Terms of Reference, WG 19 described ecosystem-based management objectives of PICES member countries and ecosystem monitoring approaches for predicting human and environmental influences on marine ecosystems. In addition, the WG evaluated indicators from the 2004 IOC/SCOR Symposium on "*Quantitative Ecosystem Indicators for Fisheries Management*" for application to the North Pacific. In fulfilling these goals, WG 19 identified lessons learned from the Bering Sea, Alaska. The WG concluded that to enable an operational ecosystem-based approach to fisheries management, requirements include the establishment of a policy, management, monitoring and assessment framework with measurable operational objectives. Indicators are then needed to quantify performance of management with respect to objectives (Kruse and Evans, 2006). For identified core indicators, each PICES member country in WG 19 summarized data availability and whether the indicators were regularly updated (see Table 3.1.3 in Perry *et al*., 2010).

In April 26–28, 2011, a 3-day FUTURE workshop entitled "*Indicators of status and change within North Pacific marine ecosystems*" (Honolulu, USA) resulted in recommendations for the utilization of a framework for identifying and calculating indicators:

- Identify objective of selecting indicators;
- Identify end user;
- Identify ecosystem attributes to be measured;
- Apply criteria to select indicators:
  - available regularly
  - available as time series
  - statistical properties are understood
  - related
  - specific
  - appropriate spatial and temporal scales
  - responsive
  - relevant
  - understandable
  - basis for comparison
- Criterion should be weighted for relevance to end user identified;
- Identify indicator reference levels;
- Test performance;
- Identify method of communication; report indicator uncertainty.

At PICES-2011 (Khabarovsk, Russia), FUTURE's AP-COVE proposed a Working Group on the *Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors* (WG 28; 2011–2015). WG 28 updated the inventory of indicators, data existence, availability, and spatial extent (Takahashi and Perry, 2019). The main recommendations from WG 28 for developing indicators were:

- The need for defined strategic goals and ecological or management objectives for indicators.
- There are multiple approaches to assess indicator responses to multiple stressors, such as data-based, expert judgement, a combination of data and expert judgement, and models. Given the strengths and challenges of these approaches and that data availability will continue to be lacking for some stressors and ecosystems, WG 28 recommended using multiple approaches to identify indicators and evaluate multiple stressors on marine ecosystems. For example, data-driven approaches are preferred. However, expert opinion may be necessary when the focus is on broad spatial scales where data are not necessarily available.

- The need for clearly documented conceptual or pathways-of-effects models and risk assessments.
- A suite of integrative indicators that cover key components and gradients at the appropriate spatial scales should be selected.
- Indices for multiple stressors 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.
- When selecting indicators, use a toolbox approach, that is, use a core set of recommended indicators for all ecosystems and include additional ecosystem-specific, pressure-linked response indicators not reflected in the core set (Takahashi and Perry, 2019).

In addition to the toolbox of indicators recommended by WG 28, the HD Committee and WG 35 identified supplemental indicators that would be beneficial to consider, such as the quantity and value of catches and landings of seaweeds, fish, shellfish, and other invertebrates from inside and outside national Exclusive Economic Zones (EEZs; Appendix 3).

WG 36 reviewed and updated inventories of data existence, availability, and spatial and temporal extents for the toolbox of recommended indicators. Members then identified those indicators that could contribute to addressing their region’s strategic goals or ecological or management objectives, covered key components of selected ecosystems, for which data time series were readily available, and covered the longest time period for analyses in their regions. Members were able to assemble time series for most, but not all, recommended core indicators that were applicable and specific to their regional ecosystems. In some cases, indicators were excluded to maximize the length of time series or because they were highly correlated with other indicators. This provided a base set of time series on which to conduct analyses of ecosystems and indicators that were the focus of WG 36 activities (Appendix 3).

3.2.1 Canada

Ecosystem

For WG 36 analyses, Canada focused on waters on the west coast of Vancouver Island (WCVI), British Columbia (BC), that fall within the northern area of Region 11 (Figs. 1.3 and 3.1). The WCVI is a highly productive upwelling area off the west coast of North America that supports some of BC’s largest fisheries (Boldt *et al*., 2021). The WCVI is at the northern extent of the California upwelling zone (Ware and McFarlane, 1989; McFarlane and Beamish, 1992; Beamish and Bouillon, 1993) and experiences seasonal (spring–summer) upwelling. The transition periods between the upwelling and downwelling seasons occur in February–April and October–November (Ware and McFarlane, 1995). Annual variation in the timing, duration, and magnitude of the spring upwelling, along with El Niño and marine heat waves events, may produce varying degrees of match or mismatch between biological processes and environmental conditions (Thomson and Ware, 1988; Jamieson *et al*., 1989; Ware and McFarlane, 1995; McFarlane *et al*., 1997; Hourston and Thomson, 2019; Mackas *et al*., 2001). Zooplankton biomass anomalies are correlated with salmon marine survival, sablefish recruitment, herring growth, and sardine production (Tanasichuk, 2002; Mackas *et al*., 2007). Predation and competition are other biological processes that may play a role in the WCVI ecosystem for some species, such as Pacific herring (Schweigert *et al*., 2010; Godefroid *et al*., 2019). For example, warm years resulting in increased hake abundance can negatively affect herring year-class strength, since hake are predators of herring and also competitors for euphausiid prey (Mysak *et al*., 1982; Ware and McFarlane, 1986). Bottom-up processes, however, appear to be important drivers in this ecosystem, since resident fish yield was found to be correlated with phytoplankton and zooplankton production in BC (Ware and Thomas, 2005; Boldt *et al*., 2021).

Exploitation

The productive WCVI area has supported multiple commercial fisheries at various times during the last century, including pelagic fisheries for Pacific herring (*Clupea pallasi*), Pacific hake (*Merluccius productus*), salmon (*Oncorhynchus* spp.), and Pacific sardine (*Sardinops sagax*), groundfish fisheries for flatfish and rockfish (variety of species), Pacific cod (*Gadus macrocephalus*), sablefish (*Anoplopoma fimbria*), lingcod (*Ophiodon elongatus*), Pacific halibut (*Hippoglossus stenolepis*), spiny dogfish (*Squalus acanthias*), as well as trap/trawl fisheries for pandalid shrimp (*Pandalus* spp.). The average total catch of fish was approximately 30,000 t during the 1920s to the mid-1960s, increasing to 100,000 t during the late 1980s to late 1990s (McFarlane *et al*., 1997). These trends are reflected in landings taken from offshore areas of statistical areas 24, 25, 124, 125, where catches were approximately 6,100 t in 1980 and increased (20,000 to 28,000 t) in the early to mid-1990s. Catches were lower in the late 1990s to mid-2000s then increased to the 20,000 to 30,000 t range. Record high catches in 2010 were due to large Pacific hake landings.

Data and indicators

For WG 36 analyses and to address ecosystem objectives (specified in Table 3.1), indicators of environmental, human, and ecosystem pressures and responses were selected based on indicator selection criteria and frameworks (*e.g*., Bundy *et al*., 2017; drivers, pressures, status, indicators, responses (DPSIR) approach; Table 3.1) and core indicators identified by previous studies (Appendix 3; Link *et al*., 2010; Shin *et al*., 2010a, b; Fu *et al*., 2012, 2015, 2019; Lucey *et al*., 2012; Boldt *et al*., 2014). Indicator time series were assembled for 1986–2017 (Table 3.1), the longest collective time period for selected indicators (Boldt *et al*., 2021).

Indicators of the physical environmental pressures that were examined included large-scale indicators of sea surface temperature change, such as the Pacific Decadal Oscillation (PDO, annual; Mantua *et al*., 1997), multivariate ENSO Index (MEI, annual; https://climatedataguide.ucar.edu/climate-data/multivariate-enso-index), and the local sea surface temperature as measured by satellite for the WCVI area (https://www.ncdc.noaa.gov/oisst; Reynolds *et al*., 2007; Banzon *et al*., 2016) (Table 3.1; Boldt *et al*., 2021). The North Pacific Gyre Oscillation (NPGO) was used as an indicator of water source (Di Lorenzo *et al*., 2008) and the magnitude and timing of upwelling were used as indicators of nutrient availability (Hourston and Thomson, 2019).

Indicators of human pressures, such as fishery removals (landings) and ecosystem function, were derived from commercial landings data (Table 3.1; Boldt *et al*., 2021). Commercial landings data were available in BC for DFO statistical areas 24/124, and 25/125, overlapping spatially and temporally with data from the fishery-independent multi-species bottom trawl survey. Indicators included total landings, trophic level of the landings, and catch of foraging groups (benthivores, planktivores, zoopivores, and piscivores; based on Lucey *et al*. (2012)), catch of habitat groups (pelagics, demersals), the ratio of pelagic to demersal fish landings, and the intrinsic vulnerability index (Cheung *et al*., 2007).

Several ecosystem response indicators were based on DFO's fishery-independent multi-species, small mesh bottom trawl survey conducted annually since 1973 in an area off the WCVI (statistical areas 124 and 125). The area covered by the survey was approximately 4,707 km^2 (statistical areas 125 and 125 combined) and stations were sampled at depths between 50 and 200 m during late April to May. Indicators from these survey data included: total surveyed biomass, biomass of foraging groups (benthivores, planktivores, zoopivores, and piscivores; based on Lucey *et al*. 2012), biomass of habitat groups (pelagics, demersals), and the ratio of pelagic to demersal fish biomass, the proportion of predatory fish, mean length, and mean lifespan (the latter two indicators were based on published information combined with survey biomass). Beginning in 1986, there were also long time-series of zooplankton biomass and community composition for this marine ecosystem (Galbraith and Young, 2018). Indicators examined included the biomass anomalies of southern, boreal, and subarctic copepods. Steller sea lion abundance time series was relatively long, but data were available every 2 to 5 years (Olesiuk, 2018).

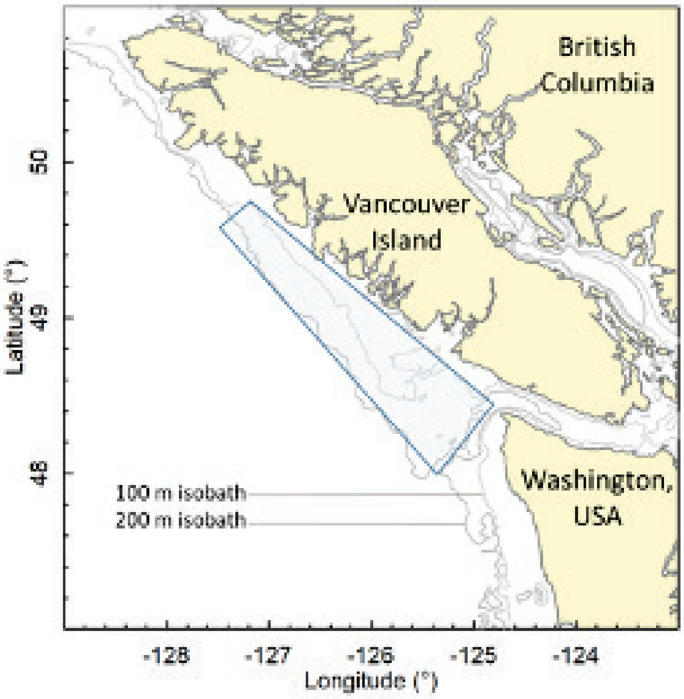


Fig. 3.1 Generalized area off the west coast of Vancouver Island (WCVI), British Columbia, Canada for which indicators were analyzed. Note: the small mesh, multi-species bottom trawl survey covers a smaller area within this generalized area.

Table 3.1 Drivers, objectives, pressures (A), responses (states and impacts) (B), indicators, and sources for the west coast of Vancouver Island and broader basin-scale ecosystem time series. Indicators in bold font were included in further analyses; other indicators were excluded because they were highly correlated (r = 0.8) either among pressure or among response indicators. From Boldt *et al*. (2021).

(A) Drivers and pressures

Component	Driver	Objective	Pressure	Pressure indicator	Source
Environment	Atmospheric pressure and greenhouse gas	Monitor effects of climate change	SST change	**Pacific Decadal Oscillation (PDO_Annual)**	a
			Large-scale circulation	**North Pacific Gyre Oscillation (NPGO)**	b
			SST change	**Multivariate ENSO Index Version 2 (MEI_Annual)**	c
			SST change	**Local sea surface temperature (SST_satellite)**	d
			Nutrient availability	**Upwelling magnitude**	e
			Nutrient availability	**Spring transition timing**	e
Human	Seafood demand	Monitor effects of fisheries	Fishery removals (landings)	**Total landings (Tot_Landings)**	f
			Ecosystem function change	**Trophic level of landings (TL_Landings)**	g
			Ecosystem function change	Intrinsic vulnerability index (IVI)	g
			Ecosystem function change	Catch of foraging groups: benthivores, planktivores, zoopiscivores, piscivores	f
			Ecosystem function change	Catch of habitat groups: demersals, pelagics	f
			Ecosystem function change	Ratio of pelagics to demersals catch (C_Pel_Dem)	f

Table 3.1 Continued.

(B) Responses – States and impacts

Component	**Objective and impact**	**Response indicator**	**Source**
Ecosystem	Maintain structure and function	**Copepods southern biomass anomalies**	h
	Maintain structure and function	**Copepods boreal biomass anomalies**	h
	Maintain structure and function	**Copepods subarctic biomass anomalies**	h
	Maintain structure and function	**Trophic level of surveyed species (TL_SurveyedComm)**	i
	Maintain structure and function	**Steller sea lion abundance**	j
	Maintain structure and function	Mean length (Mean_Len)	g
	Maintain stability and resistance to perturbations	Mean lifespan	g
	Conserve biodiversity	**Proportion predatory fish (Prop_PredFish)**	i
	Maintain resource potential	**Biomass of surveyed species (Tot_B_Survey)**	i
	Maintain resource potential, structure, function	Survey biomass of foraging groups: benthivores, planktivores, zoopiscivores, piscivores	i
	Maintain resource potential, structure, function	Survey biomass of habitats groups: pelagics, demersals	i
	Maintain resource potential, structure, function	**Ratio of pelagics to demersals survey biomass (B_Pel_Dem**)	i

Source:

a. http://research.jisao.washington.edu/pdo/PDO.latest.txt; Mantua *et al*., 1997

b. Di Lorenzo *et al*., 2008

c. National Center for Atmospheric Research Staff (Eds). Last modified 20 August 2013. “The Climate Data Guide: Multivariate ENSO Index.” Retrieved from https://climatedataguide.ucar.edu/climate-data/multivariate-enso-index

d. https://www.ncdc.noaa.gov/oisst. Dataset citation: Banzon *et al*., 2016; Reynolds *et al*., 2007

e. Hourston and Thomson, 2019

f. Maria Surry, Shelee Hamilton, Leslie Barton, Mary Thiess (DFO.

g. Caihong Fu (DFO)

h. Moira Galbraith, Kelly Young, Ian Perry (DFO); Galbraith and Young, 2018

i. Brenda Waddell, Ian Perry, small mesh multi-species survey (DFO)

j. Olesiuk, 2018.

3.2.2 China

Ecosystem

For WG 36 analysis, China focused on waters on the east coast of Mainland China in the northern area of Region 20 (Fig. 1.3 and see Guan *et al*., 2020 Fig. 1), a semi-closed basin on the continental shelf of the Northwest Pacific (Fig. 3.2). In the broader large marine ecosystem, the mean sea surface temperature (SST) rose by 0.67°C during 1982–2006. This rate of warming was much higher than the global mean rate over the same period. Moreover, with the general acceleration of ocean warming (Cheng *et al*., 2019), rapid warming continues in study region, especially during the months of May and August (Fig. 3.3; also see Guan *et al.* (2020) Fig. 2). In addition, the system is a very productive ecosystem and serves as crucial spawning, nursery or feeding grounds for various fish stocks.

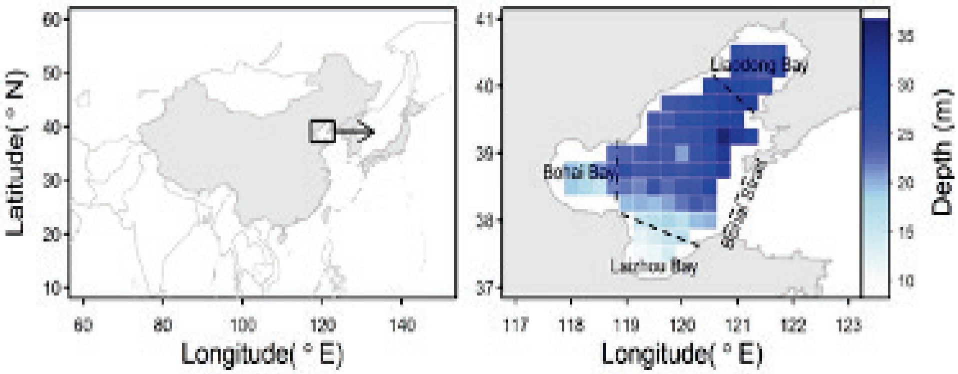


Fig. 3.2 Study system for China's case study (left) and regular fisheries monitoring focus on shaded area with bathymetric information (right). From Guan *et al*. (2020).

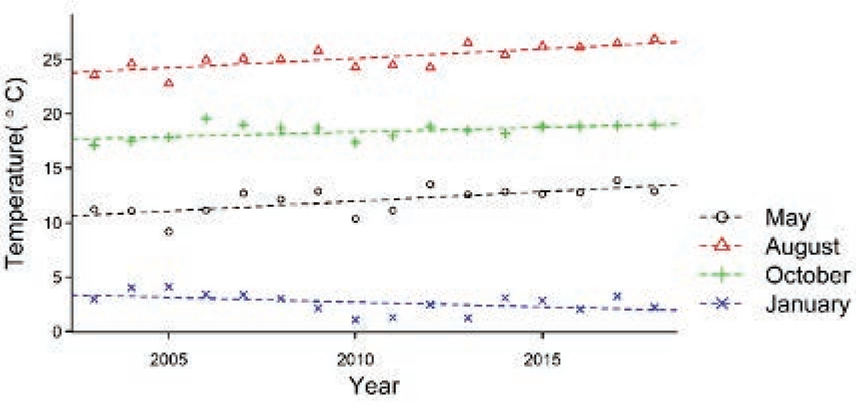


Fig. 3.3 Temporal trends in average sea surface temperatures (SST) in China's study system in May, August, October and January. From Guan *et al*. (2020).

Exploitation

Fisheries in the northern area of Region 20 mainly operate with three types of fishing gears (trawl, gillnet and stow net). Most fisheries target at multi-species and could land all their captures before 2018, except nationally protected animals. A minimum size limit strategy has been implemented for 15 commercially important fish species throughout China's marine waters since 2018 in order to promote effective protection of juvenile and yearling fish. Moreover, all fisheries except those using monofilament gillnets or jigs were prohibited in this ecosystem from June 1 to September 1 from 2009 to 2016. This suspension of fishing activities has been extended by one month earlier since 2017.

Under the combined impact of human activities and climatic changes, many stocks have been depleted, especially those at high trophic levels, *e.g*., small yellow croaker (*Larimichthys polyactis*), largehead hairtail (*Trichiurus japonicus*), Japanese Spanish mackerel (*Scomberomorus niphonius*), chub mackerel (*Scomber japonicus*) and Chinese shrimp (*Fenneropenaeus chinensis*). After 2000, major productions of capture fisheries in this ecosystem became increasingly dependent on small pelagic fish like anchovies and invertebrates, including crabs, mantis shrimp (*Oratosquilla oratoria*), *Acetes* and squids. Their annual landings have been around half a million tons in recent years, with a rough worth of 18 billion RMB (~$249 million US).

Data

Fishery-independent monitoring extended to the whole northern area of Region 20 in the 1980s and 1990s. The first round of fishery resource surveys occurred monthly in this ecosystem from April 1982 to May 1983, and included bottom trawl surveys for adult and juvenile nektonic species and horizontal trawl surveys for different types of plankton, especially ichthyoplankton (Deng *et al*., 1988a; Bian *et al*., 2018, 2022). The established sampling protocol of these surveys has remained in use. For each bottom trawl, catches of nektonic species were recorded by species for counting, weighing, and sampling. Catches per trawl by species in number and biomass were recorded on the spot, along with depth, temperature, and salinity at the beginning and end locations. In addition, sampled individuals for each species were measured for length and weight, with some samples being analyzed for feeding condition, maturity stage, diet composition, fecundity, and/or age identification. Such fishery resource surveys ceased in subsequent years but were conducted again by season in August 1992 to May 1993 and May 1998 to February 1999 (Jin, 2001). The surveys of the 1980s and 1990s in the northern area of Region 20 have provided ample data for studying the biology and ecology of various fishes and invertebrates, as well as species composition, community structure, biodiversity, and food web dynamics of fishery resources (*e.g*., Deng *et al.*, 1988a, b; Jin and Deng, 2000; Tong *et al*., 2000; Jin *et al*., 2001; Deng, 2018).

Based on these historical fishery-independent surveys, regime shifts (including abrupt changes in species abundance, community composition and trophic organization) were recognized in the northern area of Region 20 at the beginning of the 21st century (Jin and Deng, 1999; Jin, 2000, 2001). Since then, this ecosystem has attracted growing monitoring efforts to evaluate the dynamics of its major fish stocks. First, fishery resource surveys increased in Laizhou Bay (one of the three major bays inside the study system) from 2003–2008, with one cruise per spring and several cruises in summer and fall, as this bay serves as critical spawning and nursery grounds for various fishes and invertebrates (Wang *et al*., 2010). These surveys have broadly covered the whole Bohai Sea in the spring, summer and fall since 2004, but did not occur regularly in 2009–2013. Recently, China initiated its national regular fisheries monitoring program in 2014, which supports two to four cruises of seasonal fishery resource surveys and additional ichthyoplankton surveys in the northern area of Region 20 each year.

Indicators

Indicators of environmental, human and ecosystem pressures were selected for WG 36 analyses and to address ecosystem objectives, based on data availability and core indicators identified by published studies. Indicators of environmental pressures included temperature, salinity, the volume and timing of freshwater discharge, and days of gale weather. Indicators of human pressures included: 1) total landings data from wild fisheries, 2) landings of different taxa (seaweed, jellyfish, shellfish, cephalopods, crustaceans and fish), 3) landings at different trophic levels, and 4) landings of habitat groups (pelagics and demersals, or cold-water and warm-water species). Ecosystem indicators included total surveyed biomass, biomass of different taxa, mean trophic level, and keystone/dominant species.

Table 3.2 Indicators of environmental and human pressures and ecosystems responses for the northern area of Region 20, China.

Component	Objective	Pressure/Response	Indicator	Source
Environment	Monitor effects of environmental changes	Temperature change	Surface and bottom temperature	c
		Salinity change	Surface and bottom salinity	c
		Nutrient availability	Volume and timing of freshwater discharge	a, d
		Disturbance on system productivity	Days of gale weather in spring	a, d
Human	Monitor effects of fisheries	Fisheries removals	Total landings from wild fisheries	e
		Effects on ecosystem structure and function	Landings of different taxa	e
			Landings at different trophic levels	b
			Landings of habitat groups	b
Ecosystem	Monitor ecosystem changes	Changes in on ecosystem structure, function and energy flow	Total biomass of fishery resources	c, f
			Biomass of different taxa	c
			Mean trophic level	h
			Keystone/dominant species	f, g

Source:
a. Deng and Ye, 1986
b. Ding *et al.*, 2021
c. Jin *et al.*, 2013
d. Liu *et al.*, 1981
e. National Bureau of Statistics of China. 2006 to 2021. Fishery Statistical Yearbooks. China Statistics Press, Beijing
f. Tang, 2006
g. Yang *et al.*, 2018
h. Zhang *et al.*, 2015

3.2.3 Japan

Ecosystem

For WG 36 analyses, Japan focused on marine areas surrounding the Shiretoko Peninsula, Hokkaido, in Regions 17 and 18 (Figs. 1.3 and 3.4). The marine area surrounding Shiretoko Peninsula is part of the Shiretoko World Natural Heritage (WNH) site. It is influenced by both the East Sakhalin cold current and the Soya warm current (Ohshima *et al*., 2001). Melting of seasonal sea ice, vertical mixing during winter, and nutrients brought by seasonal upwelling develop one of the richest and most diverse marine ecosystems in the world (Sakurai, 2006). The highly productive marine area supports a wide range of species, including marine mammals, seabirds, and commercially important species (Sakurai, 2007). The Shiretoko WNH site is also characterized by its close interrelationship between marine and terrestrial ecosystems (Makino and Sakurai, 2012).

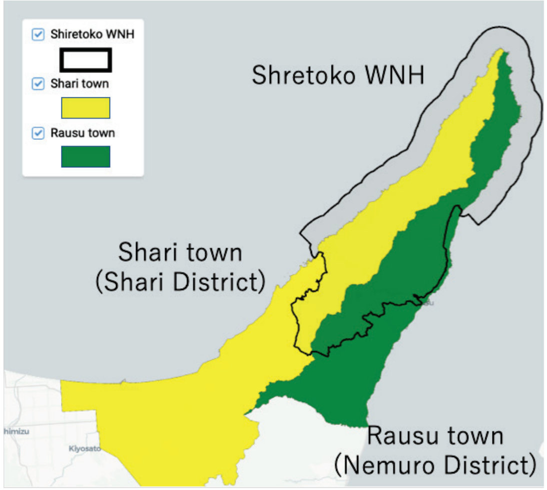


Fig. 3.4 Generalized area of the Shiretoko Peninsula, Hokkaido, Japan, for which indicators were analyzed (Regions 17 and 18, Fig. 1.3).

Exploitation

The marine area surrounding the Shiretoko Peninsula is one of the most productive fishing grounds in Japan (Sakurai, 2006). Main target species are salmonids such as chum salmon (*Oncorhynchus keta*) and pink salmon (*O. gorbuscha*), Japanese common squid (*Todarodes pacificus*), walleye pollock (*Theragra chalcogramma*), Pacific cod (*Gadus macrocephalus*), and Atka mackerel (*Pleurogrammus azonus*) (Makino and Sakurai, 2012). Fisheries are one of the most important industries in both Shari Town and Rausu Town. Annual fish catches of major species off Shari Town in 2018, facing the Sea of Okhotsk, was 16,338 tons, equivalent to 10.2 billion Japanese Yen (~$742 million USD) (Shari Town, 2020). For five years, from 2014 to 2018, respective annual fish catches were lower than the average fish catch from 1985 to 2018, *i.e*., 25,273 tons (Shari Town, 2020). For Rausu Town, also the Sea of Okhotsk, annual fish catch of major species in 2019 was 21,289 tons, equivalent to 6.8 billion Japanese Yen (~$46 million USD) (Rausu Town, 2019). Respective annual fish catches of major species of Rausu Town from 2017 to 2019 have been the lowest level since 2002, less than half of its peak of 50,600 tons in 2013 (Rausu Town, 2019; Kushiro Natural Environment Office of Ministry of the Environment *et al*., 2013). Sea lions are one of the major predator species at high trophic level in marine ecosystems in the Shiretoko WNH. In parallel with salmonids, walleye pollock and Japanese common squid, the sea lion is designated as one of the indicator species in the Multiple Use Integrated Marine Management Plan for Shiretoko WNH Site (Ministry of the Environment and the Hokkaido Prefectural Government, 2018).

Data and indicators

In the marine area of the Shiretoko Peninsula, the Ministry of the Environment of Japan and the Hokkaido Prefectural Government have carried out long-term monitoring for: 1) marine environment conditions, 2) fish and shellfish, 3) sea mammals, 4) sea birds, and 5) local communities. Indicators were selected from long-term monitoring results, and compiled for WG 36 analysis (Table 3.3).

For indicators of physical environmental pressures, sea surface water temperature (SST), current velocity and direction were selected to understand changes in sea conditions. The data were obtained from long-term monitoring of oceanographic buoys by the Shiretoko Data Center, the Ministry of the Environment (Shiretoko Data Center, 2005–2018). Observation data were averaged by season (spring: April–June, summer: July–September, and autumn: October–December). Here, the winter observation data were not used for the analysis due to lack of data. Summer and autumn current velocity and direction data in 2016 were also not used in the analysis due to the passage of four typhoons over eastern Hokkaido from August to October of the same year.

For indicators of human pressures, the fish catches of ocean salmonids that were included with chum salmon (*Oncorhynchus keta*), walleye pollock (*Gadus chalcogrammus*), common squid (*Todarodes pacificus*), and yellowtail (*Seriola quinqueradiata*) in Shari and Rausu towns were selected to understand the effects of human activities. Data were obtained from the Annual Fishery Production Statistics (MAFF, 2006–2018). Here, yellowtail was added as an indicator due to the rapid increase in catches by salmon set nets in recent years. In addition, populations of Steller sea lion (*Eumetopias jubatus*), which occur mainly along the coast of Hokkaido, have been controlled in order to reduce severe fisheries damage caused by them. Thus, the number of captured Steller sea lions was selected as an indicator, and the data were obtained from the State of Conservation Report of Shiretoko (Government of Japan, 2016). Note that the data include the number of individuals captured not only within the Shiretoko WNH marine area but also outside the area, in the Nemuro district.

For ecosystem response indicators, migrating populations of chum salmon, walleye pollock, common squid, and yellowtail, and the abundance of Steller sea lions in the Shiretoko WNH marine area were selected as indicators. Data on chum salmon, walleye pollock, and yellowtail stocks were obtained from the Japan Fisheries Research and Education Agency stock assessment results report (FRA, 1994–2019). Steller sea lion abundance data were referenced from the State of Conservation Report of Shiretoko (Government of Japan, 2016).

Table 3.3 Indicators of (A) environmental and human pressures, (B) ecosystem responses for the Shiretoko Peninsula, Hokkaido. Data sources are listed below.

(A)

Component	Pressure	Indicator	Source
Human	Fishery removals (landings)	Catch of salmon (including ocean salmonids other than chum salmon) in Shari and Rausu towns	1
	Fishery removals (landings)	Catch of walleye pollock in Shari and Rausu towns	1
	Fishery removals (landings)	Catch of common squid in Shari and Rausu towns	1
	Fishery removals (landings)	Catch of yellowtail in Shari and Rausu towns	1
	Ecosystem function change	Number of captured Steller sea lions in Nemuro Strait	2
Environmental pressures	SST change	Local sea surface temperature (spring, summer, autumn) by observation buoys in Shari side	3
	Current variability	Local current velocity (spring, summer, autumn) by observation buoys in Shari side	3
	Current variability	Local current direction (spring, summer, autumn) by observation buoys in Shari side	3

(B)

Component	Objective	Indicator	Source
Ecosystem	Maintain resource potential, structure and function	Age specific CPUE for chum salmon captured during summers in the Bering Sea.	4
	Maintain resource potential, structure and function	Predicted fish stock of walleye pollack (southern Sea of Okhotsk)	4
	Maintain resource potential, structure and function	Predicted fish stock of Yellowtail (all over Japan)	4
	Maintain resource potential, structure and function	Predicted the winter-spawning stock of common squid (all over Japan)	4
	Maintain structure and function	Number of Steller sea lion in Nemuro Strait by visual count from land (annual maximum number)	2

Source:

1. MAFF (2004–2018) 2005–2018 Annual Fishery Production Statistics, https://www.maff.go.jp/j/tokei/kouhyou/kaimen_gyosei/ (in Japanese)
2. Government of Japan (2016). State of Conservation Report of Shiretoko: In response to the World Heritage Committee Decision 39 COM7B.13, http://shiretoko-whc.com/data/management/nature/hozen_report_39_en.pdf
3. Shiretoko Data Center (2005–2019). Marine observation buoys, http://shiretoko-whc.com/monitoring/bui.html (in Japanese)
4. FRA (1994–2019). Results of the stock assessment. http://abchan.fra.go.jp/digests2019/index.html (in Japanese)

3.2.4 Korea

Ecosystem

For WG 36 analyses, Korea focused on the coastal waters around the Korean Peninsula in PICES Regions 19, 20, and 21 (Figure 1.3, 3.5). The sea surface temperature of these waters increased during the last 51 years (1968–2018), at a rate 2.5 times higher than the global trend (Han and Lee, 2020). Since the 1970s, low-oxygen water masses (hypoxia) caused by rising seawater temperature and eutrophication in the coastal areas have caused economic loss to the marine ecosystem and to fishers. Zooplankton biomass and copepod biomass increased in the late 1980s and early 1990s. The biomass increases were associated with a climate regime shift that occurred in 1989 (Rebstock and Kang, 2003). The spawning ground area was highly correlated with the total catch of common squid, *Todarodes pacificus*, throughout four decades (1970–2010). The Pacific Decadal Oscillation (PDO) was negatively correlated with the area of the spawning ground in the southern areas of Regions 19, 20, and 21 (Kim *et al*., 2018). These preceding studies indicate close relationships between changes in the marine ecosystems in Regions 19, 20, and 21 and climate.

Exploitation

The coastal waters around the Korean Peninsula provide spawning and breeding grounds and fishing grounds for various commercial fish species, including skate, sole, hairtail (*Trichiurus lepturus*), eel (*Muraenesox cinereus*), mackerel (*Scomber japonicus*) Pacific saury (*Cololabis saira*), blackthroat seaperch (*Doederleinia berycoides*), cod (*Gadus macrocephalus*), sailfin sandfish (*Arctoscopus japonicus*), anchovy (*Engraulis japonicus*), pollock) (*Theragra chalcogramma*), conger (*Conger myriaster*), blue crab (*Portunus trituberculatus*), and prawn (*Penaeus chinensis*). According to the Korea Statistical Office report (https://kosis.kr/eng/), warm-water fish species such as mackerels, anchovies, and squid have increased in the coastal waters since 1990 due to increased seawater temperature. The annual catch of mackerel was approximately 96,300 tons in 1991, and it rose to 115,000 tons in 2017. The annual catch of anchovies was about 130,200 tons in 1991, and it increased to 211,000 tons in 2017. The annual catch of squid was approximately 74,200 tons in 1991, rising to 87,000 tons in 2017. However, cold-water fish species such as pollock and saury have decreased. The annual catch of pollock was approximately 9,800 tons in 1991, but rapidly reduced to 1 ton in 2017. The annual catch of saury was about 5,300 tons in 1991, which decreased to 757 tons in 2017.

Data and indicators

For WG 36 analyses, we selected indicators of environmental and human pressures and ecosystem responses for the surface waters around the Korean Peninsula based on long-term data availability (Fig. 3.5, Table 3.4).

The environmental pressures included physical properties (temperature and salinity), seawater pollution index (Chemical Oxygen Demand, COD), oxygen condition (Dissolved Oxygen, DO), nutrient availability (NH_4-N, NO_2-N, NO_3-N, DIN, DIP, and SiO_2-Si concentrations), pH, suspended solids (SS), and transparency. Data of indicators for the environmental pressures were obtained from the Marine Environmental Monitoring Program (MEMP) operated by the Korea Marine Environment Management Corporation (KOEM) (Fig. 3.5). Monitoring occurs four times each year (February, May, August, and November). We estimated the annual means for each year and compiled the time series of annual means for each indicator from 2006 to 2016 using the monitoring data. Note that the KOEM data are only available in the coastal waters around the Korean Peninsula. We also used climate indices related to changes in sea surface temperature, such as the Pacific Decadal Oscillation (PDO, https://www.ncdc.noaa.gov/teleconnections/pdo/), Nino3.4 (https://psl.noaa.gov/gcos_wgsp/Timeseries/Nino34/), and Multivariate ENSO Index (MEI, https://www.psl.noaa.gov/enso/mei). The North Pacific Gyre Oscillation (NPGO, http://climexp.knmi.nl/getindices.cgi?) index was used as an indicator of water mass transport (Di Lorenzo *et al*., 2008). The annual means were used to compile the time series for each climate index during the 17 years.

For indicators of human pressures, the annual means of fish catches (squid, anchovy, eel, crab, shrimp, croaker, hairtail, mackerel, bighead croaker, and mysid shrimp), total amount of fish landings, and total ships tonnages were obtained from the Fisheries Information Portal (FIP, https://fips.go.kr/p/Main/) (Table 3.4).

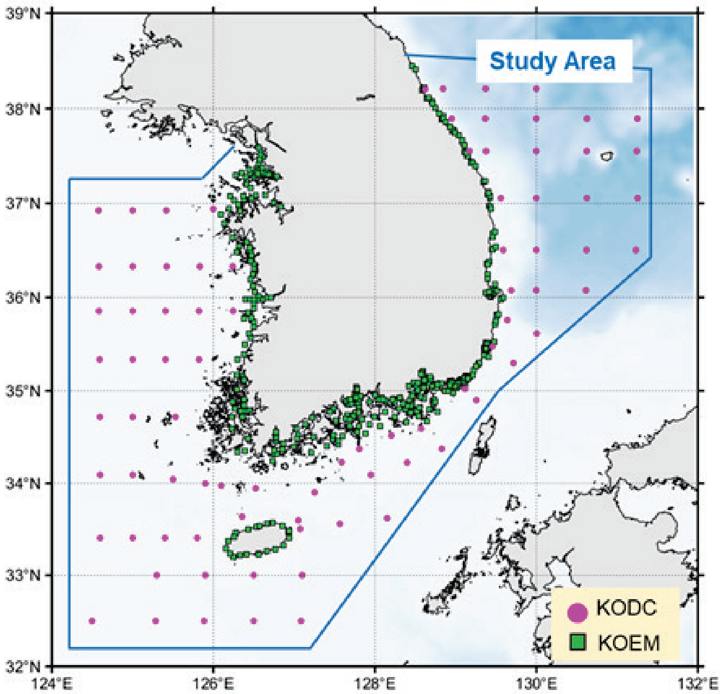


Fig. 3.5 Study area and long-term monitoring stations around the Korean Peninsula for time series of environment and human pressures and ecosystem indicators (Regions 19, 20, and 21, Fig. 1.3). KODC = Korea Oceanographic Data Center, KOEM = Korea Marine Environment Management Corporation

Table 3.4 Indicators of (A) environment and human drivers and pressures and (B) ecosystem responses for the coastal waters around the Korean Peninsula (Regions 19, 20, and 21, Fig. 1.3).

(A) Drivers and pressures

Component	Pressure	Indicator	Source
Environmental drivers	SST change	Sea Surface Temperature (SST)	a
	SSS change	Sea Surface Salinity (SSS)	a
	pH change	Sea surface pH	a
	Oxygen change	Sea surface Dissolved Oxygen (DO)	a
	Seawater pollution	Chemical Oxygen Demand (COD)	a
	Nutrient availability	Sea surface nutrient: NH_4-N, NO_2-N, NO_3-N, DIN, DIP, SiO_2-Si	a
	Productivity and light availability	Suspended Solids (SS)	a
	Light availability	Transparency	a
	SST change	Pacific Decadal Oscillation (PDO)	b
		Nino3.4	c
		Multivariate ENSO Index (MEI)	c
	Transport of water mass	North Pacific Gyre Oscillation (NPGO)	d
Human drivers	Fishery removal (landing)	Catch: squid, anchovy, eel, crab, shrimp, croaker, hairtail, mackerel, bighead croaker, mysid shrimp	e
		Total amount of fish landings	e
		Total ships tonnages	e

(B) Responses

Component	Impact	Indicator	Source
Ecosystem responses	Phytoplankton biomass and productivity	Chlorophyll-a	f
	Zooplankton productivity	Number of individuals of zooplankton: copepods, euphausiids, chordata, *Noctiluca*	f
		Zooplankton wet weight	f

Source:

a. Marine Environmental Monitoring System (MEMS) operated by the Korea Marine Environment Management Corporation (KOEM), https://meis.go.kr/portal/main.do
b. NOAA/NCDC, https://www.ncdc.noaa.gov/teleconnections/pdo/
c. NOAA/PSL, https://www.psl.noaa.gov/
d. Di Lorenzo *et al*., 2008, http://climexp.knmi.nl/getindices.cgi?
e. Fisheries Information Portal (FIP), https://fips.go.kr/p/Main/
f. Korea Oceanographic Data Center (KODC), https://www.nifs.go.kr/kodc/index.kodc

Chlorophyll-a concentrations, number of zooplankton individuals (copepods, euphausiids, chordata, and *Noctiluca*), and zooplankton wet weight were selected to consider the ecosystem responses to the environmental or human pressures in the Korean study area. Chlorophyll-a and zooplankton data for the ecosystem responses were obtained from the MEMP and the Korea Oceanographic Data Center (KODC, http://www.nifs.go.kr/kodc/index.kodc), respectively (Fig. 3.5). In the same way as the time series of environmental indicators, the annual means of chlorophyll-a and zooplankton data were compiled. The zooplankton data measured five times each year (February, May, August, October, and December) were used to calculate the annual means.

3.2.5 Russia

Indicators and data

Among the several indicators submitted by Russia for consideration by WG 35 in preparing NPRESR3, were annual and monthly means of trophic level (TL) catches and marine trophic index (MTI, which were calculated from the subset of TL ≥ 3.25). Those Ecosystem Time Series Observations (ETSOs) were grouped by fishing zones in the Russian EEZ of Region 19 (Fig. 1.3), matching approximately the regions suggested by WG 35. Unfortunately, MTI and TL time series were not used by Russian specialists in the NPESR3 chapters. Meanwhile, traditional ETSOs like biomass of different groups of animals and plants, water temperature, ice concentrations, *etc*. were analyzed. In addition to NPESR3, specialists from the Pacific and Sakhalin branches of the Russian Federal Research Institute of Fisheries and Oceanography (VNIRO) published their peer-reviewed research on the state and trends of different components in the Sea of Okhotsk ecosystem, which is the main fishing ground of Russia in the Pacific (Zuenko *et al*., 2019). That publication was used as a source of ETSOs after digitizing them. We had to digitize many more time series from publications to extend available timeframe and spatial coverage. VNIRO took the leading role in that process. Finally, we prepared a dataset which included different temporal and spatial slices of abiotic pressures or drivers, suspected of acting as an influence on the fish (https://doi.org/10.17632/d5hy9smz5p.3#file-c90adcdd-803c-485f-a00b-c3f519699f0c). The problem is that many time series have different time spans, *e.g*., many abiotic factors (described in papers) end before the year of the paper being published and have no data afterwards. Therefore, we could not use Gradient Forest Analysis directly to join tables with abiotic stressors and biological indicators, although we are planning to do so after selecting appropriate subsets. So, we started checking nonlinear relations using pairwise maximal information coefficient (MIC) calculations, hoping that we would not find many strong relations, and creation of a suitable subset for Gradient Forest Analysis would be fast. However, we found thousands of significant MICs between abiotic and biotic factors without lags and even more with lags. Most of those relationships were overly complex, but considering more than one stressor in multiple regressions (GAM) made splines linear in several cases, one of which was walleye pollock in the western part of Region 19. An overview of those findings has been published recently (Datsky *et al*., 2021, Appendix 4).

3.2.6 U.S.A.

Ecosystem

The southern area of Region 11 (Fig. 1.3), located off the U.S. west coast, is a highly productive eastern boundary current system which supports a diversity of marine life and fisheries. This area can be divided into three alongshore regions based on differences in physical and biological processes (Fig. 3.6). The southernmost region encompasses waters from south of Point Conception to Baja California, Mexico (though the U.S.–Mexico border (31–34.5°N) demarcates the EEZ), the central region spans between Point Conception and Cape Mendocino (34.5–40.5°N), and the northern region extends north of Cape Mendocino to the U.S.–Canada border (40.5-47°N). Some of the major processes driving species dynamics in this biogeographic region at seasonal, inter-annual, and decadal time scales include changes in source waters, timing and intensity of coastal upwelling, surface temperature, and vertical stratification. Multiple studies have demonstrated strong linkages between variability of source waters and upwelling and the recruitment of pelagic juvenile groundfish and forage species (Santora *et al*., 2014; Ralston *et al*., 2015; Schroeder *et al*., 2019). For example, in the central region, high abundance of pelagic juvenile groundfish, squid, and krill is associated with strong upwelling and/or higher transport of cool, fresh subarctic waters into the region, whereas forage fishes, such as sardines and anchovies, are more abundant during weaker upwelling conditions (Ralston *et al*., 2015; Schroeder *et al*., 2019). Higher transport of subarctic waters into the northern region is also linked to enhanced biomass of lipid-rich northern copepods, a valuable component of the food web in this region. In contrast, higher transport of warm sub-tropical waters results in higher biomass of lipid-poor southern copepods (Peterson *et al*., 2015).

Shifts in ocean temperature also have important effects on marine fauna. Changes in ocean temperature affect prey abundance and cause shifts in their distributions, which in turn can impact the growth and survival of their predators (Santora *et al*., 2020). For example, if adult female sea lions need to travel farther in search of sufficient quality food, they may leave their offspring without sustenance for long periods of time, and seabirds experience higher die-offs and abandon their colonies due to a lack of high-quality prey (Piatt *et al*., 2020). Increases in ocean temperature also contribute to stronger vertical stratification, which prevents the delivery of nutrient- and oxygen-rich waters to the upper ocean. This, in turn, causes declines in lower trophic level productivity and lower dissolved oxygen content in continental shelf waters, both of which can impact the survival and abundance of marine fauna.

Exploitation

The southern area of Region 11 has supported numerous fisheries over the past century. Commercial landings peaked at over 700,000 mt in the mid-1930s, a period during which coastal pelagic species, namely Pacific sardine, dominated fisheries landings (Miller *et al*., 2017). In the 1970s, salmon fisheries thrived as the most lucrative fisheries and groundfish landings surpassed landings of coastal pelagic species. Rockfish and flatfish comprised the highest groundfish landings until the early 1990s when Pacific hake (whiting) became the top fishery. Pacific hake has dominated fisheries landings the southern area of Region 11 ever since. Over the past 20 years, the average annual landings and dollar value of Pacific hake have been around 180,000 mt and $33 million, respectively (NOAA, https://www.fisheries.noaa.gov/national/sustainable-fisheries/commercial-fisheries-landings). Pacific sardine, market squid, and Dungeness crab have also contributed to the bulk of fisheries landing during this period, with the most highly valued fishery in the southern area of Region 11 being Dungeness crab followed by squid and salmon (NOAA, https://www.fisheries.noaa.gov/national/sustainable-fisheries/commercial-fisheries-landings).

Data and indicators

The ecosystem, environmental and human dimensions indicators used in the U.S. case study (Table 3.5) are an extension of those used in previous analyses of ecosystem thresholds conducted by Samhouri and colleagues (2017). The indicators and time series used in their study and in our analysis were compiled from NOAA's California Current Ecosystem Integrated Ecosystem Assessment (CCIEA; Harvey *et al*., 2014). The CCIEA is an indicator framework that provides science support for ecosystem-based management in the southern area of Region 11. WG 36 applied analyses to time series for a modified set of CCIEA indicators, which are publicly available on the CCIEA website at https://www.integratedecosystemassessment.noaa.gov/regions/california-current.

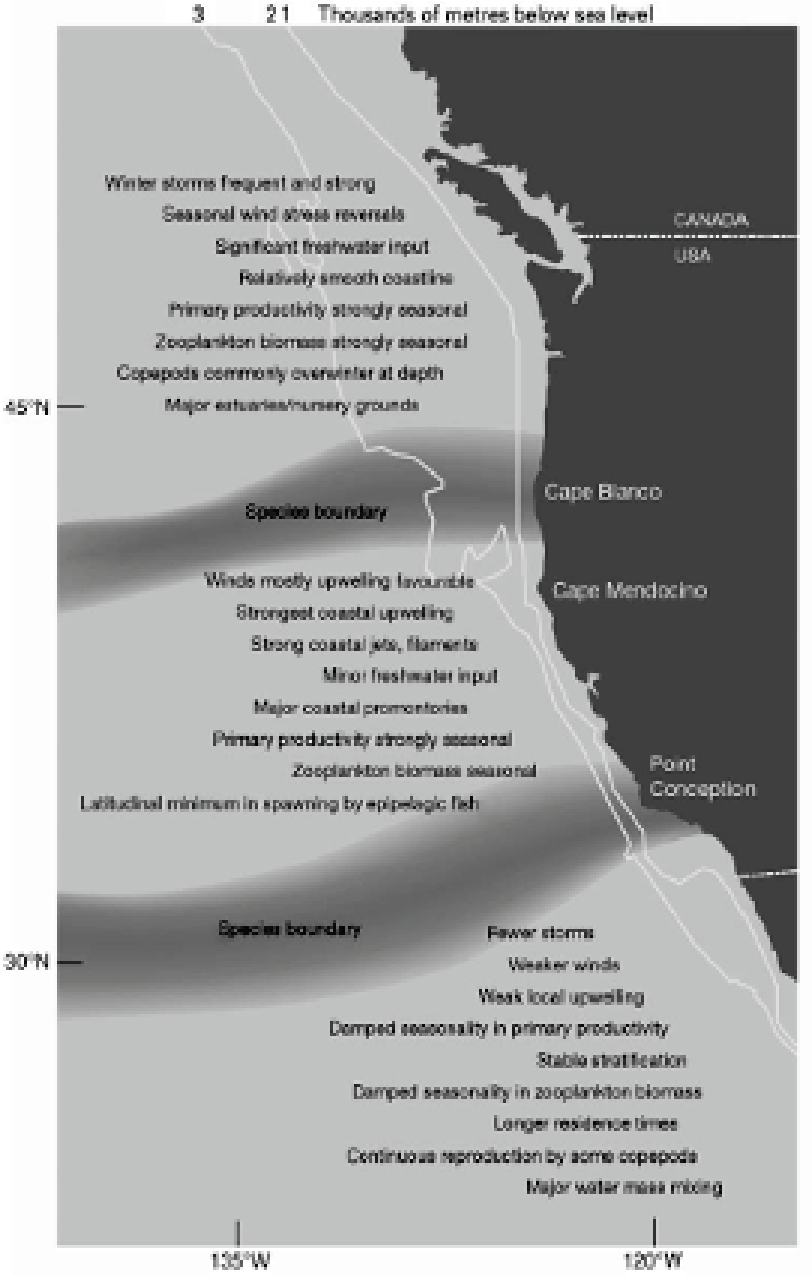


Fig. 3.6 Generalized variations in physical and biological processes across three sub-regions within the southern area of PICES Region 11 (from Agostini *et al*., 2005).

Table 3.5 Indicators of environmental and human pressures (A) and ecosystem objectives, ecosystem pressures and responses (B) for the U.S. case study.

(A)

Component	Pressure	Indicator	Region	Years	Source
Environment	SST change	Pacific Decadal Oscillation (PDO)	Coastwide	1970–2019	a, b
	Transport	North Pacific Gyre Oscillation (NPGO)	Coastwide	1970–2019	c, b
	SST change	Multivariate ENSO Index (MEI)	Coastwide	1970–2019	b
	SST change	Oceanic Niño Index (ONI)	Coastwide	1970–2019	b
	Sea level pressure	Northern Oscillation Index (NOI)	Coastwide	1970–2019	d, b
	Sea level pressure	Area of North Pacific High (NPH)	Coastwide	1970–2019	e, b
	SST change	Sea surface temperature (SST)	SCC, CCC, NCC	1982–2019	b
	Productivity	Upwelling (CUTI)	SCC, CCC, NCC	1988–2019	f, b
	Surface nitrate flux	Nitrate (BEUTI)	SCC, CCC, NCC	1988–2019	f, b
	Oxygen change	Dissolved oxygen	SCC	1990–2018	b
Human	Fishery removals	Total landings	Coastwide	1996–2018	g, b
		Coastal pelagic species (CPSI) landings	Coastwide	1981–2018	g, b
		Groundfish landings	Coastwide	1996–2018	g, b

(B)

Component	Objective	Indicator	Region	Years	Source
Ecosystem	Main structure and function	Brandt’s cormorant reproductive success	CCC	1972–2019	h, b
		Cassin’s auklet reproductive success	CCC	1972–2019	h, b
		Common murre reproductive success	CCC	1972–2019	h, b
		Pigeon guillemot reproductive success	CCC	1971–2019	h, b
		Rhinocerus auklet reproductive success	CCC	1986–2019	h, b
		Female California sea lion pup growth	SCC	1997–2019	b
		Female California sea lion pup production	SCC	1997–2019	b
		Adult forage fish catch	CCC	1990–2019	b
		Adult anchovy catch	CCC	1990–2019	b
		Adult sardine catch	CCC	1990–2019	b
		All young-of-year (YOY) catch	CCC	1990–2019	b
		Anchovy YOY catch	CCC	1990–2019	b
		Pacific hake YOY catch	CCC	1990–2019	b
		Rockfish YOY catch	CCC	1990–2019	b
		Sardine YOY catch	CCC	1990–2019	b
		All larval fish abundance	SCC	1983–2019	b
		Pacific hake larvae abundance	SCC	1983–2019	b
		Pacific sardine larvae abundance	SCC	1983–2019	b
		Copepod biomass anomaly summer	NCC	1996–2019	i, b
		Copepod biomass anomaly winter	NCC	1997–2019	i, b

Table 3.5 Continued.

SSC = Southern California Current, CCC = Central California Current, NCC = Northern Central California Current

Source:
a. Mantua *et al*., 1997
b. California Current Integrated Ecosystem Assessment: https://www.integratedecosystemassessment.noaa.gov/regions/california-current
c. Di Lorenzo *et al*., 2008
d. Schwing *et al*., 2002
e. Schroeder *et al*., 2013
f. Jacox *et al*., 2018
g. Pacific Fisheries Information System
h. Point Blue Conservation Science
i. Peterson *et al*., 2015

Coastwide indicators of physical environmental pressures used in U.S. case study are similar to those included in the analysis for the WCVI in British Columbia, Canada. The PDO index tracks changes in sea surface patterns in the Northeast Pacific and the North Pacific Gyre Oscillation (NPGO) index tracks the strength of transport by the North Pacific Gyre. The multivariate ENSO index (MEI) and Oceanic Niño Index (ONI) are also large-scale indicators of sea surface temperature, and the Northern Oscillation Index (NOI) and area of the North Pacific High are measures of changes in sea level pressure. In addition, we included several regional level physical indicators. For each sub-region of the southern area of Region 11 (north: 33°N; central: 39°N; south = 45°N, Fig. 3.6), we used remotely sensed sea surface temperature data, estimates of dissolved oxygen, the Coastal Upwelling Transport Index (CUTI), and the Biologically Effective Upwelling Transport Index (BEUTI). The CUTI and BEUTI indices are measures of coastal vertical transport and nitrate flux, respectively (Jacox *et al*., 2018).

Indicators of human pressure on ecosystem components included coastwide estimates of fisheries landings. Specifically, we used the summed total of fisheries landings (combined commercial and recreational landings on the U.S. west coast) and separate estimates for coastal pelagic species (northern anchovy, Pacific sardine, Pacific herring, round herring, chub mackerel, jack mackerel) and groundfish species (flatfishes, rockfishes, and abundant demersal fishes).

Ecosystem response indicators used in the analysis were based on the ecological integrity indicators compiled for the CCIEA. The indicators for higher trophic level biology included seabird productivity anomalies at the southeast Farallon Islands in the central region of the study region, and female California sea lion pup production and growth rates at San Miguel Island in the southern region of the study system. We also included indicators for middle and lower trophic level species that were derived from U.S. west coast monitoring surveys. These included larval fish abundances in the southern region, catches of forage fish and young-of-year groundfish in the central region, and copepod biomass anomalies in northern region of the case study ecosystem.

3.3 Summary

Towards the goal of examining nonlinear ecosystem responses to climate and anthropogenic drivers and pressures, WG 36 members selected indicators from a toolbox of recommended indicators (based on those identified by WG 28, WG 35, and the HD committee) for each region of study. Many of the recommended core indicators were selected in all ecosystems to reflect environmental and human pressures and ecosystem responses. However, not all core indicators could be examined because, for example, data were not available or not available to maximize the length of the time series examined. Besides the core indicators, some additional ecosystem-specific indicators were included. For these analyses, a data-based approach was used (time series of data to calculate indicators) and indicators were selected to address ecosystem-based management objectives, where possible.

3.4 Conclusions

WG 36 selected indicators from a toolbox of recommended indicators for each region of study.

- Many of the recommended core indicators were selected in all ecosystems to reflect environmental and human pressures and ecosystem responses. However, not all core indicators could be examined (because, for example, data were not available or not available to maximize the length of the time series examined). Member countries had different priorities for their recommended core indicators that influenced their data collection and sharing protocols.
- Besides the core indicators, some additional ecosystem-specific indicators were included.
- For these analyses, a data-based approach was used (time series of data to calculate indicators) and indicators were selected to address ecosystem-based management objectives, where possible.

3.5 Literature cited

Agonstini, V.N. 2005. Climate, ecology and productivity of Pacific sardine (*Sardinops sagax*) and hake (*Merluccius productus*), PhD thesis, University of Washington, Seattle, WA, USA. 188 pp.

Banzon, V., Smith, T.M., Chin, T.M., Liu, C. and Hankins, W. 2016. A long-term record of blended satellite and in situ sea-surface temperature for climate monitoring, modeling and environmental studies. *Earth System Science Data* **8**: 165–176, https://doi.org/10.5194/essd-8-165-2016.

Beamish, R.J. and Bouillon, D.R. 1993. Pacific salmon production trends in relation to climate. *Canadian Journal of Fisheries and Aquatic Sciences* **50**: 1002–1016, https://doi.org/10.1139/f93-11.

Bian, X., Wan, R., Jin, X., Shan, X. and Guan, L. 2018. Ichthyoplankton succession and assemblage structure in the Bohai Sea during the past 30 years since the 1980s. *Progress in Fishery Sciences* **39**: 1–15.

Bian, X., Wan, R., Shan, X. and Jin, X. 2022. Preliminary analysis on recruitment variation and the exogenous driving factors to early life stages of small pelagic fishes in the Laizhou Bay. *Journal of Fishery Sciences of China* **29**: 446–468.

Boldt, J.L., Fu, C., Hazen, E., Hunsicker, M., Perry, R.I. and Xiujuan, S. 2021. Quantifying ecosystem responses to environmental and human pressures on the west coast of Vancouver Island. *Ecological Indicators* **132**: 108232, https://doi.org/10.1016/j.ecolind.2021.108232.

Boldt, J.L., Martone, R., Samhouri, J., Perry, R.I., Itoh, S., Chung, I.K., Takahashi, M. and Yoshie, N. 2014. Developing ecosystem indicators for responses to multiple stressors. *Oceanography* **27**: 116–133, https://doi.org/10.5670/oceanog.2014.91.

Bundy, A., Gomez, C. and Cook, A., 2017. Guidance framework for the selection and evaluation of ecological indicators. Canadian Technical Report of Fisheries and Aquatic Sciences 3232, xii + 212 pp. https://doi.org/10.13140/RG.2.2.17297.12647.

Cheng, L., Zhu, J., Abraham, J., Trenberth, K., Fasullo, J., Zhang, B., Yu, F., Wan, L., Chen, X. and Song, X. 2019. 2018 continues record global ocean warming. *Advances in Atmospheric Sciences* **36**: 249–252.

Cheung, W.W., Watson, R., Morato, T., Pitcher, T.J. and Pauly, D. 2007. Intrinsic vulnerability in the global fish catch. *Marine Ecology Progress Series* **333**: 1–12, doi:10.3354/meps333001.

Datsky, A.V., Kulik, V.V. and Datskaya, S.A. 2021. The dynamics of the abundance of commercial fish in the Far Eastern seas and adjacent areas of the open part of the Pacific Ocean and factors influencing it. *Trudy VNIRO*. **186**: 31–77 (in Russian with English abstract). https://doi.org/10.36038/2307-3497-2021-186-31-77.

Deng, J. 1988. Ecological bases of marine ranching and management in the Bohai Sea. *Marine Fisheries Research* **9**: 1–11.

Deng, J. and Ye, C. 1986. The prediction of penaeid shrimp yield in the Bohai Sea in autumn. *Chinese Journal of Oceanology and Limnology* **4**: 343–352.

Deng, J., Meng, T., Ren, S., Qiu X. and Zhu, J. 1988a. Species composition, abundance and distribution of fishes in the Bohai Sea. *Marine Fisheries Research* **9**: 11–91.

Deng, J., Zhu, J., Cheng, J. and Hua, D. 1988b. Main invertebrates in the Bohai Sea and their fishery biology. *Marine Fisheries Research* **9**: 91–121

Di Lorenzo, E., Schneider, N., Cobb, K.M., Franks, P.J.S., Chhak, K., Miller, A.J., McWilliams, J.C., Bograd, S.J., Arango, H., Curchister, E., Powell, T.M. and Riviére, P. 2008. North Pacific Gyre Oscillation links ocean climate and ecosystem change. *Geophysical Research Letters* **35**: L08607, https://doi.org/10.1029/2007GL032838.

Ding, Q., Shan, X., Jin, X. and Gorfine, H. 2021. A multidimensional analysis of marine capture fisheries in China's coastal provinces. *Fisheries Science* **87**: 297–309, doi:10.1007/s12562-021-01514-9.

FRA (Japan Fisheries Research and Education Agency) 1994–2019. Results of the stock assessment. http://abchan.fra.go.jp/digests2019/index.html (in Japanese).

Fu, C., Gaichas, S., Link, J.S., Bundy, A., Boldt, J.L., Cook, A.M., Gamble, R., Utne, K. R., Liu, H. and Friedland, K.D. 2012. Relative importance of fishing, trophodynamic and environmental drivers in a series of marine ecosystems. *Marine Ecology Progress Series* **459**: 169–184, https://doi.org/10.3354/meps09805.

Fu, C., Large, S., Knight, B., Richardson, A., Bundy, A., Reygondeau, G., Boldt, J., van der Meeren, G.I., Torres, M.A., Sobrino, I., Auber, A., Travers-Trolet, M., Piroddi, C., Diallo, I., Jouffre, D., Mendes, H., Borges, M.F., Lynam, C., Coll, M., Shannon, L.J. and Shin, Y.J. 2015. Relationships among fisheries exploitation, environmental conditions, and ecological indicators across a series of marine ecosystems. *Journal of Marine Systems* **148**: 101–111, https://doi.org/10.1016/j.jmarsys.2015.01.004.

Fu, C., Xu, Y., Bundy, A., Grüss, A., Coll, M., Heymans, J.J., Fulton, E.A., Shannon, L.J., Halouani, G., Velez, L., Akoglu, E., Lynam, C.P. and Shin, Y.-J. 2019. Making ecological indicators management ready: Assessing their ability to detect impacts of fishing and environmental change. *Ecological Indicators* **105**: 16–28, https://doi.org/10.1016/j.ecolind.2019.05.055.

Galbraith, M. and Young, K. 2018. West Coast British Columbia zooplankton biomass anomalies 2017, pp. 69–75 *in:* State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2017 *edited by* P.C. Chandler, S.A. King and J.L. Boldt, Canadian Technical Report of Fisheries and Aquatic Sciences 3266, https://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2017/index-eng.html.

Godefroid, M., Boldt, J.L., Thorson, J., Forrest, R., Gauthier, S. Flostrand, L., Perry, R.I., Ross, A.R.S. and Galbraith, M. 2019. Spatio-temporal models provide new insights on the biotic and abiotic drivers shaping Pacific herring (*Clupea pallasi*) distribution. *Progress in Oceanography* **178**: 102198, https://doi.org/10.1016/j.pocean.2019.102198.

Government of Japan. 2016. State of conservation report of Shiretoko: In response to the World Heritage Committee Decision 39 COM7B.13, http://shiretoko-whc.com/data/management/nature/hozen_report_39_en.pdf.

Guan, L., Shan, X, Jin, X., Gorfine, H., Yang T. and Li, Z. 2020. Evaluating spatio-temporal dynamics of multiple fisheries-targeted populations simultaneously: A case study of the Bohai Sea ecosystem in China. *Ecological Modelling* **422**: 108987, https://doi.org/10.1016/j.ecolmodel.2020.108987.

Han, I.-S. and Lee, J.-S. 2020. Change the annual amplitude of sea surface temperature due to climate change in a recent decade around the Korean Peninsula. *Journal of the Korean Society of Marine Environment and Safety* **23**: 233–241, https://doi:10.7837/kosomes.2020.26.3.233.

Harvey, C., Garfield, N., Hazen. E. and Williams, G. (Eds.) 2014. The California Current Integrated Ecosystem Assessment: Phase III Report. U.S. Department of Commerce, NOAA.

Holmes, E.E., Ward, E.J. and Wills, K. 2012. MARSS: Multivariate autoregressive state-space models for analyzing time-series data. *The R Journal* **4**: 11–19.

Hourston, R.A.S. and Thomson, R.E. 2019. Wind-driven upwelling/downwelling along the northwest coast of North America: timing and magnitude, pp. 21–23 *in:* State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2018 *edited by* J.L. Boldt, J. Leonard, and P.C. Chandler, Canadian Technical Report of Fisheries and Aquatic Sciences 3314, vii + 248 pp.

Jacox, M.G., Edwards, C.A., Hazen, E.L. and Bograd, S.J. 2018. Coastal upwelling revisited: Ekman, Bakun, and improved upwelling indices for the U.S. west coast. *Journal of Geophysical Research* **123**: 7332–7350, https://doi:10.1029/2018JC014187.

Jamieson, G.S., Phillips, A.C. and Huggett, W.S. 1989. Effects of ocean variability on the abundance of Dungeness crab (*Cancer magister*) megalopae, pp. 305–325 *in:* Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models *edited by* R.J. Beamish and G.A. McFarlane, Canadian Special Publication of Fisheries and Aquatic Sciences 108.

Jin, X. 2000. The dynamics of major fishery resources in the Bohai Sea. *Journal of Fishery Sciences of China* **4**: 22–26.

Jin, X. and Deng, J. 1999. Yearly variations of fishery resources and biodiversity in the Laizhou Bay. *Marine Fisheries Research* **1**: 6–12.

Jin, X. and Deng, J. 2000. Variations in community structure of fishery resources and biodiversity in the Laizhou Bay, Shandong. *Diversity Sciences* **1**: 65–72.

Jin, X., Hamre, J. Zhao, X. and Li, F. 2001. Study on the quota management of anchovy (*Engraulis japonicas*) in the Yellow Sea. *Journal of Fishery Sciences of China* **3**: 27–30.

Jin, X.S., Shan, X.J., Li, X. Sen, Wang, J., Cui, Y. and Zuo, T. 2013. Long-term changes in the fishery ecosystem structure of Laizhou Bay, China. *Science China Earth Sciences* **56**: 366–374, doi:10.1007/s11430-012-4528-7.

Kim, Y.-H., Jung, H.K. and Lee, C.I. 2018. Changes in the spawning ground environment of the common squid, *Todarodes pacificus* due to climate change. *Ocean Polar Research* **40**: 127–143, https://doi:10.4217/OPR.2018.40.3.127.

Kruse, G.H. and D. Evans. 2006. Development of operational objectives for the southeastern Bering Sea ecosystem, pp. 3–15 *in:* Report of the PICES/NPRB Workshop on Integration of Ecological Indicators of the North Pacific with Emphasis on the Bering Sea *edited by* G.H. Kruse, P.A. Livingston, J.E. Overland, G.S. Jamieson, S. McKinnell and R.I. Perry, PICES Scientific Report No. 33, https://meetings.pices.int/publications/scientific-reports/Report33/Rep_33.pdf.

Kushiro Natural Environment Office of Ministry of the Environment, Hokkaido Regional Forest Office of Forestry Agency, Hokkaido Prefectural Government, Shiretoko World Natural Heritage Scientific Committee. 2013. Shiretoko White Paper, http://dc.shiretoko-whc.com/data/research/annual_report/H24annual_report.pdf (in Japanese).

Large, S.I., Fay, G., Friedland, K.D. and Link, J.S. 2013. Defining trends and thresholds in responses of ecological indicators to fishing and environmental pressures. *ICES Journal of Marine Science* **70**: 755–767, https://doi.org/10.1093/icesjms/fst067.

Link, J.S., Megrey, B.A., Miller, T.J., Essington, T., Boldt, J.L., Bundy, A., Moksness, E., Drinkwater, K.F. and Perry, R.I. 2010. Comparative analysis of marine ecosystems: international production modelling workshop. *Biology Letters* **6**: 723–726, https://doi:10.1098/rsbl.2010.0526.

Liu, C., Yan, J. and Cui, W. 1981. A study on the method of prediction for the autumnal prawn catches in Bohai Sea. *Journal of Fisheries of China* **5**: 65–73.

Lucey, S.M., Cook, A.M., Boldt, J.L., Link, J.S., Essington, T. and Miller, T.J. 2012. Comparative analyses of surplus production dynamics of functional feeding groups across 12 large marine ecosystems. *Marine Ecology Progress Series* **459**: 219–229, https://doi.org/10.3354/meps09825.

Mackas, D.L., Thomson, R.E. and Galbraith, M. 2001. Changes in the zooplankton community of the British Columbia continental margin, 1985-1999, and their covariation with oceanographic conditions. *Canadian Journal of Fisheries and Aquatic Sciences* **58**: 685–702, https://doi.org/10.1139/f01-00.

Mackas, D.L., Batten, S. and Trudel, M. 2007. Effects on zooplankton of a warming ocean: recent evidence from the North Pacific. *Progress in Oceanography* **75**: 223–252, https://doi.org/10.1016/j.pocean.2007.08.010.

MAFF (Ministry of Agriculture, Forestry and Fisheries of Japan). 2005–2018. Annual fishery production statistics, https://www.maff.go.jp/j/tokei/kouhyou/kaimen_gyosei/ (in Japanese).

Makino, M. and Sakurai, Y. 2012. Adaptation to climate-change effects on fisheries in the Shiretoko World Natural Heritage area, Japan. *ICES Journal of Marine Science* **69**: 1134–1140, https://doi.org/10.1093/icesjms/fss098.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M. and Francis, R.C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* **78**: 1069–1079, https://doi.org/10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2.

McFarlane, G.A. and Beamish, R.J. 1992. Climatic influence linking copepod production with strong year-classes in sablefish, *Anoplopoma fimbria*. *Canadian Journal of Fisheries and Aquatic Sciences* **49**: 743–753, https://doi.org/10.1139/f92-083.

McFarlane, G.A., Ware, D.M., Thomson, R., Mackas, D. and Robinson, C. 1997. Physical, biological and fisheries oceanography of a large ecosystem (west coast of Vancouver Island) and implications for management. *Oceanologica Acta* **20**:191–200.

Miller, R.R., Field, J.C., Santora, J.A., Monk, M.H., Kosaka, R. and Thomson, C. 2017. Spatial valuation of California marine fisheries as an ecosystem service. *Canadian Journal of Fisheries and Aquatic Sciences* **74**: 1732–1748, https://doi.org/10.1139/cjfas-2016-0228.

Ministry of the Environment and the Hokkaido Prefectural Government. 2018. http://dc.shiretoko-whc.com/data/management/kanri/seawg_kanri_3rdterm_en.pdf.

Mysak, L.A., Hsieh, W.W. and Parsons, T.R. 1982. On the relationship between interannual baroclinic waves and fish populations in the Northeast Pacific. *Biological Oceanography* **2**: 63–103.

Ohshima, Kay I., Mizuta, G., Itoh, M., Fukamachi, Y., Watanabe, T., Nabae, Y., Suehiro, K. and Takatsuchi, M. 2001. Winter oceanographic conditions in the southwestern part of the Okhotsk Sea and their relation to sea ice. *Journal of Oceanography* **57**: 451–460, https://doi:10.1023/A:1021225303621.

Olesiuk, P.F. 2018. Recent trends in abundance of Steller sea lions (*Eumetopias jubatus*) in British Columbia. DFO Canadian Science Advisory Secretariat Science Research Document 2018/006, v + 67 pp.

Perry, R.I., Livingston, P. and Fulton, E.A. 2010. Ecosystem indicators, pp. 83–89 *in:* Report of Working Group 19 on Ecosystem-based Management Science and its Application to the North Pacific *edited by* G. Jamieson, P. Livingston, and C.-I. Zhang, North Pacific Marine Science Organization (PICES) Scientific Report No. 37, https://meetings.pices.int/publications/scientific-reports/Report37/Rep37.pdf.

Peterson, W.T., Fisher, J.L, Peterson, J.O., Morgan, C.A., Burke, B.J. and Fresh, K.L. 2015. Applied fisheries oceanography: Ecosystem indicators of ocean conditions inform fisheries management in the California Current. *Oceanography* **27**: 80–89, http://dx.doi.org/10.5670/oceanog.2014.88.

Piatt, J.F., Parrish, J.K., Renner, H.M., Schoen, S.K., Jones, T.T., Arimitsu, M.L., Kuletz, K.J., Bodenstein, B., García-Reyes, M., Suerr, R.S., Corcoran, R.M., Kaler, R.S.A., McChesney, G.J., Golighlty, R.T., Coletti, H.A., Suryan, R.M., Burgess, H.K., Lindsey, J., Lindquist, K., Warzybok, P.M., Jahncke, J., Roletto, J. and Sydeman, W.J. 2020. Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014-2016. *PLoS ONE* **15**: e0226087, https://doi.org/10.1371/journal.pone.0226087.

Ralston, S., Field, J.C. and Sakuma, K.M. 2015. Long-term variation in a central California pelagic forage assemblage. *Journal of Marine Systems* **146**: 26–37, https://doi.org/10.1016/j.jmarsys.2014.06.013.

Rausu Town. 2019. Fisheries in Rausu Town, https://www.rausu-town.jp/img/files/6_info/26_tokei/suisan/suisan_r1.pdf (in Japanese).

Rebstock, G.A. and Kang, Y.S. 2003. A comparison of three marine ecosystems surrounding the Korean peninsula: Response to climate change. *Progress in Oceanography* **59**: 357–379, https://doi:10.1016/j.pocean.2003.10.002.

Reynolds, R.W., Smith, T.M., Liu, C., Chelton, D.B., Casey, K.S. and Schlax, M.G. 2007. Daily high-resolution-blended analyses for sea surface temperature. *Journal of Climate* **20**: 5473–5496, https://doi:10.1175/JCLI-D-14-00293.1.

Russian Federation of Fisheries. 2018. https://fish.gov.ru/about/polozhenie/ (in Russian).

Sakurai, Y. 2006. Conserving both rich marine ecosystems and fisheries in the Shiretoko World Natural Heritage. *National Parks* **645**: 4–9 (in Japanese).

Sakurai, Y. 2007. An overview of the Oyashio ecosystem. *Deep-Sea Research II* **54**: 2526–2542, https://doi.org/10.1016/j.dsr2.2007.02.007.

Samhouri, J.F., Andrews, K.S., Fay, G., Harvey, C.J., Hazen, E.L., Hennessey, S.M., Holsman, K., Hunsicker, M.E., Large, S.I., Marshall, K.N., Stier, A.C., Tam, J.C. and Zador, S.G. 2017. Defining ecosystem thresholds for human activities and environmental pressures in the California Current. *Ecosphere* **8**: e01860, https://doi.org/10.1002/ecs2.1860.

Santora, J.A., Schroeder, I.D., Field, J.C., Wells, B.K. and Sydeman, W.J. 2014. Spatio-temporal dynamics of ocean conditions and forage taxa reveal regional structuring of seabird–prey relationships. *Ecological Applications* **24**: 1730-1747, https://doi.org/10.1890/13-1605.1.

Santora, J.A., Mantua, N.J., Schroeder, I.D., Field, J.C., Hazen, E.L., Bograd, S.J., Sydeman, W.J., Wells, J. Calambokidis, B.K., Saez, L., Lawson, D. and Forney, K.A. 2020. Habitat compression and ecosystem shifts as potential links between marine heatwave and record whale entanglements. *Nature Communications* **11**: 536, https://doi.org/10.1038/s41467-019-14215-w.

Schroeder, I., Black, B.A., Sydeman, W.J., Bograd, S.J., Hazen, E.L., Santora, J.A. and Wells, B.K. 2013. The North Pacific High and wintertime pre-conditioning of California current productivity. *Geophysical Research Letters* **40**: 541–546, https://doi.org/10.1002/grl.50100.

Schroeder, I.D., Santora, J.N., Bograd, S.J., Hazen, E.L., Sakuma, K.M., Moore, A.M., Edwards, C.A., Wells, B.K. and Field, J.C. 2019. Source water variability as a driver of rockfish recruitment in the California Current Ecosystem: implications for climate change and fisheries management. *Canadian Journal of Fisheries and Aquatic Sciences* **76**: 950–960, https://doi.org/10.1139/cjfas-2017-0480.

Schweigert, J.F., Boldt, J.L., Flostrand, L. and Cleary, J.S. 2010. A review of factors limiting recovery of Pacific herring stocks in Canada. *ICES Journal of Marine Science* **67**: 1903–1913.

Schwing, F.B., Murphree, T. and Green, P.M. 2002. The Northern Oscillation Index (NOI): a new climate index for the northeast Pacific. *Progress in Oceanography* **53**: 115–139, https://doi:16/S0079-6611(02)00027-7

Shari Town, 2020. Statistics on fisheries, https://www.town.shari.hokkaido.jp/03admini/50toukei/10bunyabetsu/fishery_population2.html (in Japanese).

Shin, Y.-J., Shannon, L.J., Simier, M., Coll, M., Fulton, E.A., Link, J.S., Jouffre, D., Ojaveer, H., Mackinson, S., Heymans, J.J. and Raid, T. 2010a. Can simple be useful and reliable? Using ecological indicators to represent and compare the states of marine ecosystems. *ICES Journal of Marine Science* **67**: 717–731, https://doi.org/10.1093/icesjms/fsp287.

Shin, Y-J., Shannon, L J., Bundy, A., Coll, M., Aydin, K., Bez, N., Blanchard, J. L., Borges, M. F., Diallo, I., Diaz, E., Heymans, J.J., Hill, L., Johannesen, E., Jouffre, D., Kifani, S., Labrosse, P., Link, J.S., Mackinson, S., Masski, H., Möllmann, C., Neira, S., Ojaveer, H., ould Mohammed Abdallahi, K., Perry, I., Thiao, D., Yemane, D. and Cury, P.M. 2010b. Using indicators for evaluating, comparing, and communicating the ecological status of exploited marine ecosystems. 2. Setting the scene. *ICES Journal of Marine Science* **67**: 692–716, https://doi.org/10.1093/icesjms/fsp294.

Shiretoko Data Center. 2005–2019. Marine observation buoys, https://shiretokodata-center.env.go.jp/monitoring/bui.html (in Japanese).

Takahashi, M. and Perry, R.I. (Eds.) 2019. Report of Working Group 28 on Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors. PICES Sci. Rep. No. 55, 245 pp., https://meetings.pices.int/publications/scientific-reports/Report55/Rpt55.pdf.

Tanasichuk, RW. 2002. Implications of interannual variability in euphausiid population biology for fish production along the southwest coast of Vancouver Island: a synthesis. *Fisheries Oceanography* **11**: 18–30, DOI:10.1046/J.1365-2419.2002.00185.X.

Tang, Q. 2006. Maine Living Resources and Environment in the China Exclusive Economic Zone. Science Press, Beijing.

Thomson, R.E. and Ware, D.M. 1988. Oceanic factors affecting the distribution and recruitment of west coast fisheries, pp. 31–65 *in:* DFO National Workshop on Recruitment. Canadian Technical Report of Fisheries and Aquatic Sciences 1626.

Tong, L., Tang, Q. and Pauly, D. 2000. A preliminary approach on mass-balance ecopath model of the Bohai Sea. *Chinese Journal of Applied Ecology* **3**: 435–440.

Wang, A., Wan, R. and Jin, X. 2010. Decadal variations of ichthyoplankton biodiversity in spring in Laizhou Bay of the Bohai Sea. *Progress in Fishery Sciences* **1**: 19–24.

Ware, D. M. and McFarlane, G.A. 1986. Relative impact of Pacific hake, sablefish and Pacific cod on west coast of Vancouver Island herring stocks. *International North Pacific Fisheries Commission Bulletin* **47**: 67–78.

Ware. D. and McFarlane, G. 1989. Fisheries production domains in the northeast Pacific Ocean, pp. 359–379 *in:* Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models *edited by* R.J. Beamish and G.A. McFarlane, Canadian Special Publication of Fisheries and Aquatic Sciences 108.

Ware, D.M. and McFarlane, G.A. 1995. Climate induced changes in hake abundance and pelagic community interactions in the Vancouver Island upwelling system, pp. 509–521 *in:* Climate Change and Northern Fish Populations *edited by* R.J. Beamish, Canadian Special Publication of Fisheries and Aquatic Sciences 121.

Ware, D. and Thomson, R. 2005. Bottom-up ecosystem trophic dynamics determine fish production in the Northeast Pacific. *Science* **308**: 1280–1284, DOI: 10.1126/science.1109.

Yang, T., Shan, X., Jin, X., Chen, Y., Teng, G. and Wei, X. 2018. Long-term changes in keystone species in fish community in spring in Laizhou Bay. *Progress in Fisheries Science* **39**: 1–11, doi:10.11758/yykxjz.20170912001.

Zhang, B., Wu, Q. and Jin, X. 2015. Interannual variation in the food web of commercially harvested species in Laizhou Bay from 1959 to 2011. *Journal of Fishery Sciences of China* **22**: 278–287, doi:10.3724/SP.J.1118.2015.14299.

Zuenko. Yu.I., Aseeva, N.L., Glebova, S.Yu., Gostrenko, L.M., Dubinina, A.Yu., Delepova, E.P., Zolotov, A.O., Laboda, S.V., Lysenko, A.V., Matveev, V.I., Muktepavel, L.S., Ovsyannikov, E.E., Figurkin, A.L. and Shatilina, T.A. 2019. Modern changes in the Sea of Okhotsk ecosystem (2008–2018). *Izvestia TINRO* **197**: 35–61, https://doi.org/10.26428/1606-9919-2019-197-35-61.

4 Methods for Determining Thresholds in Ecosystem Indicators

4.1 Introduction

Over the past few decades, there have been many advancements in statistical methods for detecting thresholds in time series data (Andersen *et al*., 2009). The application of these methods in environmental sciences has also been accelerating, as thresholds hold promise within management and regulatory frameworks as reference points for informing decision-making. Until recently, threshold detection methods have mostly been applied to univariate time series. For example, myriad studies have used these methods to the identify the status of single species or ecosystem state, and to identify evidence of regime shifts in climate and biological time series (Rodionov, 2004; Kortsch *et al*., 2012; Möllmann and Diekmann, 2012; McMahon *et al*., 2015; Yonezaki *et al*., 2015; Jung *et al*., 2017; Furuichi *et al*., 2020; Goto *et al*., 2020; Nishijima *et al*., 2020). However, increased attention on understanding mechanisms driving ecosystem dynamics coupled with the desire to avoid large, abrupt changes in social–ecological systems has galvanized the development and application of tools to detect nonlinearities and thresholds in relationships between ecosystem components and human and environmental pressures.

The primary goal of TOR 3 was to summarize methods used to quantify nonlinearities and thresholds in pressure–response relationships in marine ecosystems, with an emphasis on the methodologies that we selected for the member country case studies presented in TOR 4. We also highlighted methods used for detecting thresholds in single time series and for identifying common trends in multivariate time series. This summary was not intended to be an exhaustive review of relevant methodologies. Instead, we aimed to provide a brief overview of methods that are commonly used in scientific literature, sometimes in multi-model frameworks, and are easily accessible (*e.g*., well documented, open-source R scripts) to a broad community of fisheries scientists across PICES member countries and beyond. A quick guide to the various methods discussed here and their key attributes are presents in Tables 4.1 and 4.2.

4.2 Identifying nonlinearities and thresholds in pressure–response relationships

4.2.1 Decision trees

Decision tree-based methods, including boosted regression trees, and random forest and gradient forest analyses have been increasingly used to model nonlinear relationships between pressures and ecological indicators and to identify thresholds in those relationships. These methods build on traditional regression and classification trees, which partition data into groups at specific split values to maximize group homogeneity, by using an ensemble approach to combine many single trees into a more powerful model. The ensemble methods differ with respect to how the single trees are aggregated and how the models are tuned (see Elith *et al*. (2008); Ellis *et al*. (2012)). However, the overall approach has substantially improved the accuracy and predictive performance of decision trees. One of the many advantages of these methods is that interactions between predictor variables and their effects on threshold locations are automatically handled (Elith *et al*., 2008). Some recent studies have used random forest and gradient forest analyses to identify the importance of human and environmental pressures on ecological indicators in marine systems and to detect ecosystem-level thresholds associated with those pressures (Large *et al*., 2015a; Samhouri *et al*., 2017; Tam *et al*., 2017; Boldt *et al*., 2021). Random forest analysis is useful for assessing the ability of multiple pressures to predict a single indicator and for quantifying possible shifts or thresholds in an indicator's response along pressure gradients. Gradient Forest Analysis, an extension of the random forest approach, can fit models to multiple indicators and pressures and identify the aggregate responses of the indicators to the pressures (Ellis *et al*., 2012). Gradient Forest is particularly useful for evaluating ecosystem-level thresholds as it detects thresholds in a multivariate context.

4.2.2 Generalized Additive Models and derivative analysis

Generalized Additive Models (GAM; Hastie and Tibshirani, 1986) are a tried-and-true method for identifying and characterizing nonlinear relationships between physical and biological pressures and ecosystem components. These relationships are captured through smooth non-parametric functions (*e.g*., splines) which allow for the flexible estimation of the functional forms of the relationship without knowing *a priori* what the functional forms might be. Within the past decade, several studies have combined GAM (or other nonlinear functions) with derivative analysis to detect thresholds in smoothed functions of ecological responses to single pressures (Fewster, 2000; Samhouri *et al*., 2010, 2017; Lindegren *et al*., 2012; Large *et al*., 2013, 2015b; Burthe *et al*., 2016; Tam *et al*., 2017; Boldt *et al*., 2021) and multiple pressures (Large *et al*., 2015a). For example, a threshold, or inflection point in the trajectory of a smoothed function, is delineated when the second derivative of the function changes sign. More specifically, the threshold point may be defined as the location where the second derivative is most different from zero and the threshold range is where the 95% confidence intervals of the second derivative are not equal to zero (Large *et al*., 2013; Samhouri *et al*., 2017). The detection and visualization of thresholds using GAMs and the derivative analysis is easily interpretable, which is a strong advantage of this method. However, the smoothed nature of GAM splines may underestimate phase shifts compared to the tree-based approaches above. GAMs and derivative analysis have also been used to detect nonlinearities and thresholds in single time series.

4.2.3 Threshold regression models / specified functional forms

Threshold regression models are similar to regression spline models (*e.g*., GAMs) in that they are capable of modeling nonlinearity in pressure–response relationships and detecting thresholds or change points. They are also easily interpretable and perhaps the most easily interpretable of all the threshold detection methods. Three common implementations of threshold regression models in R include the 'segmented' (Muggeo, 2008, 2022), 'strucchange' (Zeileis *et al*., 2019), and the 'chngpt' (Fong *et al*., 2017) packages, all of which take a fixed number of change points and a user-specified regression model or functional form, *e.g*., step, hinge, segmented. The chngpt package builds on the other packages by supporting models with interaction terms between predictors and providing confidence intervals around the estimates of change points to account for uncertainty (*e.g.*, Fong *et al*., 2017). In addition, a recent Bayesian implementation of threshold regression allows users to specify the functional form on a per-segment basis when there are multiple change points (mcp, Lindeløv, 2020). An example of how threshold regression models can be used to detect ecological thresholds for setting management targets in North Pacific marine ecosystems is illustrated by Samhouri *et al*. (2010, 2011) and Bestelmeyer *et al*. (2011).

4.2.4 Nonparametric multiplicative regression

Nonparametric multiplicative regression (NPMR) models are used to assess the relationships between an ecological response and multiple pressures. An advantage of this parameter-free method is that it can adapt to any type of response shape, including thresholds. Unlike the parametric regression models discussed above, specific shapes or shape families are not imposed *a priori* on data patterns; instead characterization of the response shape is guided by the data itself (Lintz *et al*., 2011; McCune, 2011). With respect to thresholds, NPMR models quantify the strength and diagonality of thresholds with multiple predictors in state space. The strength of the threshold is defined by the abruptness of the threshold in state space, and diagonality measures the degree to which the response shape is influenced by more than one predictor (Lintz *et al*., 2011; McCune 2011). NPMR models may also be used to estimate causality (Nicolau and Constandinou, 2016), which may help elucidate causal understanding of thresholds. One potential limitation of this method is that it cannot accurately capture discontinuous or cusp response surfaces, but only smooth functions between a response and predictor variables (Nicolau and Constandinou, 2016). This approach has been applied to habitat modeling and animal movement data. For example, Palacios *et al*. (2019) used this method to model the relationship between the movement behavior of blue whales and environmental variables.

4.3 Detecting thresholds in single time series

4.3.1 Change point analysis

Change point analysis is different from the models described above in that it only detects structural changes in single times along a time series or sequence. An advantage of change point analysis is that the number of change points does not need to be known *a priori*. One of the disadvantages is that it only provides point estimates of change points. Some studies have used the sequential t-test analysis of regime shifts (STARS) to detect abrupt shifts in climatology (Gardner and Sharp, 2007) and in marine ecosystems (Daskalov *et al*., 2007). STARS is a sequential algorithm that tests for regime shifts in the mean of individual time series and was developed by Rodionov (2004). This data-driven approach does not require an *a priori* hypothesized estimate of when a regime shift occurred, can be used on raw or standardized data, and may be able to detect regime shifts relatively early (Rodionov, 2004, 2015). Rodionov (2015, 2016) expanded this approach in the Sequential Regime Shift Detector (SRSD) software package. This package can be used to detect regime shifts in the mean and variance of individual time series and in the correlation coefficients of two variables. While STARS is not available as an R package, there are several R packages available to analyze change points (*e.g.*, changepoint, Killick and Eckley (2014); cpm, Ross (2015)).

4.4 Identifying common trends in multivariate time series

4.4.1 Dynamic Factor Analysis (DFA)

This dimension-reducing multivariate analysis identifies shared trends (common patterns) in a suite of indicators (*e.g.*, ecosystem response indicators), detects their relationship with explanatory variables (*e.g.*, pressures), and may be able to predict trends 2 to 3 years into the future (Zuur *et al.*, 2003). Limitations of DFA are that: 1) it is computer intensive, 2) does not address nonlinearities among the suite of indicators when looking for common trends, and 3) large numbers of time series or including covariates increases the complexity of the model and results can be difficult to interpret (Hasson and Heffernan, 2011). Some applications of this method in marine ecosystems include the detection of trends in the abundance of ichthyoplankton (Marshall *et al.*, 2019), zooplankton (Kimmel and Duffy-Anderson, 2020), fish stocks (Azevdo *et al.*, 2008) and community dynamics (Suryan *et al.*, 2021). In addition, a Bayesian implementation of DFA has been developed by Ward *et al.* (2019, 2021) that allows for the detection of rare or extreme events (Anderson *et al.*, 2017) and regime shifts in shared trends (Litzow *et al.*, 2020; Hunsicker *et al.*, 2022).

Table 4.1 A quick guide to various methods used to detect nonlinearities and thresholds in single and multivariate time series, and to identify common trends among environmental and ecological time series.

Methodology	**Purpose**	**Examples**
Regression/ Classification trees	Identify nonlinearities in pressure–response relationships (not limited to temporal time series) and threshold values in univariate responses to multiple pressures.	Elith *et al.*, 2008; Jouffray *et al.*, 2015
Decision-tree based ensemble methods	Detects thresholds in univariate and multivariate responses to multiple pressures.	Large *et al.*, 2015a; Samhouri *et al.*, 2017; Tam *et al.*, 2017; Boldt *et al.*, 2021
Generalized additive models	Identify nonlinearities in single time series and pressure–response relationships, determine the signs and forms of those relationships, and can include threshold formulation.	Ciannelli *et al.*, 2004; Llope *et al.*, 2011; Hunsicker *et al.*, 2016; Boldt *et al.*, 2018, https://saskiaotto.github.io/INDperform/
Derivative analysis	Determines sign and inflection point in single time series and pressure–response relationships.	Lindegren *et al.*, 2012; Large *et al.*, 2013, 2015b; Samhouri *et al.*, 2017; Boldt *et al.*, 2021
Threshold regression models / Specified functional forms	Identify nonlinearities in single time series and pressure–response relationships, as well as signs and forms of those relationships, and threshold values.	Samhouri *et al.*, 2010; Bestelmeyer *et al.*, 2011
Non-parametric multiplicative regression	Quantifies threshold strength and diagonality (measurable shape attributes of multi-dimensional thresholds).	Lintz *et al.*, 2011; McCune, 2011; Palacios *et al.*, 2019
Changepoint analysis	Threshold detection in single time series.	Rodionov, 2004 (STARS)
Dynamic Factor Analysis	Identifies common trends in multiple time series and detect relationships between time series and explanatory variables. Detects extreme events and regime shifts in common trends.	Zuur *et al.*, 2003; Tam *et al.*, 2017; Ward *et al.*, 2019; Boldt *et al.*, 2021

Table 4.2 Key attributes of methods used to detect thresholds in pressure–response relationships.

Attributes	**Specified functional forms**	**Threshold regression models**	**Generalized additive models**	**Derivative analyses**	**Non-parametric multiplicative regression**	**Gradient Forest Analysis**	**Random forest, boosted regression tree**
Unknown functional form / versatility	–	–	+	+	+	+	+
Multiple stressors	–	–	+	+	+	+	+
Multiple responses	–	–	–	–	–	+	–
Significance test	+	+	+	+	+	+	+
Requires long time series	–	+	+	+	+	–	–
Handles missing data	–	+	–	–	–	–	+
Handles interactions among pressures automatically	–	–	–	–	–	+	+
Easily interpretable	+	+	+	+	+	–	–

4.5 *Summary and Conclusions*

- We provided an overview of a suite of quantitative methods that are more commonly used to detect thresholds in pressure–response relationships in marine ecosystems, as well as methods to detect thresholds in single time series and common trends in multivariate time series.
- All of the methods reviewed here have advantages and drawbacks. For example, some can handle multiple pressures and multiple responses, but are not easily interpretable while others are easily interpretable, but require long time series and cannot handle missing data.
- There are additional advanced statistical methods for threshold detection that we did not review here because either 1) to the best of our knowledge there are no existing applications to marine ecosystems, or 2) the methodology (*e.g.*, R code) is not easily accessible.
- To address TOR 4, we selected Generalized Additive Models with derivative analysis, Gradient Forest Analysis, and Dynamic Factor Analysis for our working group activities. These analyses were selected because 1) the methods have been thoroughly vetted by ecologists and fisheries scientists, 2) multiple working group members had prior knowledge of and experience working with these methods, 3) the R code associated with the analyses are well documented and were readily available for our working group.

4.6 Literature Cited

Andersen, T., Carstensen, J., Hernández-García, E. and Duarte, C.M. 2009. Ecological thresholds and regime shifts: approaches to identification. *Trends in Ecology and Evolution* **24**: 49–57, doi: 10.1016/j.tree.2008.07.014.

Anderson, S.C., Branch, T.A., Cooper, A.B. and Dulvy, N.K. 2017. Black-swan events in animal populations. *Proceedings of the National Academy of Sciences of the United States of America* **114**: 3252–3257, https://doi.org/10.1073/pnas.1611525114.

Azevedo, M., Duarte, R., Cardador, F., Sousa, P., Fariña, C., Sampedro, P., Landa, J. and Costas, G. 2008. Application of dynamic factor analysis in the assessment of Iberian anglerfish stocks. *ICES Journal of Marine Science* **65**: 1362–1369, https://doi.org/10.1093/icesjms/fsn096.

Bestelmeyer, B.T., Ellison, A.M., Fraser, W.R., Gorman, K.B., Holbrook, S.J., Laney, C.M., Ohman, M.D., Peters, D.P.C., Pillsbury, F.C., Rassweiler, A., Schmitt, R.J. and Sharma, S. 2011. Analysis of abrupt transitions in ecological systems. *Ecosphere* **2**: art129–26, https://doi.org/10.1890/ES11-00216.1.

Boldt, J.L., Thompson, M., Rooper, C.N., Hay, D.E., Schweigert, J.F., Quinn II, T.J., Cleary, J.S. and Neville, C.M. 2018. Bottom-up and top-down control of small pelagic forage fish: factors affecting juvenile herring in the Strait of Georgia, British Columbia. *Marine Ecology Progress Series* **617-618**: 53–66, https://doi.org/10.3354/meps12485.

Boldt, J.L., Fu, C., Hazen, E., Hunsicker, M., Perry, R.I. and Xiujuan, S. 2021. Quantifying ecosystem responses to environmental and human pressures on the west coast of Vancouver Island. *Ecological Indicators* **132**: 108232, https://doi.org/10.1016/j.ecolind.2021.108232.

Burthe, S.J, Henrys, P.A., Mackay, E.B., Spears, B.M., Campbell, R., Carvalho, L., Dudley, B., Gunn, I.D.M., Johns, D.G., Maberly, S.C., May, L., Newell, M.A., Wanless, S., Winfield, I.J., Thackeray, S.J., Daunt, F. and Allen, C. 2016. Do early warning indicators consistently predict nonlinear change in long-term ecological data? *Journal of Applied Ecology* **53**: 666–676, https://doi.org/10.1111/1365-2664.12519.

Ciannelli, L., Chan, K.-S., Bailey, K.M. and Stenseth, N.C. 2004. Nonadditive effects of the environment on the survival of a large marine fish population. *Ecology* **85**: 3418–3427, https://doi.org/10.1890/03-0755.

Daskalov, G.M., Grishin, A.N., Rodionov, S. and Mihneva, V. 2007. Trophic cascades triggered by overfishing reveal possible mechanisms of ecosystem regime shifts. *Proceedings of the National Academy of Sciences of the United States of America* **104**: 10518–10523, https://doi.org/10.1073/pnas.0701100104.

Elith, J., Leathwick, J.R. and Hastie, T. 2008. A working guide to boosted regression trees. *Journal of Animal Ecology* **77**: 802–813, https://doi.org/10.1111/j.1365-2656.2008.01390.x.

Ellis, N., Smith, S.J. and Pitcher, C.R. 2012. Gradient forests: calculating importance gradients on physical predictors. *Ecology* **93**: 156–168, https://doi.org/10.1890/11-0252.1.

Fewster, R.M., Buckland, S.T., Siriwardena, G.M., Baillie, S.R. and Wilson, J.D. 2000. Analysis of population trends for farmland birds using generalized additive models. *Ecology* **81**: 1970–1984.

Fong, Y., Gilbert, P.B. and Permar, S.R. 2017. chngpt: threshold regression model estimation and inference. *BMC Bioinformatics* **18**: 454–454, https://doi.org/10.1186/s12859-017-1863-x.

Furuichi, S., Niino, Y., Kamimura, Y. and Yukami, R. 2020. Time-varying relationships between early growth rate and recruitment in Japanese sardine. *Fisheries Research* **232**: 105723, https://doi.org/10.1016/j.fishres.2020.105723.

Jouffray, J.-B., Nyström, M., Norström, A.V., Williams, I.D., Wedding, L.M., Kittinger, J.N. and Williams, G.J. 2015. Identifying multiple coral reef regimes and their drivers across the Hawaiian archipelago. *Philosophical Transactions of the Royal Society B* **370**: 1–8, https://doi.org/10.1098/rstb.2013.0268.

Gardner, A.S. and Sharp, M. 2007. Influence of the Arctic circumpolar vortex on the mass balance of Canadian high Arctic glaciers. *Journal of Climate* **20**: 4586–4598, https://doi.org/10.1175/JCLI4268.1.

Goto, T., and A. Takanashi. 2020. Changes in the strategy of a small-scale jigging fishery for Japanese flying squid *Todarodes pacificus* off northeastern Japan. *Fisheries Science* **86**: 1–11.

Hasson, C.J. and Heffernan, K.S. 2011. Dynamic factor analysis and the exercise sciences. *Pediatric Exercise Science* **23**: 17–22, https://doi.org/10.1123/pes.23.1.17.

Hastie, T.J. and Tibshirani, R. 1986. Generalized Additive Models. *Statistical Science* **1**: 297–310, https://doi.org/10.1214/ss/1177013604.

Hunsicker, M.E., Kappel, C.V., Selkoe, K.A., Halpern, B.S., Scarborough, C., Mease, L. and Amrhein, A. 2016. Characterizing driver–response relationships in marine pelagic ecosystems for improved ocean management. *Ecological Applications* **26**: 651–663, https://doi.org/10.1890/14-2200.

Hunsicker, M.E., Ward, E.J., Litzow, M.A., Anderson, S.C., Harvey, C.J., Field, J.C., Gao, J., Melin, S., Thompson, A.R. and Warzybok, P. 2022. Tracking and forecasting community responses to climate perturbations in the California Current Ecosystem. *PLOS Climate* **1**: e0000014, https://doi.org/10.1371/journal.pclm.0000014.

Jung, H.K., Rahman, S.M., Kang, C.-K., Park, S.-Y., Lee, S.H., Park, H.J., Kim, H.-W. and Lee, C.I. 2017. The influence of climate regime shifts on the marine environment and ecosystems in the East Asian Marginal Seas and their mechanisms. *Deep-Sea Research II* **143**: 110–120, https://doi.org/10.1016/j.dsr2.2017.06.010

Killick, R. and Eckley, I.A. 2014. Changepoint: An R package for changepoint analysis. *Journal of Statistical Software* **58**: 1–19, https://doi.org/10.18637/jss.v058.i03.

Kimmel, D.G. and Duffy-Anderson, J.T. 2020. Zooplankton abundance trends and patterns in Shelikof Strait, western Gulf of Alaska, USA, 1990–2017. *Journal of Plankton Research* **42**: 334–354, https://doi.org/10.1093/plankt/fbaa019.

Kortsch, S., Primicerio, R., Beuchel, F., Renaud, P.E., Rodrigues, J., Lønne, O.J. and Gulliksen, B. 2012. Climate-driven regime shifts in Arctic marine benthos. *Proceedings of the National Academy of Sciences of the United States of America* **109**: 14052–14057, https://doi.org/10.1073/pnas.1207509109.

Large, S.I., Fay, G., Friedland, K.D. and Link, J.S. 2013. Defining trends and thresholds in responses of ecological indicators to fishing and environmental pressures. *ICES Journal of Marine Science* **70**: 755–767, https://doi.org/10.1093/icesjms/fst067.

Large, S.I., Fay, G., Friedland, K.D. and Link, J.S. 2015a. Quantifying patterns of change in marine ecosystem response to multiple pressures. *PLoS ONE* **10**: e0119922, https://doi.org/10.1371/journal.pone.0119922.

Large, S.I., Fay, G., Friedland, K.D. and Link, J.S. 2015b. Critical points in ecosystem responses to fishing and environmental pressures. *Marine Ecology Progress Series* **521**: 1–17, https://doi.org/10.3354/meps11165.

Lindegren, M., Dakos, V., Groger, J., Gårdmark, A., Kornilovs, G., Otto, S. and Möllmann, C. 2012. Early detection of ecosystem regime shifts: A multiple method evaluation for management application. *PloS ONE* **7**: e38410, https://doi.org/10.1371/journal.pone.0038410.

Lindeløv, J.K. 2020. mcp: An R package for regression with multiple change points. https://doi.org/10.31219/osf.io/fzqxv.

Lintz, H.E., McCune, B., Gray, A.N. and McCulloh, K.A. 2011. Quantifying ecological thresholds from response surfaces. *Ecological Modelling* **222**: 427–436. https://doi.org/10.1016/j.ecolmodel.2010.10.017.

Litzow, M.A., Hunsicker, M.E., Ward, E.J., Anderson, S.C., Gao, J., Zador, S.G., Batten, S., Dressel, S.C., Duffy-Anderson, J., Fergusson, E., Hopcroft, R.R., Laurel, B.J. and O'Malley, R. 2020. Evaluating ecosystem change as Gulf of Alaska temperature exceeds the limits of preindustrial variability. *Progress in Oceanography* **186**: 102393, https://doi.org/10.1016/j.pocean.2020.102393.

Llope, M., Daskalov, G.M., Rouyer, T.A., Mihneva, V., Chan, K.-S., Grishin, A.N. and Stenseth, N.C. 2011. Overfishing of top predators eroded the resilience of the Black Sea system regardless of the climate and anthropogenic conditions. *Global Change Biology* **17**: 1251–1265, https://doi.org/10.1111/j.1365-2486.2010.02331.x.

Marshall, K.M., Duffy-Anderson, J.T., Ward, E.J., Anderson, S.C., Hunsicker, M.E. and Williams, B.C. 2019. Long-term trends in ichthyoplankton assemblage structure, biodiversity, and synchrony in the Gulf of Alaska and their relationships to climate. *Progress in Oceanography* **170**: 34–145, https://doi.org/10.1016/j.pocean.2018.11.002.

McCune, B. 2011. Nonparametric multiplicative regression for habitat modeling. Technical Report, Oregon State University, Corvallis, Oregon, USA, http://www.pcord.com/NPMRintro.pdf.

McMahon, K.M., McCarthy, M.D., Sherwood, O.A., Larsen, T. and Guilderson, T.P. 2015. Millennial-scale plankton regime shifts in the subtropical North Pacific Ocean. *Science* **350**: 1530–1533, https://doi.org/10.1126/science.aaa9942.

Möllmann, C. and Diekmann, R. 2012. Marine ecosystem regime shifts induced by climate and overfishing, pp. 303–347 *in:* Advances in Ecological Research *edited by* G. Woodard, Vol. 47, Elsevier Science and Technology, https://doi.org/10.1016/B978-0-12-398315-2.00004-1.

Muggeo, V.M.R. 2008. Segmented: An R package to fit regression models with broken-line relationships. *R News* **8/1**: 20–25.

Muggeo, V.M.R. 2022. https://cran.r-project.org/web/packages/segmented/segmented.pdf.

Nicolaou, T. and Constandinou, G. 2016. A nonlinear causality estimator based on non-parametric multiplicative regression. *Frontiers in Neuroinformatics* **10**: 19, https://doi.org/10.3389/fninf.2016.00019.

Nishijima, S., Kubota, H., Kaga, T., Okamoto, S., Miyahara H. and Okamura, H. 2020. State-space modeling clarifies productivity regime shifts of Japanese flying squid. *Population Ecology* **63**: 27–40, https://doi.org/10.1002/1438-390X.12062.

Palacios, D.M., Bailey, H., Becker, E.A., Bograd, S.J., DeAngelis, M.L., Forney, K.A., Hazen, E.L., Irvine, L.M. and Mate, B.R. 2019. Ecological correlates of blue whale movement behavior and its predictability in the California Current Ecosystem during the summer-fall feeding season. *Movement Ecology* **7**: 26–26, https://doi.org/10.1186/s40462-019-0164-6.

Rodionov, S.N. 2004. A sequential algorithm for testing climate regime shifts. *Geophysical Research Letters* **31**: L09204, https://doi.org/10.1029/2004GL019448.

Rodionov, S.N. 2015. A sequential method of detecting abrupt changes in the correlation coefficient and its application to Bering Sea climate. *Climate* **3**: 474–491, https://doi.org/10.3390/cli3030474.

Rodionov, S.N. 2016. A comparison of two methods for detecting abrupt changes in the variance of climatic time series. *Advances in Statistical Climatology, Meteorology and Oceanography* **2**: 63–78, https://doi.org/10.5194/ascmo-2-63-2016.

Ross, G.J. 2015. Parametric and nonparametric sequential change detection in R: The cpm package. *Journal of Statistical Software* **66**: 1–20, https://doi.org/10.18637/jss.v066.i03.

Samhouri, J.F., Levin, P.S. and Ainsworth, C.H. 2010. Identifying thresholds for ecosystem-based management. *PloS ONE* **5**: e8907–e8907, https://doi.org/10.1371/journal.pone.0008907.

Samhouri, J.F., Levin, P.S., James, C.A., Kershner, J. and Williams, G. 2011. Using existing scientific capacity to set targets for ecosystem-based management: A Puget Sound case study. *Marine Policy* **35**: 508–518, https://doi.org/10.1016/j.marpol.2010.12.002.

Samhouri, J.F., Andrews, K.S., Fay, G., Harvey, C.J., Hazen, E.L., Hennessey, S.M., Holsman, K., Hunsicker, M.E., Large, S.I., Marshall, K.N., Stier, A.C., Tam, J.C. and Zador, S.G. 2017. Defining ecosystem thresholds for human activities and environmental pressures in the California Current. *Ecosphere* **8**: e01860, https://doi.org/10.1002/ecs2.1860.

Suryan, R., Arimitsu, M.L., Coletti, H.A., Hopcroft, R.R., Lindeberg, M.R., Barbeaux, S.J., Batten, S.D., Burt, W.J., Bishop, M.A., Bodkin, J.L., Brenner, R., Campbell, R.W., Cushing, D.A., Danielson, S.L., Dorn, M.W., Drummond, B., Esler, D., Gelatt, T., Hanselman, D.H., Hatch, S.A., Haught, S., Holderied, K., Iken, K., Irons, D.B., Kettle, A.B., Kimmel, D.G., Konar, B., Kuletz, K.J., Laurel, B.J., Maniscalco, J.M., Matkin, C., McKinstry, C.A.E., Monson, D.H., Moran, J.R., Olsen, D., Palsson, W.A., Pegau, W.S., Piatt, J.F., Rogers, L.A., Rojek, N.A., Schaefer, A., Spies, I.B., Straley, J.M., Strom, S., Sweeney, K.L., Szymkowiak, M., Weitzman, B.P., Yasumiishi, E.M. and Zador, S.G. 2021. Ecosystem response persists after a prolonged marine heatwave. *Scientific Reports* **11**: 6235–6217, https://doi.org/10.1038/s41598-021-83818-5.

Tam, J.C., Link, J.S., Large, S.I., Andrews, K., Friedland, K.D., Gove, J., Hazen, E., Holsman, K., Karnauskas, M., Samhouri, J.F., Shuford, R., Tomilieri, N. and Zador S. 2017. Comparing apples to oranges: Common trends and thresholds in anthropogenic and environmental pressures across multiple marine ecosystems. *Frontiers in Marine Science* **4**: 282, https://doi.org/10.3389/fmars.2017.00282.

Ward, E.J., Anderson, S.C., Daminano, L.A., Hunsicker, M.E. and Litzow, M.A. 2019. Modeling regimes with extremes: the bayesdfa package for identifying and forecasting common trends and anomalies in multivariate time-series data. *The R Journal* **11**: 46–55.

Ward, E.J., Anderson, S.C., Hunsicker, M.E. and Litzow, M.A. 2021. Smoothed dynamic factor analysis for identifying trends in multivariate time series. *Methods in Ecology and Evolution* **13**: 908–918, https://doi.org/10.1111/2041-210X.13788.

Yonezaki, S., Kiyota, M. and Okamura, H. 2015. Long-term ecosystem change in the western North Pacific inferred from commercial fisheries and top predator diet. *Deep Sea Research II* **113**: 91–101, https://doi.org/10.1016/j.dsr2.2014.10.027.

Zeileis, A., Friedrich, L., Hornik, K., Kleiber, C., Hansen, B., Merkle, E.C. and Umlauf, N. 2019. https://cran.r-project.org/web/packages/strucchange/strucchange.pdf.

Zuur, A.F., Tuck, I.D. and Bailey, N. 2003. Dynamic factor analysis to estimate common trends in fisheries time series. *Canadian Journal of Fisheries and Aquatic Sciences* **60**: 542–552, https://doi.org/10.1139/f03-03.

5 Identifying Shapes or Functional Forms of Pressure–Response Relationships from Available Datasets, and Quantifying Thresholds to Identify Potential Ecosystem Reference Points

5.1 Introduction

Coastal ocean ecosystems are increasingly vulnerable to the impacts of a rapidly changing climate coupled with an expansion of anthropogenic activities. To sustainably manage targeted fish populations and broader ecosystem components in the face of ocean change, there is a pressing need for information that can help resource managers and stakeholders better anticipate the response of marine organisms to climate perturbations and anthropogenic pressures (Mason *et al*., 2022). Such knowledge could improve decision making in a manner that reduces the potential for ecological surprises, socio-economic hardship, and irreversible shifts in ecosystem structure and function.

Understanding the functional forms or shapes of the relationships between climate and human pressures and ecosystem components is key for anticipating ecological responses and for identifying appropriate management strategies (Selkoe *et al*., 2015). For example, strong nonlinear relationships, where a small incremental change in a pressure elicits a disproportionately large response, could result in abrupt, unintended outcomes that are difficult to reverse (Liu *et al*., 2007; deYoung *et al*., 2008). Often these relationships have quantifiable thresholds (*i.e*., inflection points, Large *et al*., 2013; Samhouri *et al*., 2017) which indicate where there is potential for abrupt change in an ecological response along the continuum of a pressure level. Such thresholds could be applied within management frameworks as ecosystem reference points for avoiding nonlinear change and for informing a broader, more holistic picture of ecosystem conditions for decision making. Knowledge of strong linear responses between pressures and ecological responses is also useful for understanding ecosystem dynamics and for decision making in coastal systems. However, there are less ecological and socio-economic risks associated with incremental changes in pressure levels when pressure–response relationships are linear than when the relationships are nonlinear with threshold dynamics.

To advance knowledge of ecosystem reference points in PICES member countries, WG 36 was tasked with TOR 4 to 1) identify the status and trends of key climate and biological variables in member country coastal ecosystems, 2) characterize key pressure–response relationships using those variables, and 3) determine whether there is evidence of ecosystem thresholds in the pressure–response relationships examined. Each member country analyses or 'case study' differed, based on data availability and previous studies conducted in those systems, and not every member country was able to complete the proposed tasks for this TOR. Here, we present case studies for waters on the west coast of Vancouver Island (WCVI) that fall within the northern area of Region 11 (Canada), waters around the Shiretoko Peninsula, Hokkaido in Regions 17 and 18 (Japan), waters around the Korean Peninsula in

Regions 19, 20, and 21 (Korea), the Primorskiy kray in the Russian continental EEZ in Region 19 (Russia), and waters off the U.S. west coast (California, Oregon, Washington) that fall within the southern area of Region 11 (U.S.A.).

5.2 Methods

A description of the indicators of environmental, human, and ecosystem pressures used in each case study is presented in TOR 2. To identify ecosystem status and trends, multivariate Dynamic Factor Analyses (DFA; Holmes *et al*., 2012) were applied to time series to identify common trends among the different sets of the environmental, anthropogenic, and ecosystem indicators. Gradient Forest Analyses (Ellis *et al*., 2012) were used to identify important environmental and human pressures on ecosystem responses and thresholds. Generalized Additive Models (GAMs; Hastie and Tibshirani, 1990) were used to examine single pressure–response relationships (environmental and human pressures of ecosystem responses) for nonlinearities and thresholds, following methods of Large *et al*. (2013) and Samhouri *et al*. (2017). The specific location and range of a threshold (inflection point) were determined, based on the second derivative of the GAM smoother. The R scripts used for all these analyses can be accessed *via* the GitHub repository (https://github.com/elhazen/WG-36).

5.3 Results

5.3.1 Canada

Status and trends

As presented in Boldt *et al*. (2021), ecosystem indicators for the WCVI showed varying trends during 1986–2017 (Fig. 5.1); the most notable trends were increases in small mesh multi-species survey biomass, total landings, and Steller sea lions over the time series, as well as declines in subarctic copepods since the 1990s, and declines in the trophic level of the catch from the early 2000s to approximately 2012. Trends in landings and trophic level of landings were likely driven in part by changes in biomass but also by management actions. Multivariate DFA reduced these to three trends: one for environmental, one for human, and one for ecosystem indicators (Fig. 5.1); model fits to most, but not all, time series were good.

Pressure–response relationship and ecosystem thresholds

In single pressure–response models, five pressure–response relationships were linear and four were nonlinear (identified using GAMs). Nonlinearities were between 1) the proportion of predatory fish and the PDO, 2) southern copepod biomass anomalies and the PDO, 3) trophic level of the surveyed community and the PDO, and 4) the boreal copepod biomass anomalies and spring transition timing (Fig. 5.2). Gradient Forest Analysis highlighted three important environmental pressures that may be associated with ecosystem thresholds (nonlinearities): PDO, spring transition timing, and sea surface temperature (Fig. 5.3). Further exploration of results from DFA and Gradient Forest Analysis will clarify important pressure–response relationships (see Boldt *et al*. (2021)). For example, the relationships among DFA trends will be important to explore. In future analyses, non-stationarity of relationships will have to be considered.

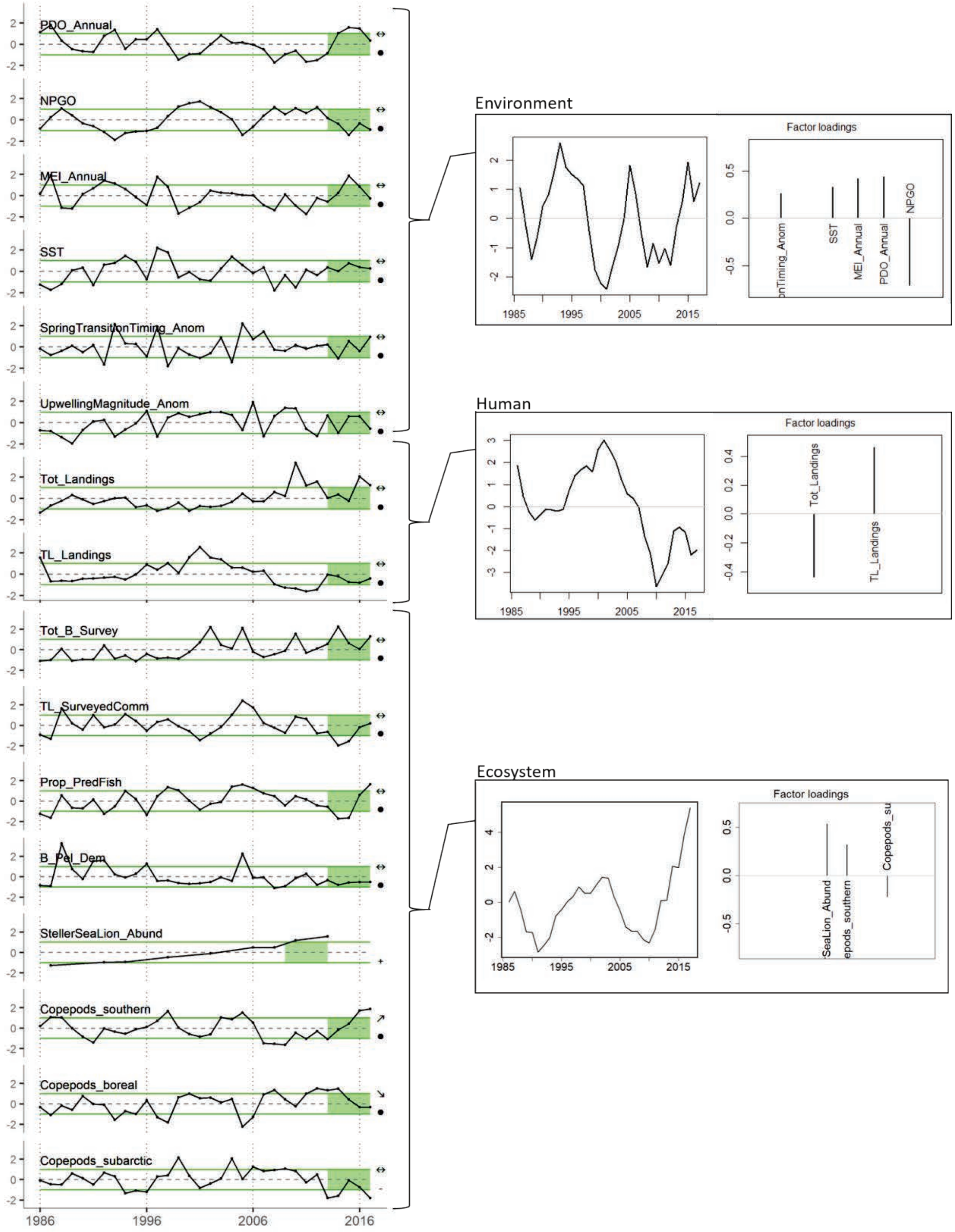


Fig. 5.1 Time series anomalies of indicators of environmental and human pressures (left column, top 8 plots) and ecosystem responses (left column, bottom 8 plots), trends identified from these indicators using Dynamic Factor Analyses (DFA; right column, left hand plots), and factor loadings on trends (right column, right hand plots; factor loadings > 0.2 are displayed) for the west coast of Vancouver Island. See Table 3.1 for indicator abbreviations. Green shaded areas represent the last five years of the time series and the green horizontal lines are plus and minus one standard deviation. Adapted from Boldt *et al.* (2021). Reproduced with permission of Creative Commons.

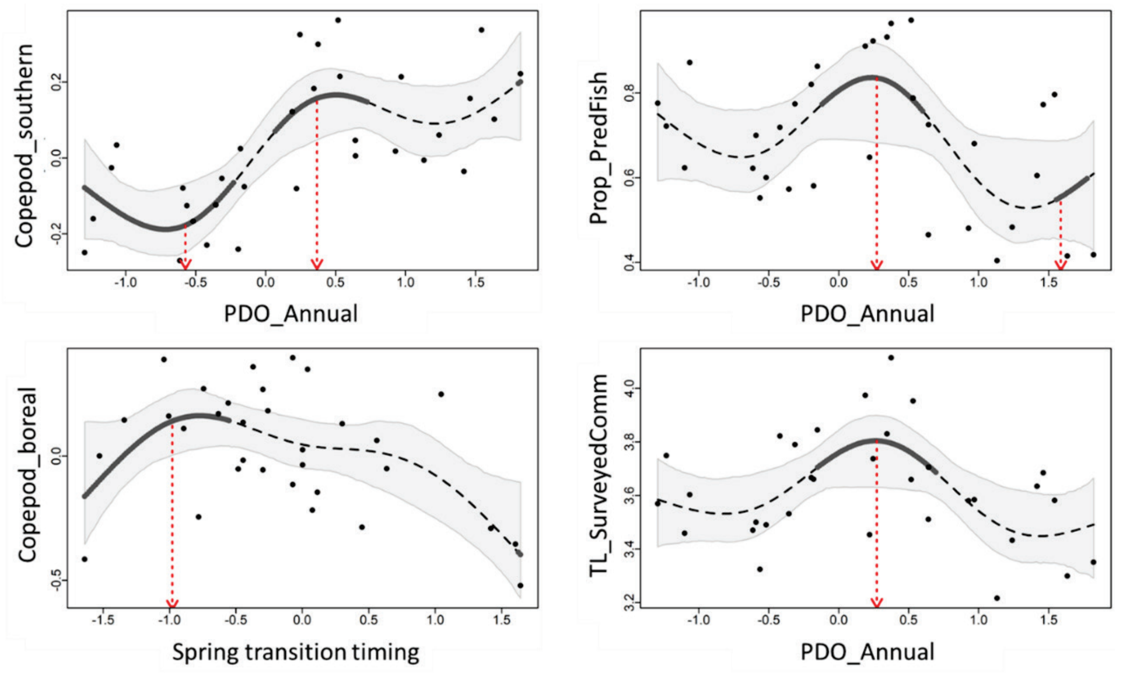


Fig. 5.2 Nonlinear relationships between environmental pressures and responses identified with General Additive Models (GAMs). Dashed line is the GAM smoother, gray shaded area is the 95% confidence interval (CI), black points are raw data, thick solid line is the threshold range where the 95% CI of the first derivative of the GAM smoother line does not include 0, and red dotted arrow indicates the best estimate of the threshold locations (*i.e.*, where the second derivative is at its absolute maximum value within the threshold range). See Samhouri *et al.* (2017) for method details. From Boldt *et al.* (2021). Reproduced with permission of Creative Commons.

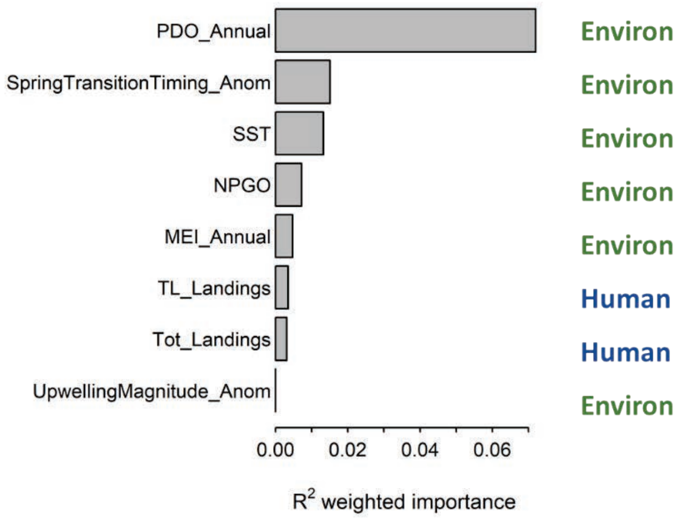


Fig. 5.3 Important environmental and human pressures of ecosystem responses identified with Gradient Forest Analysis. Adapted from Boldt *et al.* (2021). Reproduced with permission of Creative Commons.

5.3.2 China

Analyses for China’s case study are in progress.

5.3.3 Japan

Status and trends

With respect to human pressures, a common linear trend was extracted (Trend 1 in Figure 5.4A). The catches of walleye pollock and ocean salmonids had a decreasing trend that responded positively to Trend 1 while the catches of yellowtail had an increasing trend that responded negatively to Trend 1. However, the catch of common squid had low correlation with Trend 1 (absolute value of factor loadings < 0.2). Here, the number of captured Steller sea lions was not used in the final analysis.

For environmental pressures, a common linear trend was extracted (Trend 1 in Fig. 5.4 B). The spring and summer SST had an increasing trend that responded positively to Trend 1. However, the SST in the autumn season had low correlation with Trend 1 (the absolute value of factor loadings < 0.2). Therefore, these results emphasize that change of the SST in spring and summer were remarkable from 2006 to 2018 in waters around the Shiretoko Peninsula. Here, observation buoy data for the velocity and direction of currents were not used in the final analysis, as significant trends could not be extracted due to lack of observation data after 2015.

Analysis of ecosystem responses indicate that Steller sea lion abundance and migrating population of common squid in waters around the Shiretoko Peninsula had a common unimodal trend with a peak in 2011 (Trend 1 in Figure 5.4C), while migrating populations of walleye pollock, chum salmon and yellowtail had low correlation with Trend 1 (the absolute value of factor loadings < 0.2). Goto *et al*. (2017) reported that Steller sea lions rarely preyed on common squid in the waters around the Shiretoko Peninsula. Therefore, the extracted trends are considered to be pseudo-correlations. However, this unimodal trend was similar to the trend of the catch of octopus (*Octopus dolfleini*) in the Nemuro Straits from 2006 to 2014 (Marine Net Hokkaido, 2021). Thus, additional data on food sources for Steller sea lions such as octopus, Pacific cod (*Gadus macrocephalus*) and Okhotsk Atka mackerel (*Pleurogrammus azonus*) are necessary to refine analysis results. In addition, it should be noted the data used as an indicator of the abundance of Steller sea lions in the Nemuro Straits as below: 1) is the annual maximum value of the number of individuals by visual count from land in the season (not the annual average value) and 2) is limited to the period from 2006 to 2016.

When comparing the trends extracted by DFA, a common pattern was observed between Trend 1 for human pressures (increasing/decreasing catches of walleye pollock, chum salmon and yellowtail) and Trend 1 for environmental pressures (increasing the SST in spring and summer). This result suggests that there were certain relationships between the trend for human pressures (fish catch) and the trend for environmental pressures (SST). However, the trend in ecosystem responses had no relationship to the trend for environmental pressures (increasing SST). This result emphasizes that additional data for environmental pressures are needed to explain the relationship to the unimodal trend for ecosystem states.

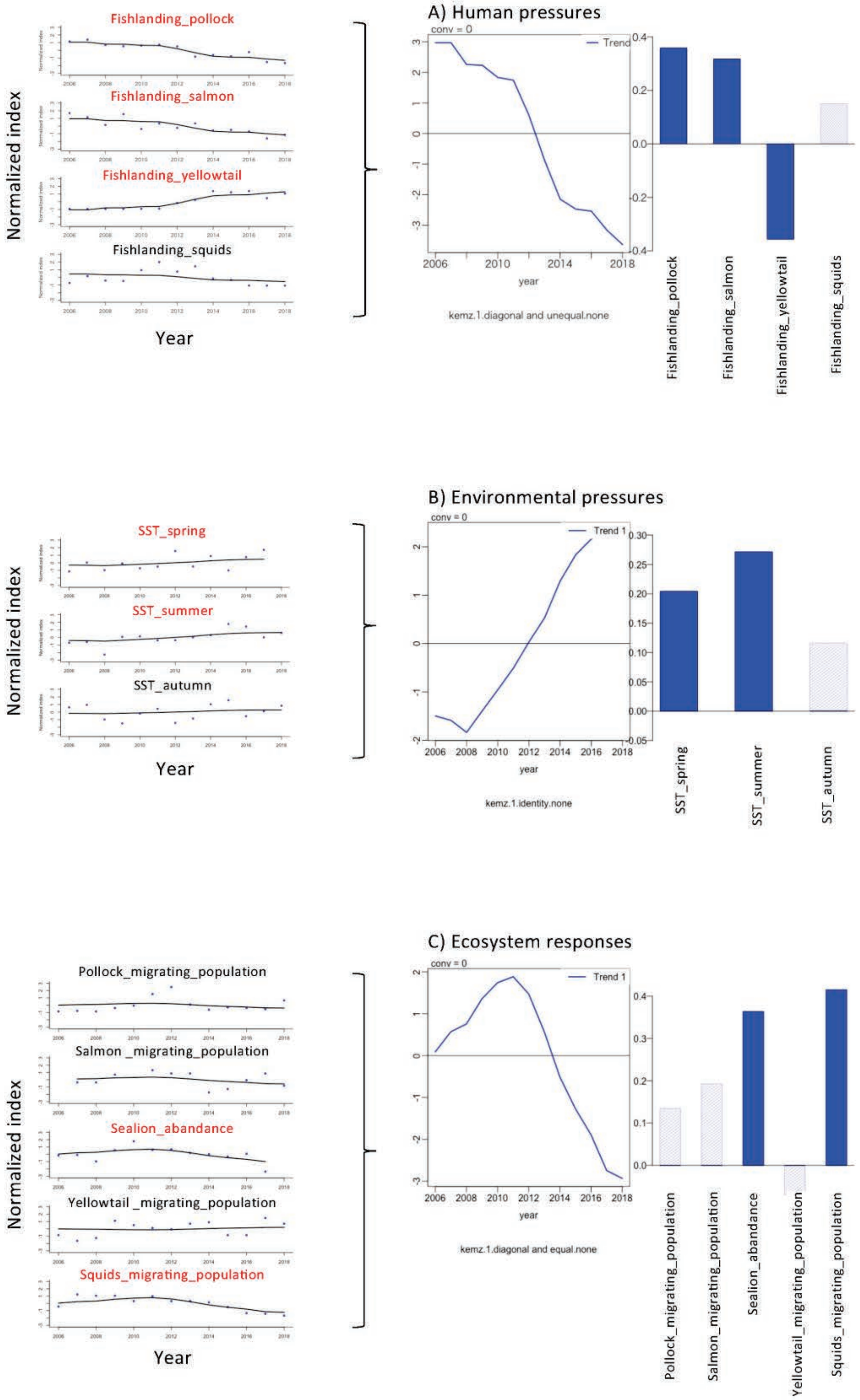


Fig. 5.4 Time series changes of indicators of human and environmental pressures, and ecosystem responses (left column) and trends and factor loadings identified from these indicators with multivariate Dynamic Factor Analyses (DFA, right column) for marine waters around the Shiretoko Peninsula. The indicators in red mean that an absolute value of factor loadings is more than 0.2.

Implications of trends

In this study, one trend for human pressures and one trend for each environmental pressure and ecosystem response were extracted from the long-term monitoring data for waters around the Shiretoko Peninsula, accumulated by the Shiretoko Data Center. Among the three trends, two were linear while another was non-linear, with a peak in 2011. These results suggest that indicators in the Multiple Use Integrated Marine Management Plan for the Shiretoko WNH Site were effective in monitoring trends for human and ecological pressures and ecosystem responses in marine areas around the Shiretoko Peninsula.

However, local SST data of the observation buoys for environmental pressure indicators could not capture the unimodal trend for ecosystem responses. Kuroda *et al*. (2020) has reported that seasonal trends of SSTs changed around Japan in the mid-2010s. This suggests that the SST dataset for this analysis does not grasp the trend of ecosystem responses due to different spatial scales. Therefore, it is necessary to define the spatial scale for the analysis, then obtain additional oceanographic data (*e.g*., chlorophyll, salinity, current velocity and direction, *etc*.) using resources such as satellite images, oceanographic models, and observation buoys. This study has focused on only four fish species and one sea mammal as ecosystem response indicators. In order to refine this research, additional data on food sources for Steller sea lions are necessary.

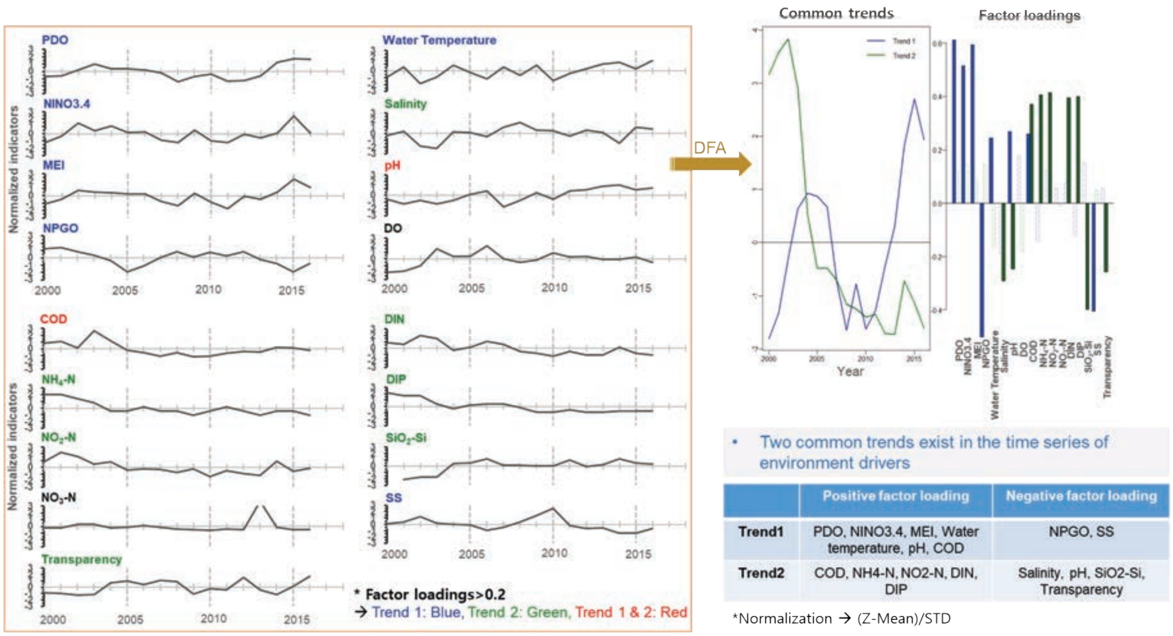
5.3.4 Korea

Status and trends

Environment indicators for the coastal seas around the Korean Peninsula show two common trends during 2000–2016 (Fig. 5.5). The first common trend (Trend 1) shows an increase until 2004, followed by a decrease until 2010, and a sharp increase after 2010. PDO, NINO3.4, and MEI series were predominantly determined by Trend 1 (Fig. 5.5). On the other hand, NPGO shows an opposite response in Trend 1. The second common trend (Trend 2) shows a sharp decrease during 2002–2016. Temporal variations of nutrients such as NH_4-N, NO_2-N, DIN, and DIP were mostly determined by the Trend 2. However, SiO_2-Si shows an opposite response to Trend 2. COD time-series were commonly associated with the two trends.

For human pressures, the catches of squid have decreased since 2002 (with positive loadings for Trend 1 in Fig. 5.6), whereas the catches of crab and croaker have increased (with negative loadings for Trend 1). The catches of anchovy and eels and the total ship tonnage increased until 2013 and have remained constant. The catches of mysid shrimp are associated with Trends 1 and 2.

To extract common trends from ecosystem indicators, we compiled time series data of chlorophyll-a concentrations, individual numbers of copepods, euphausiids, chordates, *Notiluca*, and total wet weight of zooplankton. One common trend was extracted from the time series of ecosystem indicators (Trend 1 in Fig. 5.7). In particular, time series of copepods, euphausiids, and chordates were predominantly determined by Trend 1. However, it should be noted that the temporal trend is only valid during the period of 2010–2016 due to the limitation of zooplankton data before 2010.



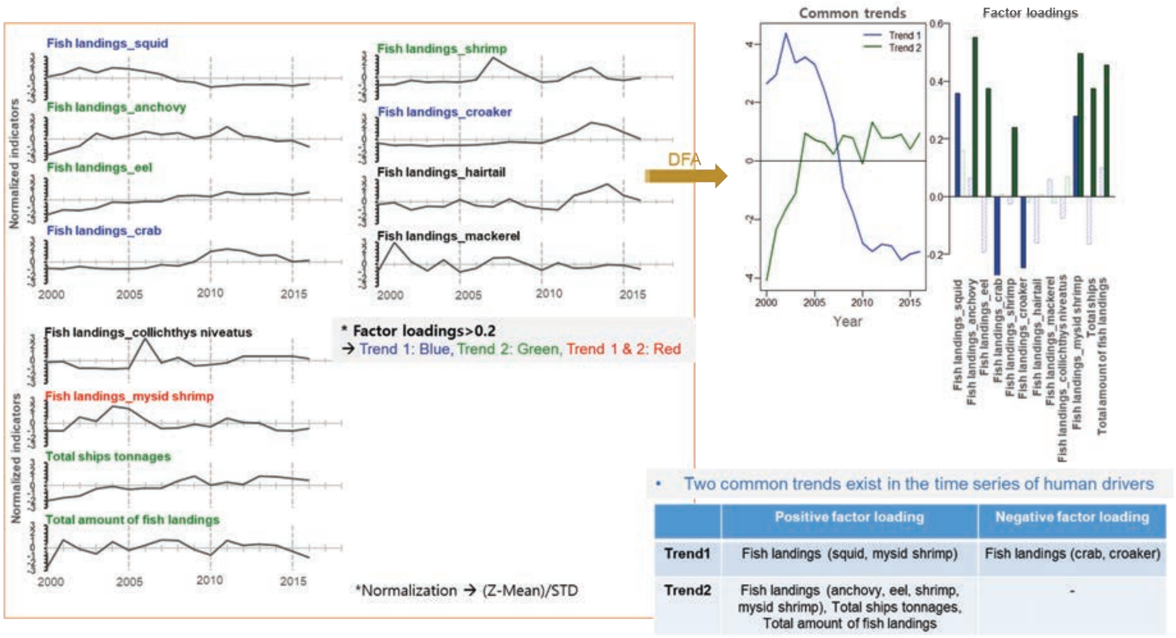
* Factor loadings>0.2
→ Trend 1: Blue, Trend 2: Green, Trend 1 & 2: Red

- Two common trends exist in the time series of environment drivers

	Positive factor loading	Negative factor loading
Trend1	PDO, NINO3.4, MEI, Water temperature, pH, COD	NPGO, SS
Trend2	COD, NH4-N, NO2-N, DIN, DIP	Salinity, pH, SiO2-Si, Transparency

*Normalization → (Z-Mean)/STD

Fig. 5.5 Temporal variations of 17 environmental pressures (left) and trends and factor loadings (right) extracted by multivariate Dynamic Factor Analyses (DFA) for the seas around the Korean Peninsula. Table in the lower right corner shows environmental pressures > 0.2 of positive or negative factor loadings in each trend.



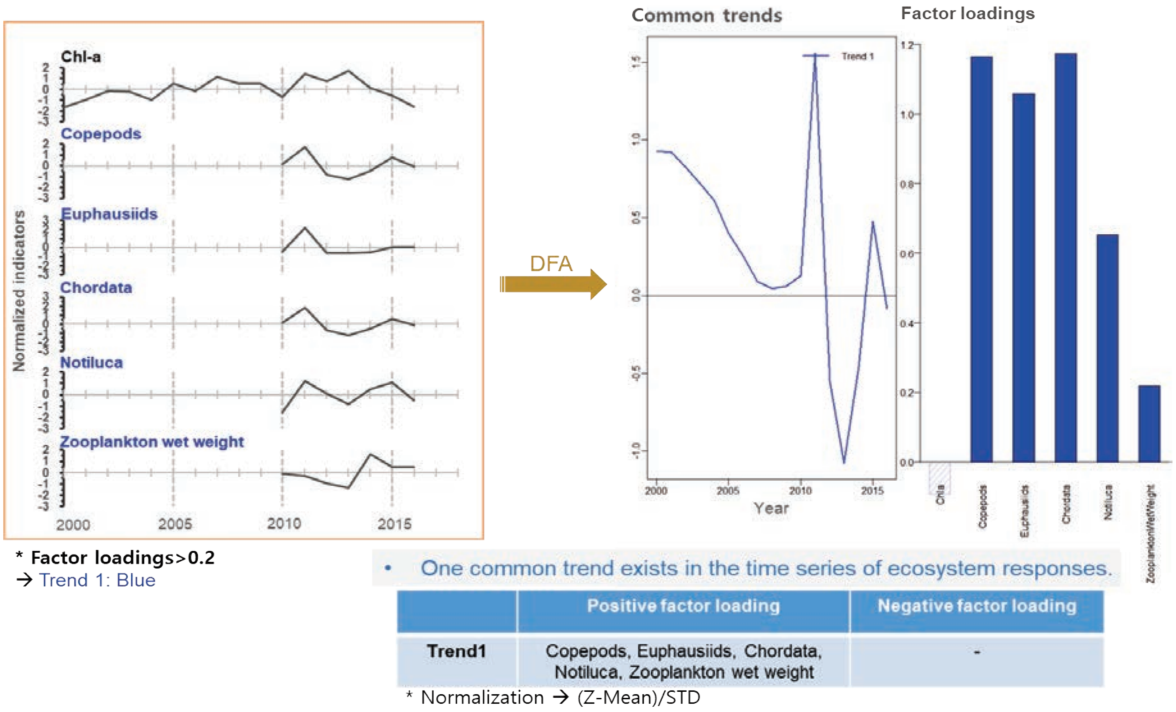
* Factor loadings>0.2
→ Trend 1: Blue, Trend 2: Green, Trend 1 & 2: Red

*Normalization → (Z-Mean)/STD

- Two common trends exist in the time series of human drivers

	Positive factor loading	Negative factor loading
Trend1	Fish landings (squid, mysid shrimp)	Fish landings (crab, croaker)
Trend2	Fish landings (anchovy, eel, shrimp, mysid shrimp), Total ships tonnages, Total amount of fish landings	-

Fig. 5.6 Temporal variations of 12 human pressures (left) and trends and factor loadings (right) extracted by multivariate Dynamic Factor Analyses (DFA) for the seas around the Korean Peninsula. Table in lower right corner shows human pressures > 0.2 of positive or negative factor loadings in each trend.



* Factor loadings>0.2
→ Trend 1: Blue

- One common trend exists in the time series of ecosystem responses.

	Positive factor loading	Negative factor loading
Trend1	Copepods, Euphausiids, Chordata, Notiluca, Zooplankton wet weight	-

* Normalization → (Z-Mean)/STD

Fig. 5.7 Temporal variations of 6 ecosystem response indicators (left) and a trend and factor loadings (right) extracted by multivariate Dynamic Factor Analyses (DFA) for the seas around the Korean Peninsula. Table in lower right corner shows ecosystem response indicators > 0.2 of positive factor loadings in Trend 1.

Implications of trends

Application of DFA to the environmental, human, and ecosystem indicators for the coastal sea around Korean Peninsula identified five trends: two for environmental pressures, two for human pressures, and one for ecosystem response indicators (Figs 5.5– 5.7). Especially, the second trend (Trend 2) for the environment indicators (NH_4-N, NO_2-N, DIN, DIP, COD) was significantly correlated with the first and second trend for human indicators of fishery landings (squid, mysid shrimp, crab, croaker, anchovy, eel, shrimp) and the first trend for ecosystem indicators (copepods, euphausiids, and chordates) (Table 5.1). These close correlations among the trends for the environmental, human, and ecosystem indicators suggest that there is some evidence of structural or functional relationships between pressures and responses in the seas around the Korean Peninsula.

Table 5.1 Pearson correlation coefficients between two trends of environmental (ENV) and human (HUM) pressures and ecosystem response (ECO) indicators.

	Trend 1 (ENV)	Trend 2 (ENV)	Trend 1 (HUM)	Trend 2 (HUM)	Trend 1 (ECO)
Trend 1 (ENV)	1	–0.22	–0.15	0.40	–0.27
Trend 2 (ENV)	–0.22	1	**0.78***	**–0.86***	**0.57***
Trend 1 (HUM)	–0.15	**0.78***	1	**–0.55***	**0.49***
Trend 2 (HUM)	0.40	**–0.86***	**–0.55***	1	–0.44
Trend 1 (ECO)	–0.27	**0.57***	**0.49***	–0.44	1

***** Bold values denote that the correlation is significant ($p < 0.05$).

5.3.5 Russia

With regard to other methods of research of multivariate environmental times series observations suggested by WG 36, we took the liberty of exploring changes in the mean annual Trophic Level (TL) and Mean Trophic Index (MTI) changes in connection with top species fishery catches. Preliminary analyses of changes in TL and MTI as response variables and catches as pressures showed that shifting time series against each other to account for time lag in effects of catch increases explained the variance in GAMs, *e.g.*, a 3-year lag led to maximal cross-correlation and made the relation non-linear (Fig. 5.8), but the absence of lags made the same relation linear and we could not extract a threshold from it as it is supposed in the R script developed for WG 36.

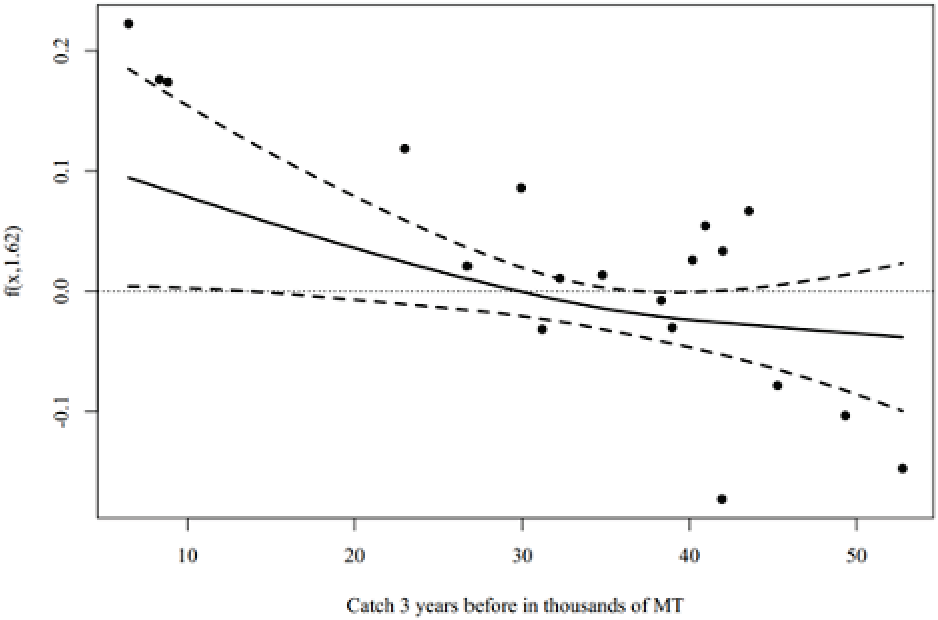


Fig. 5.8 Thin plate regression spline over centered with 4.18 intercept in Generalized Additive Mixed Models for Trophic Level (TL) dependence from catches 3 years before (*i.e.*, 3-year time lag) in the Russian Exclusive Economic Zone (EEZ) in Region 19.

We selected the Primorye fishing zone (Russian continental EEZ in Region 19) for further research because it had the strongest linear decrease of MTI and TL in the timeframe of NPESR3, between 2011 and 2016 (Fig. 5.9). Moreover, it was the only place where we could clearly see a bell-shaped trace plot between mean TL and the catches (Fig. 5.10).

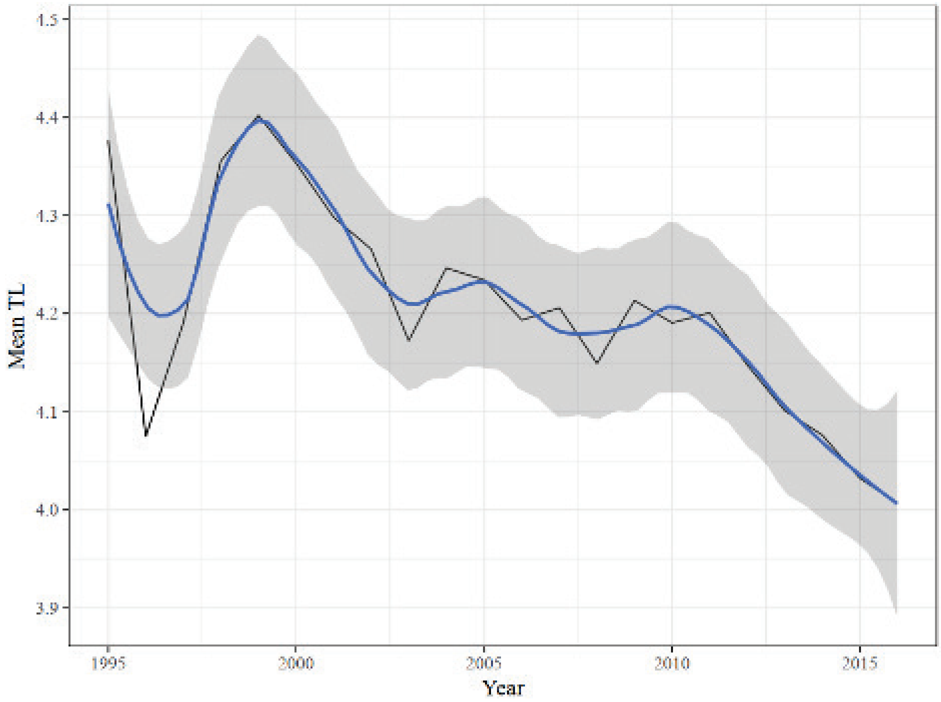


Fig. 5.9 Mean annual Trophic Level (TL) of catches in the Russian part of Region 19.

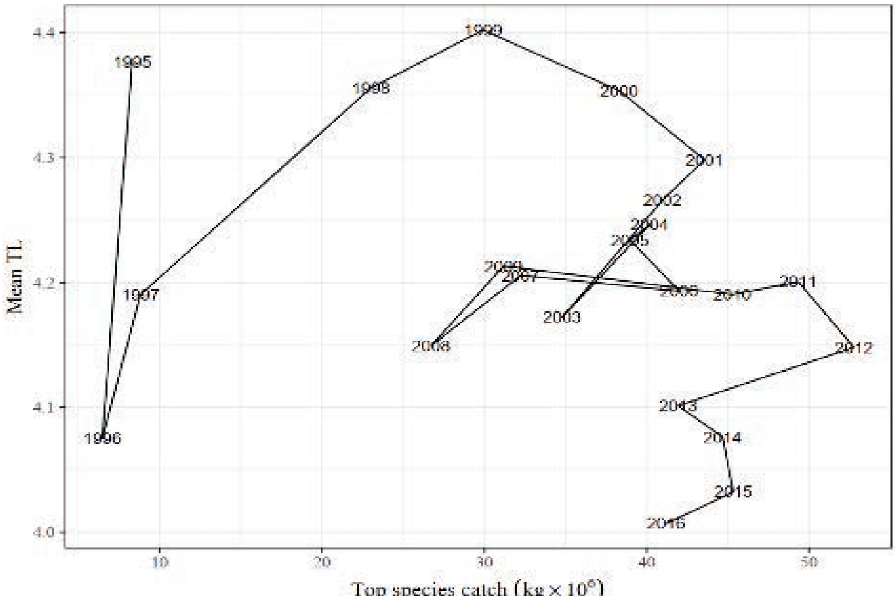


Fig. 5.10 Mean Trophic Levels (TLs) *vs* the catches in the Russian part of Region 19.

Following the examples provided with the source code for R prepared for WG 36, we tested catches in the Russian part of Region 19 against TL and MTI. Methods of extracting tipping points from GAM could not find the threshold in the relation between TL and catches because it was linear. However, Gradient Forest was tuned without errors. Some of the results are shown in Figures 5.11–5.16) using abbreviations from the Cornell Ecology Program (R package rioja version 0.9-15.2) for species names. A weighted importance plot (Fig. 5.11) confirmed our previous results from Principal Component Analyses (see NPSER3) that changes in TL and MTI were positively related to the catch variation of Okhotsk Atka mackerel (*Pleurogrammus azonus* Jordan and Metz, 1913), which had high trophic level 4.9 as a main fishing target in the Hexagrammidae family. In the opposite low trophic level, species such as shrimps decreased TL and MTI when their catches were high. Recently (in the second decade of the 21st century), the catch of another carnivorous fish, the Pacific cod (*Gadus macrocephalus*), began to increase and we expect that TL and MTI will return back to the average level. Unfortunately, that new data were not included in the analyses, but we will follow the suggested methods by WG 36 in the near future and will extend pressures and responses with other sources other than just catches and TL. Thus, we found that development of R scripts by WG 36 were very useful for us to begin research to include more stressors and indicators using modern methods.

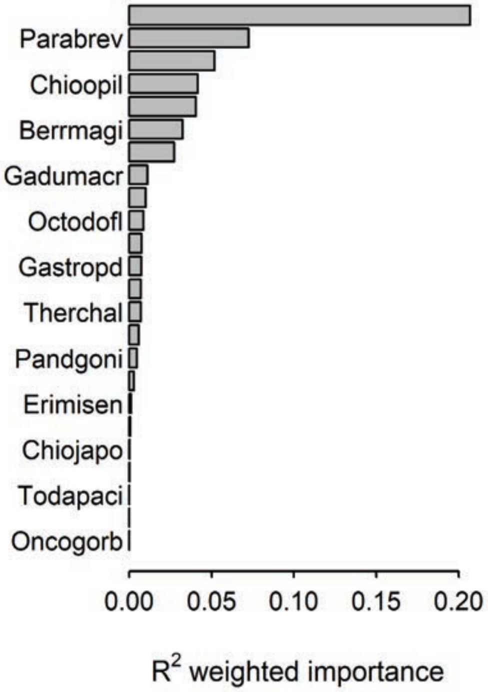


Fig. 5.11 Weighted importance of catches on changes in Trophic Level (TL) and Mean Trophic Index (MTI). Top 3 are Hexagrammidae fish (mainly Okhotsk Atka mackerel), *Paralithodes brevipes* and Pacific herring (*Clupea pallasii*).

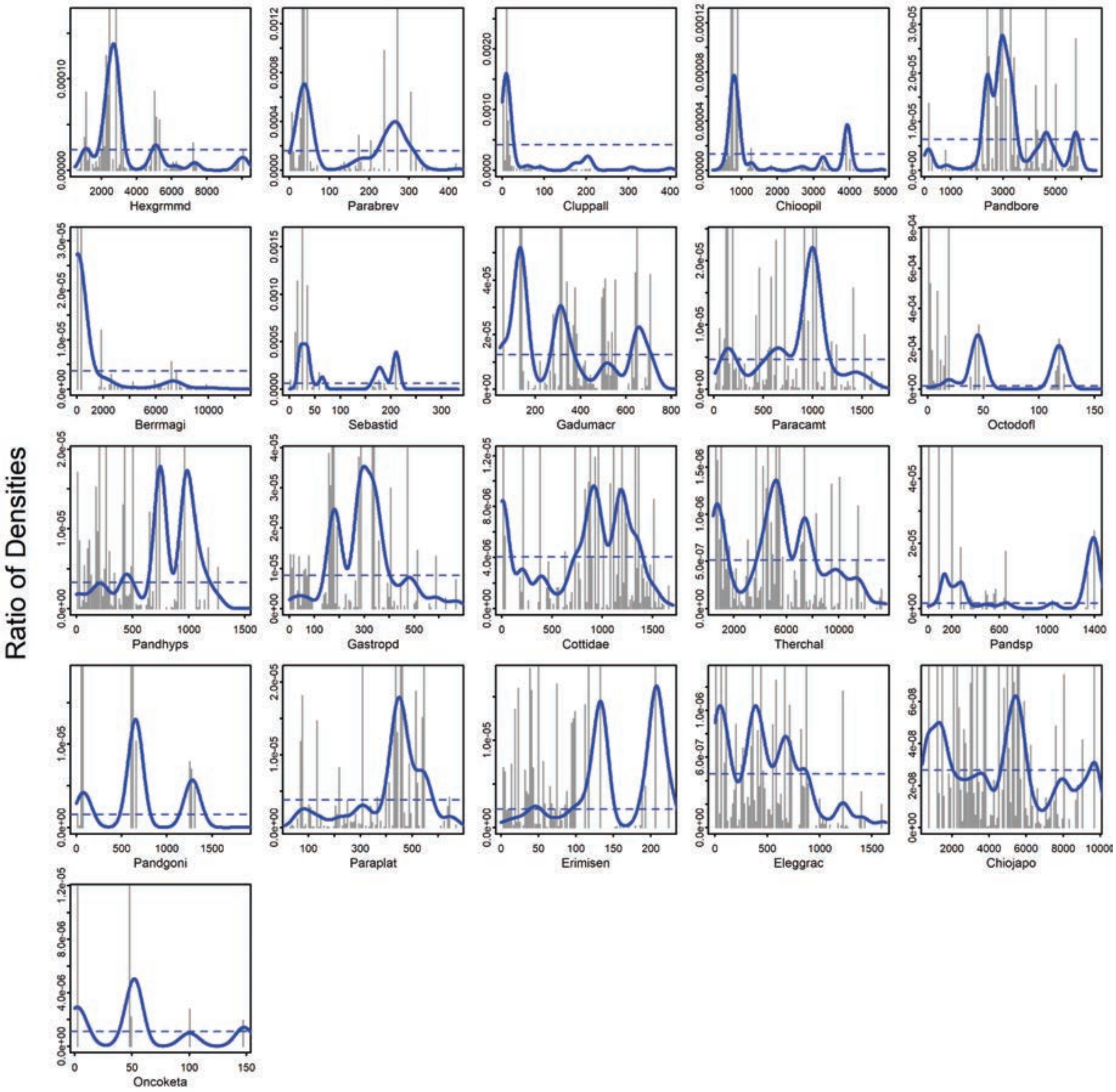


Fig. 5.12 Estimated importance computed as the ratio of importance density to predictor value density (blue line), with the horizontal dashed line indicating where the ratio is 1.

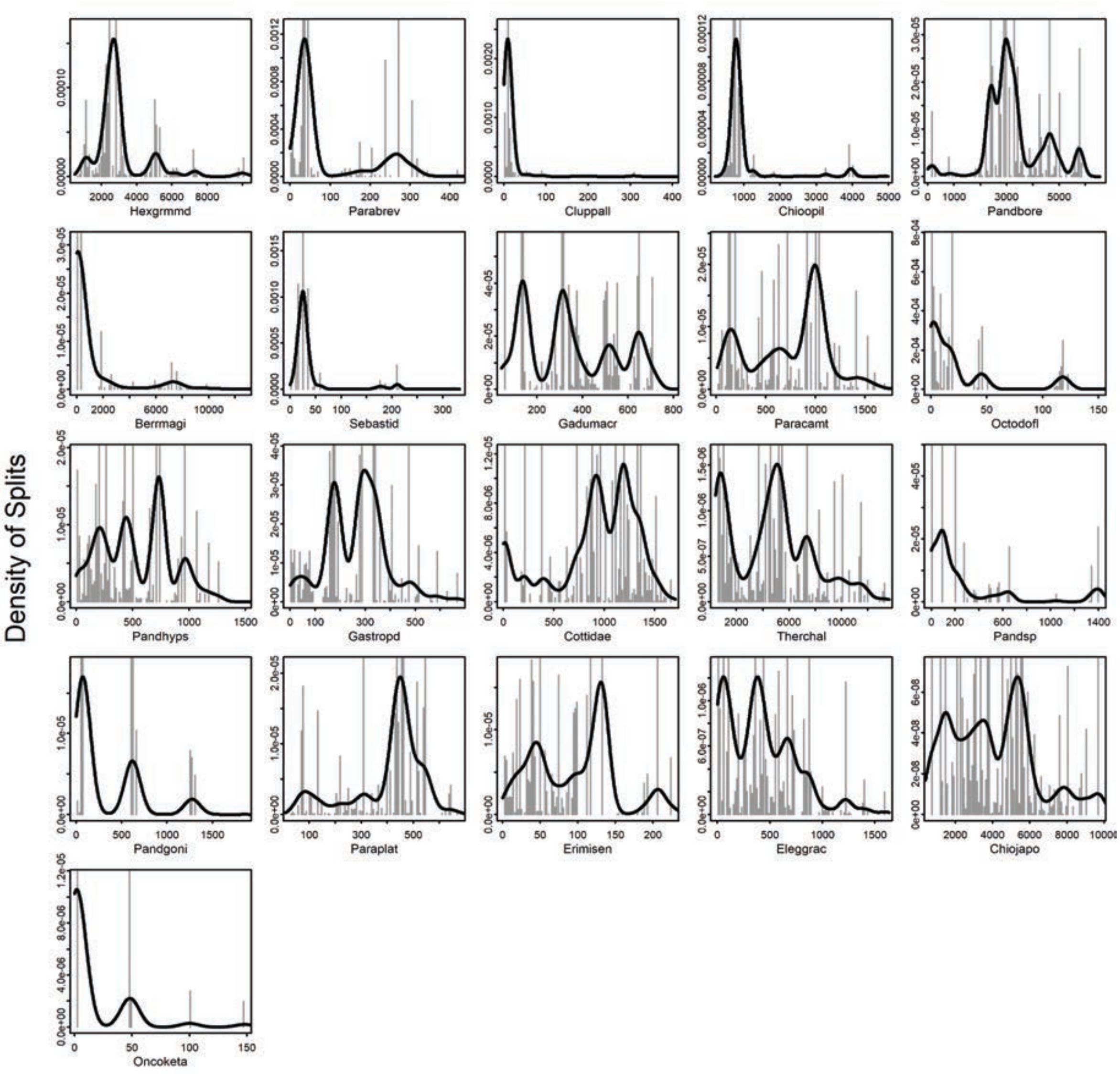


Fig. 5.13 Raw importance density computed by kernel density estimation of split points weighted by importance (black line) and binned raw importance density (gray bars).

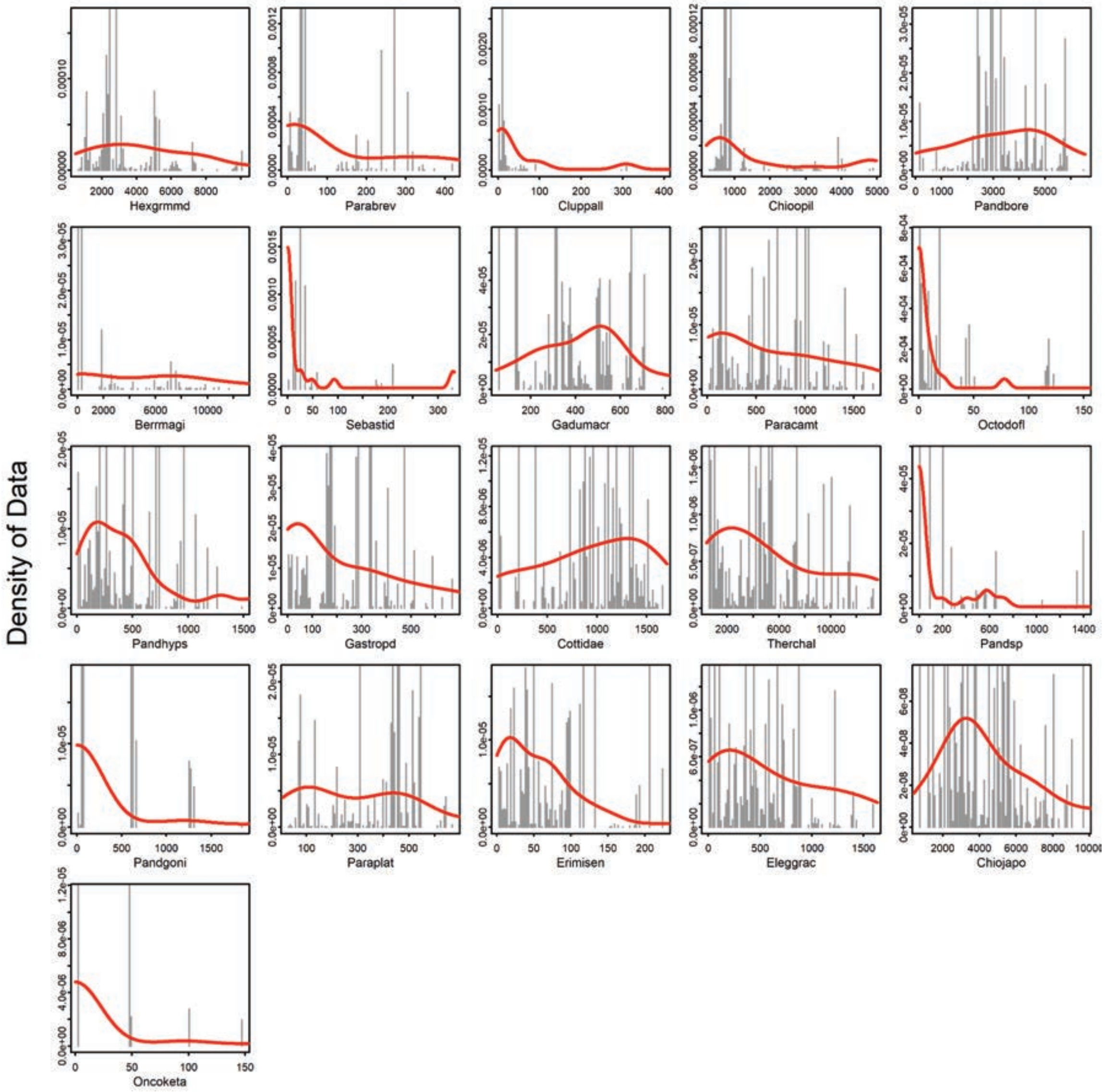


Fig. 5.14 Density of observed predictor values (red line).

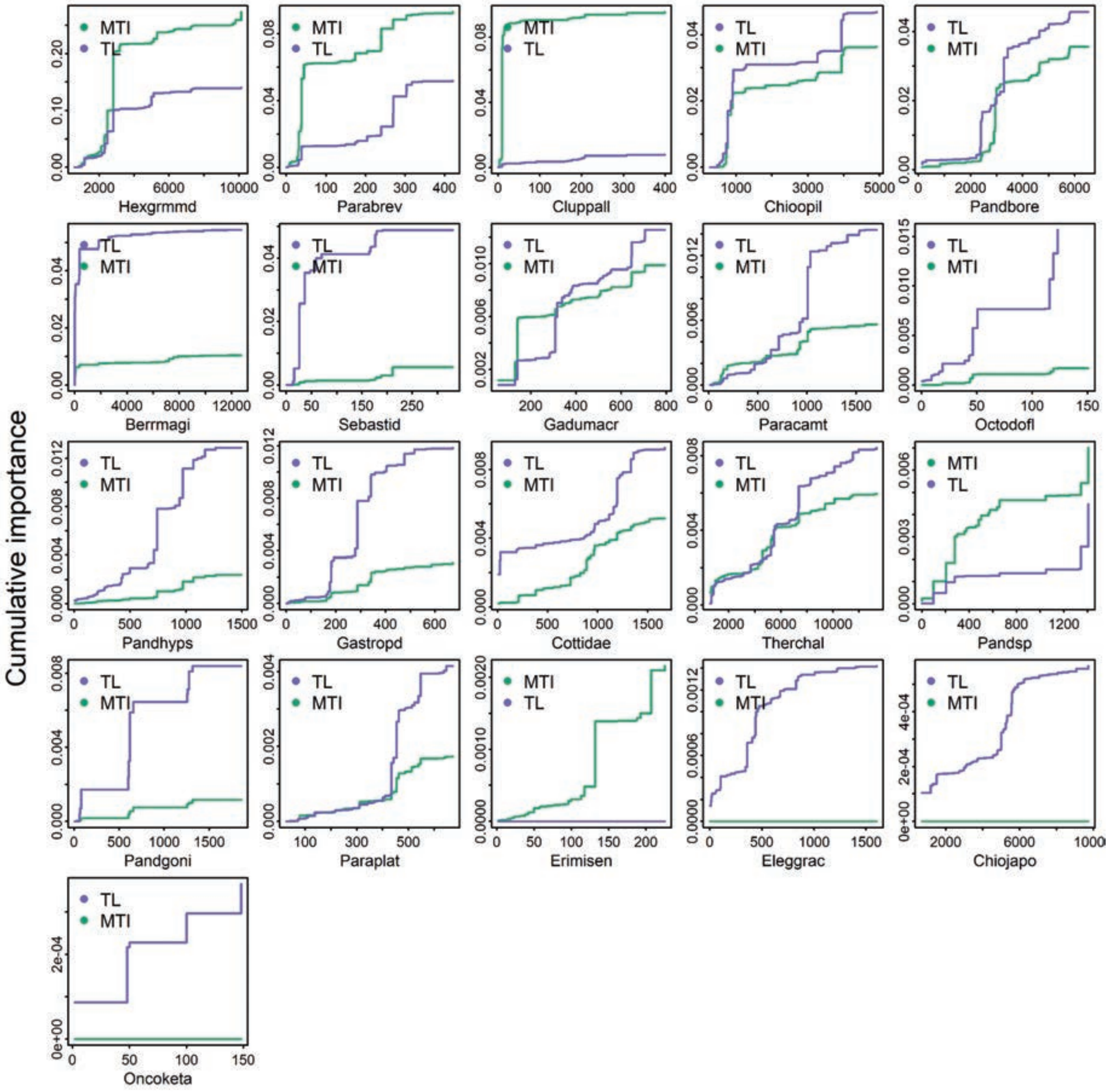


Fig. 5.15 Overall compositional turnover function for Trophic Level (TL) and Mean Trophic Index (MTI) estimated from Gradient Forests.

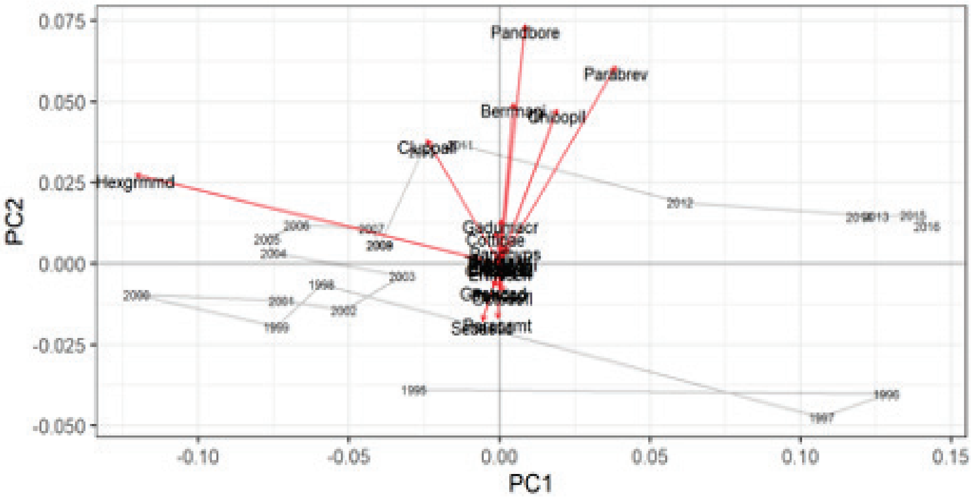


Fig. 5.16 Principal component analysis (PCA) biplot for CEP names of taxon groups and years.

5.3.6 U.S.A.

Status and trends

Concurrently with WG 36's efforts, Hunsicker *et al*. (2022) used a Bayesian version of Dynamic Factor Analysis (Ward *et al*., 2019) to summarize climate and biological variability in the southern and central regions of Region 11. A strong motivation for this analysis was to examine the ecosystem's response to the 2014–2016 marine heatwave in comparison to past climate perturbations. Many of the regional climate and biological time series used in that study were also applied to the U.S. case study for WG 36, described below. The DFA applied to the climate series indicated that all but one of the climate time series were associated with a single trend (Fig. 5.17 top). Sea surface temperature, sea surface height, and water column stratification (Brunt-Väisälä frequency) time series from the southern and central sub-regions of Region 11 loaded positively on this trend (Fig. 5.17 bottom). The Biologically Effective Upwelling Transport Index (BEUTI) and Coastal Upwelling Transport Index (CUTI) times series from both sub-regions and the isothermal layer depth time series from the central sub-region loaded negatively on the trend (Fig. 5.17 bottom). Overall, the climate trend captured a well-documented cooling period in the California Current Ecosystem (CCE) between 1980–2010 (Trenbeth and Fasullo, 2013), as well as strong El Niño events (*e.g*., 1982–83, 1997–98, 2015–16) and the 2014–2016 marine heatwave. The trends and loadings indicate that these climate events were associated with weaker upwelling, reduced mixed layer depth, low nutrient flux, and warm stratified waters (Fig. 5.17).

The DFA applied to the biology series showed strong coherence in the community signal; a majority of the time series (31 of 38) loaded strongly on a single trend and most of them demonstrated positive loadings (Fig. 5.18). The trends and loadings reflect the response of the relative abundance of most juvenile groundfishes (rockfish, flatfish), squid, krill, and some ichthyoplankton species to the climate perturbations mentioned above. Interestingly, the results suggest that the relative abundance of these species increased and the reproductive success of some seabird species was higher around the time of the 2014–2016 heatwave, whereas an opposite response is observed for the El Niño events. The few time series loading negatively on the trend indicate a reduction in sea lion pup growth rate and in the abundance of juvenile sardine and a few ichthyoplankton species (*e.g*., larval northern anchovy and Pacific hake) associated with the heatwave.

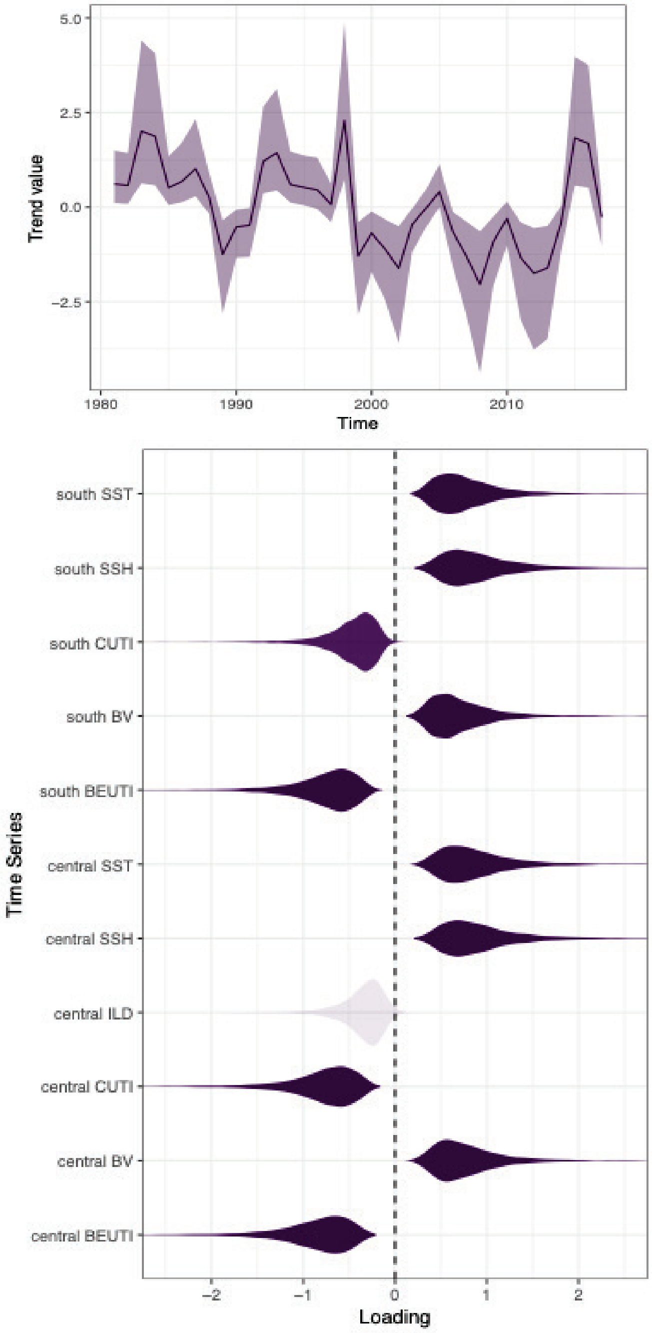


Fig. 5.17 Climate variability in the southern and central regions of the study ecosystem: a) shared trend with 95% credible intervals (1981–2017, top figure), b) posterior distributions for loadings on all of the individual time series (bottom figure). Loadings with darker shading indicate time series loading most strongly on the climate trend. SST = sea surface temperature; SSH = sea surface height; ILD = isothermal layer depth; BV = Brunt-Väisälä frequency (stratification); CUTI = Coastal Upwelling Transport Index; BEUTI = Biologically Effective Upwelling Transport Index. See Hunsicker *et al*. (2022) for more information. Adapted from Hunsicker *et al*. (2022). Reproduced with permission of Creative Commons.

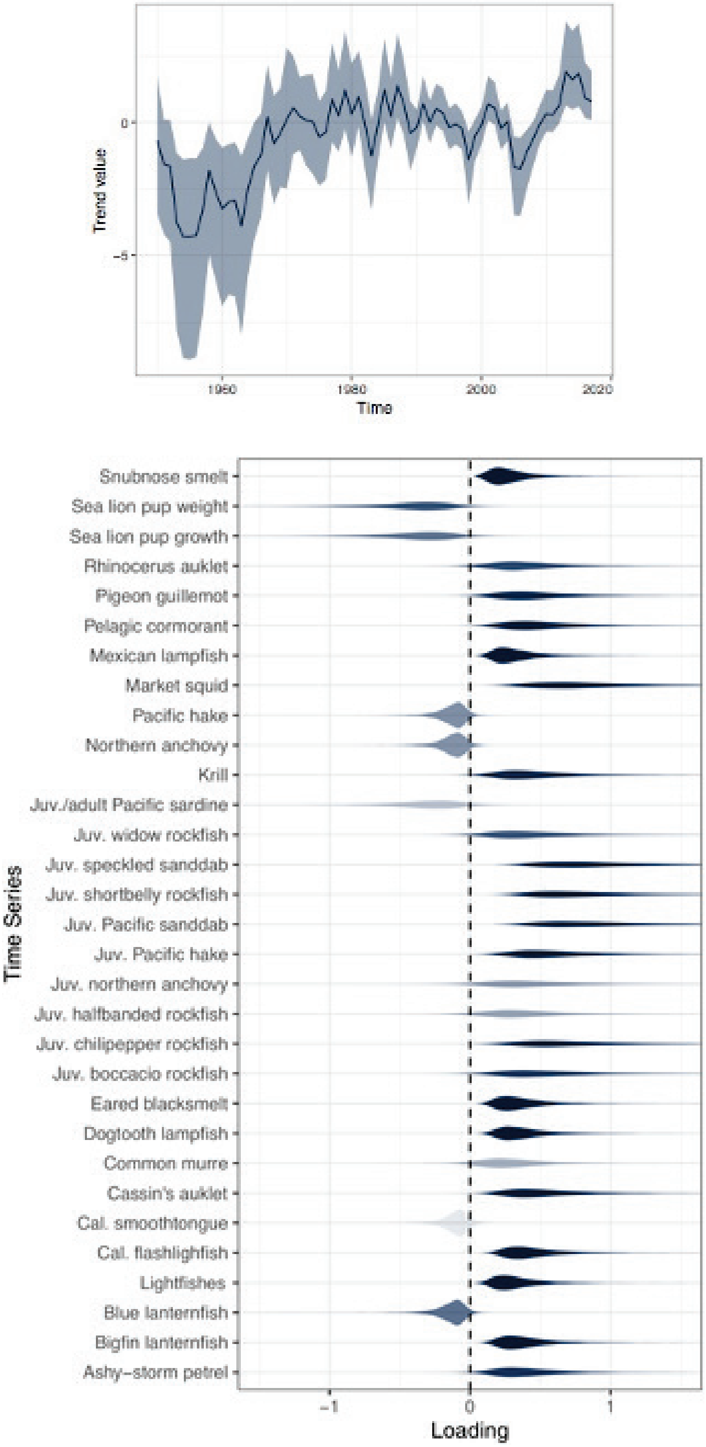


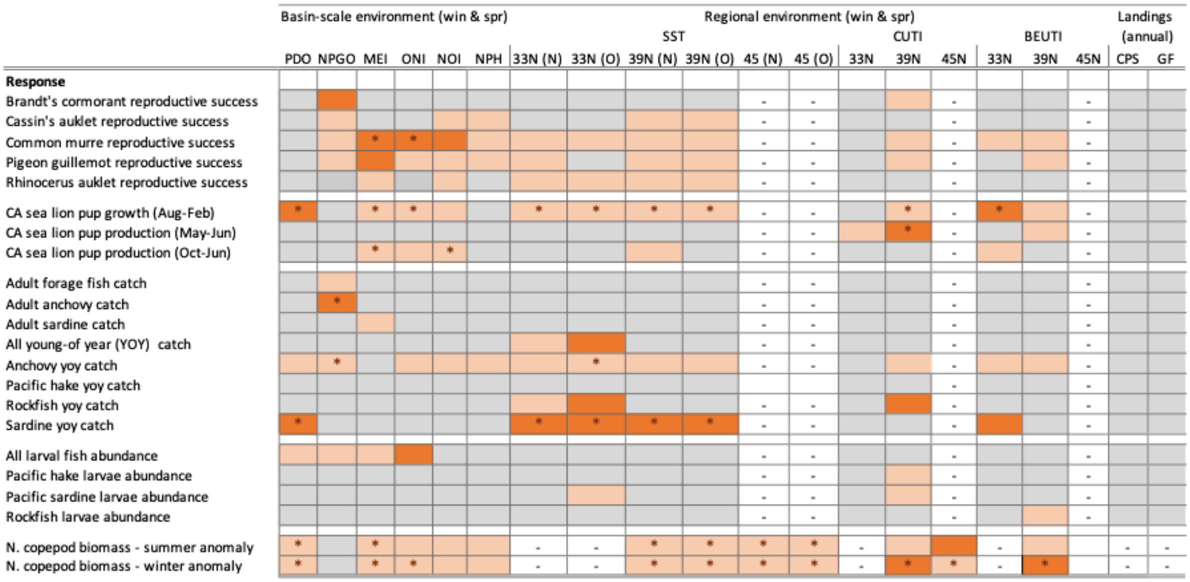
Fig. 5.18 Community variability in the southern region of the study ecosystem: a) shared trend with 95% credible intervals (1951–2018, top figure), b) posterior distributions for loadings on individual time series (only time series with ≥ 90% of the loading distributions above or below zero are shown, bottom figure). Loadings with darker shading indicate time series loading most strongly on the biology trend. See Table S1 in Hunsicker *et al.* (2022) for times series details. Cal. = California, Juv. = juvenile fish stage, Larv. = larval fish stage, Juv./adult = juvenile and adult stages combined. See Hunsicker *et al*. (2022) for more information. Adapted from Hunsicker *et al*. (2022). Reproduced with permission of Creative Commons.

Pressure–response relationship and ecosystem thresholds

The goal of the U.S. case study for WG 36 was to identify the presence of nonlinear and threshold dynamics in pressure–response relationships off the U.S. west coast, with a focus on the response of ecology to basin- and regional-scale climate variables. This work builds on the analyses of pressure–response relationships presented in Samhouri *et al*. (2017). We applied the same modeling approach to a broader suite of climate variables and ecological indicators that are included in the California Current Integrated Ecosystem Assessment (CCIEA). All of the climate and biology times series used in our analysis are described in Table 3.5 and are available on the CCIEA website (https://www.integratedecosystemassessment.noaa.gov/regions/california-current).

Overall, we tested 600 pressure–response relationships. The nonlinear model was the best supported model for 25 relationships (Table 5.2). The linear model was the best supported model for the remaining pressure–response relationships with 119 of those relationships considered significant at an alpha level of 0.05. In addition, 41 pressure–response relationships had R-squared values greater than 0.33, indicating that those relationships were moderate to strong (Table 5.2). Below, we present examples of the strongest nonlinear pressure–response relationships for four taxa: sea lions, seabirds, coastal pelagic fishes, and zooplankton. We also indicate those nonlinear pressure–response relationships that have persisted for at least the past five consecutive years, *i.e.*, 2015–2019. This was determined by applying the GAM analysis to the first 15 years of the time series and then iteratively adding an additional year of data to the analysis until we reached the end of the time series. We do not show results for pressure–response relationships in which larval fish were the ecological response or human activities were the pressures because those relationships were fairly weak overall (Table 5.2).

Table 5.2 Results of analyses to identify nonlinear and threshold dynamics in pressure–response relationships in the southern area of Region 11, with a focus on the response of the ecology to basin- and regional-scale climate variables.*



	Basin-scale environment (win & spr)						Regional environment (win & spr)												Landings (annual)	
							SST						CUTI			BEUTI				
	PDO	NPGO	MEI	ONI	NOI	NPH	33N (N)	33N (O)	39N (N)	39N (O)	45 (N)	45 (O)	33N	39N	45N	33N	39N	45N	CPS	GF
Response																				
Brandt's cormorant reproductive success	░	▓	░	░	░	░	░	░	░	░	-	-	░	▒	-	░	░	-	░	░
Cassin's auklet reproductive success	░	▒	░	░	▒	▒	░	░	▒	▒	-	-	░	░	-	░	░	-	░	░
Common murre reproductive success	░	▒	▓ *	▓ *	▓	▒	▒	▒	▒	▒	-	-	░	▒	-	▒	▒	-	░	░
Pigeon guillemot reproductive success	░	▒	▓	▒	▒	▒	▒	░	▒	▒	-	-	░	▒	-	░	▒	-	░	░
Rhinocerus auklet reproductive success	░	░	▒	░	▒	░	▒	▒	▒	▒	-	-	░	░	-	░	░	-	░	░
CA sea lion pup growth (Aug-Feb)	▓ *	░	▒ *	▒ *	▒	░	▒ *	▒ *	▒ *	▒ *	-	-	░	▒ *	-	▓ *	▒	-	░	░
CA sea lion pup production (May-Jun)	░	░	░	░	░	░	░	░	░	░	-	-	▒	▓ *	-	░	▒	-	░	░
CA sea lion pup production (Oct-Jun)	░	░	▒ *	▒	▒ *	░	░	░	▒	░	-	-	░	░	-	▒	░	-	░	░
Adult forage fish catch	░	▒	░	░	░	░	░	░	░	░	-	-	░	░	-	░	░	-	░	░
Adult anchovy catch	░	▓ *	░	░	░	░	░	░	░	░	-	-	░	░	-	░	░	-	░	░
Adult sardine catch	░	░	▒	░	░	░	░	░	░	░	-	-	░	░	-	░	░	-	░	░
All young-of year (YOY) catch	░	░	░	░	░	░	▒	▓	░	░	-	-	░	░	-	░	░	-	░	░
Anchovy yoy catch	▒	▒ *	░	▒	▒	▒	▒	▒ *	▒	▒	-	-	░	▒	-	▒	▒	-	░	░
Pacific hake yoy catch	░	░	░	░	░	░	░	░	░	░			░	░	-	░	░	-	░	░
Rockfish yoy catch	░	░	░	░	░	░	▒	▓	░	░	-	-	░	▓	-	░	░	-	░	░
Sardine yoy catch	▓ *	░	░	░	░	░	▓ *	▓ *	▓ *	▓ *	-	-	░	░	-	▓	░	-	░	░
All larval fish abundance	▒	▒	▒	▓	░	░	░	░	░	░	-	-	░	░	-	░	░	-	░	░
Pacific hake larvae abundance	░	░	░	░	░	░	░	░	░	░	-	-	░	▒	-	░	░	-	░	░
Pacific sardine larvae abundance	░	░	░	░	░	░	░	▒	░	░	-	-	░	▒	-	░	░	-	░	░
Rockfish larvae abundance	░	░	░	░	░	░	░	░	░	░	-	-	░	░	-	░	▒	-	░	░
N. copepod biomass - summer anomaly	▒ *	░	▒ *	▒	▒	▒	-	-	▒ *	▒ *	▒ *	▒ *	-	▒	▓	-	▒		-	-
N. copepod biomass - winter anomaly	▒ *	░	▒ *	▒ *	▒	▒	-	-	▒ *	▒ *	▒ *	▒ *	-	▓ *	▒ *	-	▓ *		-	-

*This table combines model results based on climate pressures averaged across winter months (December, January, February) and spring months (March, April, May) with the exception for models in which sea lion pup growth or production was the response variable (see legends in Figure 5.20 for details). Regional climate variables were estimated at three latitudes: 33°N, 39°N, 45°N; with heights of 1 degree (*e.g.*, 33°N is the average of all points between 32.5°N to 33.5°N). For sea surface temperature (SST), both nearshore (N, 0–75 km) and offshore (O, 75–150 km) times series were included in our analysis. Dark orange cells = nonlinear relationship, light orange cells = significant linear relationship (*p* value < 0.05), and gray cells = non-significant linear relationship. Asterisks indicate those relationships with $R^2 > 0.33$, indicating moderate to strong relationships. CUTI = Coastal Upwelling Transport Index, BEUTI = Biologically Effective Upwelling Transport Index, PDO = Pacific Decadal Oscillation, NPGO = North Pacific Gyre Oscillation, MEI = Multivariate ENSO Index, ONI = Oceanic Niño Index, NOI = Northern Oscillation Index, NPH = area of North Pacific High.

Seabirds – The strongest nonlinear pressure–response relationships for seabirds were between common murre reproductive success and basin-scale variables. Specifically, common murre productivity was high when the winter-averaged Multivariate El Niño/Southern Oscillation (ENSO) index (MEI) and spring-averaged Oceanic Niño Index (ONI) were low and their productivity abruptly declined as MEI and ONI values approached 1 and 0.5, respectively (Fig. 5.19A, B). These relationships have persisted for more than 25 consecutive years and likely reflect the abundance, availability and quality of prey available to common murre under different ocean conditions.

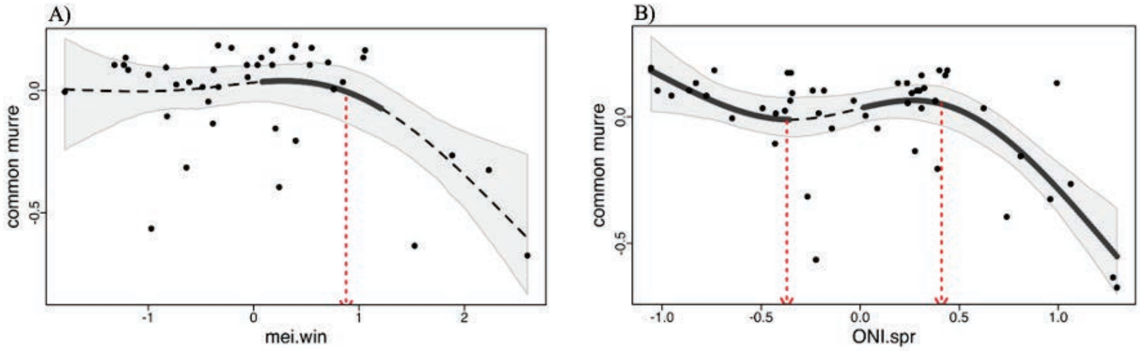


Fig. 5.19 General Additive Model (GAM) analyses showing response of common murre reproductive success to A) the winter-averaged MEI ($R^2 = 0.33$) and B) the spring-averaged ONI ($R^2 = 0.48$). Dashed black line is the GAM smoother, gray polygon is the 95% confidence interval (CI), black points are raw data, thick solid line indicates the threshold range where the 95% CI of the second derivative does not include 0, and red dotted arrow indicates the best estimate of the location of the threshold (*i.e.*, where the second derivative is at its absolute maximum value within the threshold range). See Samhouri *et al*. (2017) for method details.

Sea lions – Our analysis indicates that California sea lion pup growth and pup production respond nonlinearly to both basin- and regional-scale climate variables. For example, pup growth was greatest when the Pacific Decadal Oscillation (PDO) index was negative (cold phase in the Northeast Pacific) and growth estimates quickly declined as the PDO index became increasingly positive (warm phase in the Northeast Pacific) (Fig. 5.20B). This relationship has persisted for the past 6 years. Our results also indicate that pup growth was high when BEUTI (a measure of nitrate flux) in the southern region of the study system was high but declined when it dropped below a threshold of 0.3–0.4 (Figure 5.20A). In addition, we found a negative linear relationship between pup growth and sea surface temperature in the southern and central regions of the study region (not shown). Similar to seabirds, these relationships are likely driven by the availability of prey to nursing sea lions that provide nourishment for young pups and are limited by how long they can leave their pups to forage for prey, rather than by a direct temperature effect. For example, cooler and nutrient-rich coastal waters have been thought to support higher production or distribution of prey in sea lion foraging areas, although the 2014–2016 marine heatwave in the Northeast Pacific demonstrated that this is not always the case (*e.g.*, anchovy abundance was high during the heatwave). The relationships between pup production and climate pressures, including cumulative upwelling (CUTI) in the central CCE and the Northern Oscillation Index (NOI), are weaker than those relationships identified for pup growth (Fig. 5.20C, D). However, they also suggest that stronger upwelling and cooler waters have supported a stronger prey base for pregnant and nursing sea lions during the study period and this translates into higher pup production and survival. Follow-up work should evaluate the response of sea pup condition to changes in prey resources directly rather than relying on ocean conditions as a proxy.

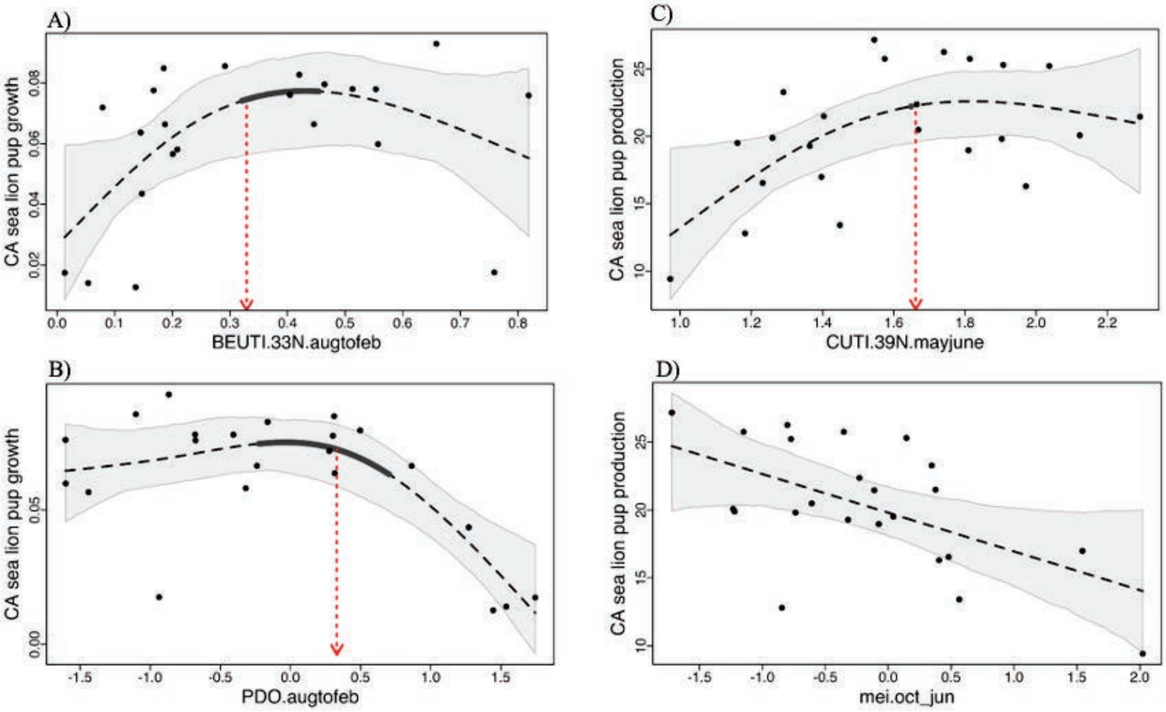


Fig. 5.20 General Additive Model (GAM) analyses showing the response of California sea lion pup growth to A) estimates of BEUTI (nitrate flux, $R^2 = 0.33$) off the Southern California Bight (33°N) and B) the PDO = 0.56. These two climate indices are averaged across August to February because sea lion pups are born in June or July and growth is measured sometime between the following October and February. Also shown are the responses of California sea lion pup production to C) estimates of CUTI (cumulative upwelling) off the coast of northern California (39°N) and averaged over months just prior to pup births (May–June, $R^2 = 0.35$), and D) the MEI averaged over months covering the gestation period for adult female sea lions (October–June, $R^2 = 0.32$).

Coastal pelagic fishes – As expected based on past literature, our analysis identified strong relationships between coastal pelagic species and climate pressures. Specifically, we found strong and persistent nonlinear relationships between juvenile Pacific sardine abundance and the winter averaged PDO index, and between juvenile Pacific sardine abundance and sea surface temperature throughout the central and southern regions of the study ecosystem (Fig. 5.21A, B). These relationships indicate that sardine production has been higher during positive PDO phases and warm ocean conditions (which are negatively correlated with upwelling in the central region, Jacox *et al*., 2014) and *vice versa*; this finding has been documented previously (see Checkley *et al*. (2017)). We also found a strong, nonlinear relationship between adult northern anchovy and the spring-averaged North Pacific Gyre Oscillation (NPGO) index (Figure 5.21C), and a moderately strong positive linear relationship between juvenile anchovy and offshore sea surface temperature in the southern region of the study system (Figure 5.21D). Our results indicate that anchovy production was highest when the NPGO index was the most negative but then declined quickly and remained low as the NPGO index increased to zero and became increasingly positive. Again, this finding aligns with past studies: negative NPGO index is indicative of lower nitrate and lower primary productivity in continental waters off the U.S. west coast and higher anchovy production has been associated with less productive ocean conditions (Santora *et al*., 2014; Ralston *et al*., 2015). However, the mechanisms driving fluctuations in anchovy and sardine abundance are complex and not well known (Checkley *et al*., 2017; Sydeman *et al*., 2020).

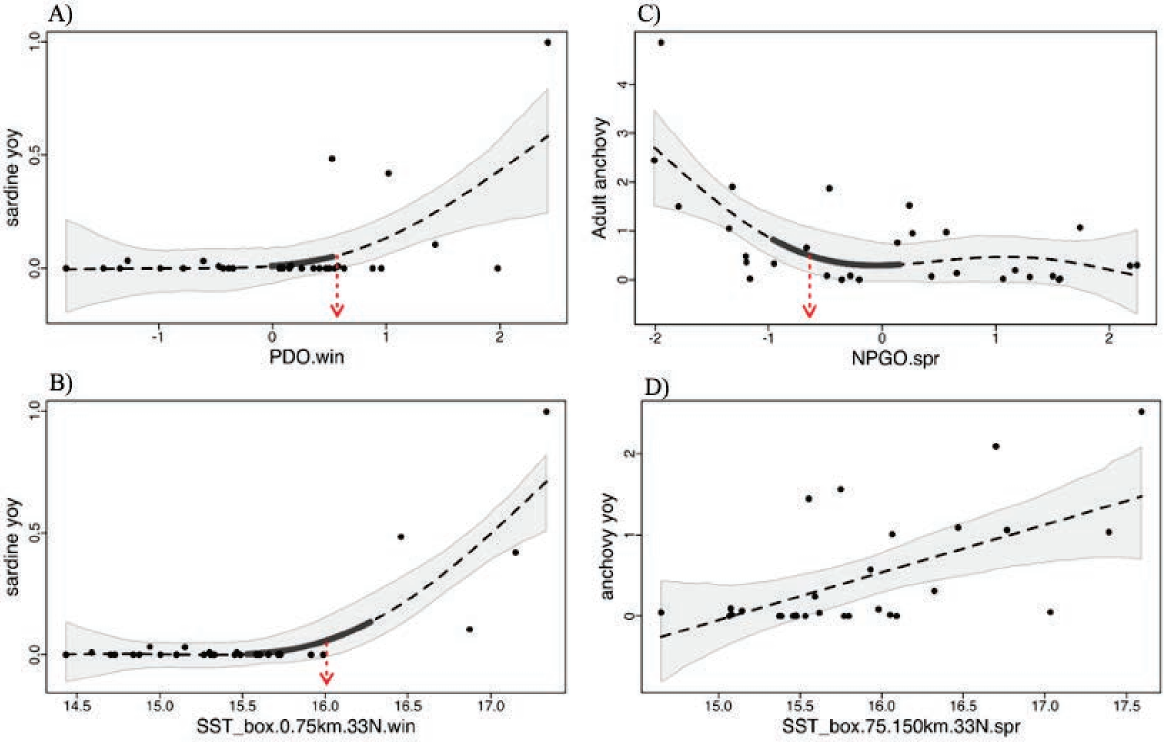


Fig. 5.21 General Additive Model (GAM) analyses showing the response of juvenile sardine abundance to A) the winter-averaged PDO index ($R^2 = 0.41$) and B) nearshore winter SST off the coast of the Southern California Bight (33°N, $R^2 = 0.74$). Also shown are C) the response of adult northern anchovy to the spring-averaged NPGO index $R^2 = 0.45$) and D) the response of juvenile anchovy to offshore spring SST in the southern California Current ($R^2 = 0.36$). We note that the estimates of uncertainty around the GAM smoothers are negative at times. Future work will evaluate alternate model formulations to identify a more appropriate model for the sardine and anchovy time series in light of the high prevalence of zeros.

Copepods – Our analysis identified strong, nonlinear relationships between northern copepod biomass anomalies and regional climate pressures. Winter northern copepod anomalies have demonstrated a persistent nonlinear response to CUTI and BEUTI, with the highest anomalies occurring during periods of strong upwelling and high nitrate flux off the coast of northern California, and *vice versa* (Fig. 5.22A, B). Summer copepod anomalies also showed a weak, nonlinear response to cumulative upwelling off the Oregon coast (Fig. 5.22C). These results are intuitive as upwelled nutrient-rich waters fuel primary production, which in turn supports the production of zooplankton, such as copepods. In addition, we identified negative linear relationships between sea surface temperature and the winter copepod anomalies (not shown) and between the winter mode of the PDO and summer copepod anomalies (Fig. 5.22D). These relationships likely reflect the transport of coastal, cold subarctic waters from the north, which is pronounced during the negative phase of the PDO, and brings a high abundance of coastal subarctic 'northern' species to waters off the Oregon coast (Peterson and Miller, 1977).

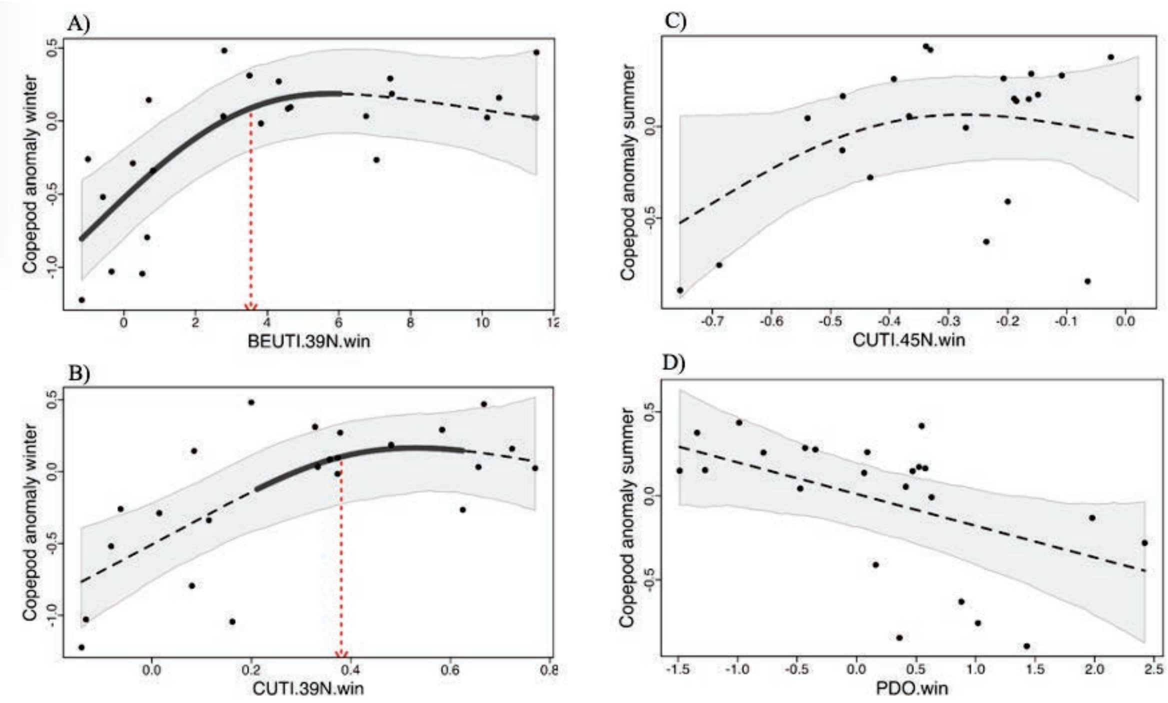


Fig. 5.22 General Additive Model (GAM) analyses showing the response of the northern copepod winter biomass anomalies to winter estimates of A) BEUTI (nitrate flux, R^2 = 0.51) and B) CUTI (cumulative upwelling) off the coast of northern California (39°N, R^2 = 0.48). Also shown are the responses of the northern copepod summer biomass anomalies to winter estimates of C) CUTI (cumulative upwelling) off the coast of Oregon (45°N, R^2 = 0.30) and D) the PDO index (R^2 = 0.49).

Comparisons to prior work

As mentioned above, the analyses for the U.S. builds on the analyses of pressure–response relationships presented in Samhouri *et al*. (2017). In our current work, we updated analyses for two pressure–response relationships identified as strongly nonlinear with thresholds in the prior study. This allowed us the opportunity to evaluate if strongly nonlinear relationships identified in the Samhouri *et al*. (2017)

study persisted with additional years of data. We found that the strongly nonlinear relationships previously identified between 1) the PDO and sea lion pup production and 2) the NPGO and northern copepod biomass anomalies broke down with five additional years of data. Neither of the relationships were significantly linear or nonlinear, based on our analysis.

5.4 Summary and conclusions

We characterized key pressure–response relationships and examined evidence of ecosystem thresholds within them. We used Dynamic Factor Analyses (DFA) to identify common trends, Gradient Forest Analyses to identify important pressures on ecosystem responses and thresholds, and general additive models (GAM) to examine nonlinearities in pressure–response relationships.

- Where significant single pressure–response relationships were found, about >50% were linear and <10% were nonlinear. The nonlinear relationships may provide leading indicators with thresholds.
- Dimension-reducing analyses, such as DFA, can simplify a suite of indicators to a few important trends. For example, for most of the case studies the pressures and ecosystem responses loaded on single trends. This was especially true for those models based on a small number of time series, *e.g*., less than 10 (Japan), and those that demonstrated strong coherence among the time series (U.S.A.). In some cases, correlations among DFA trends can be used to provide evidence of structural or functional relationships between pressures and responses (*e.g*., Korea). Future analyses could be aimed at combining human pressures, environmental pressures, and ecosystem responses within the same model to evaluate potential associations among the time series.
- The west coast of Vancouver Island (WCVI) case study applied both gradient forest and GAM analyses to environmental and biological time series. The Gradient Forest Analysis identified similar nonlinearities as the single pressure–response GAM models, as well as additional nonlinearities. These findings support the use of a multi-model approach to detect nonlinearites and thresholds in marine ecosystems.
- Top pressures include both basin- and regional-scale environmental pressures. Human pressures were not identified as important in the WCVI or the U.S. case studies. However, human pressures were important in the Samhouri *et al*. (2017) U.S. case study, especially in the Gradient Forest Analysis.
- Identification of pressure–response relationships likely depends on the length of the time series, frequency of measurements (seasonal *vs* annual), spatial scale of indicators analyzed, as well as the ecosystem being examined. A recent update of the Samhouri *et al*. (2017) analyses using a longer time series resulted in the identification of fewer nonlinearities (M. Hunsicker *et al*., unpublished). Very high signal-to-noise-ratios may also be needed to reliably detect thresholds in ecosystem variables (Hillebrand *et al*., 2020).
- Future studies could take into account more proximate pressures of ecological responses. For example, changes in predator abundances could be evaluated with respect to prey abundance and condition rather than using environmental pressures as a proxy. The potential for nonstationarity in pressure–response relationships also deserves consideration in future efforts to quantify nonlinearities and threshold locations in those relationships.

5.5 Literature cited

Boldt, J.L., Hazen, E.L., Hunsicker, M.E., Fu, C. and Perry, R.I. 2021. Quantifying ecosystem responses to environmental and human pressures in the marine ecosystem off the west coast of Vancouver Island. *Ecological Indicators* **132**: 108232, https://doi.org/10.1016/j.ecolind.2021.108232.

Checkley, D.M., Asch, R.G. and Rykaczewski, R.R. 2017. Climate, anchovy, and sardine. *Annual Review of Marine Sciences* **9**: 469–493, https://doi.org/10.1146/annurev-marine-122414-033819.

deYoung, B., Barange, M., Beaugrand, G., Harris, R., Perry, R.I., Scheffer, M. and Werner, F. 2008. Regime shifts in marine ecosystems: detection, prediction and management. *Trends in Ecology and Evolution* **23**: 402–409, DOI: 10.1016/j.tree.2008.03.008.

Ellis, N., Smith, S.J. and Pitcher, C.R.2012. Gradient forests: calculating importance gradients on physical predictors. *Ecology* **93**: 156–168, https://doi.org/10.1890/11-0252.1.

Goto, Y., Wada, A., Hoshino, N., Takashima, T., Mitsuhashi, M., Hattori, K. and Yamamura, O. 2017. Diets of Steller sea lions off the coast of Hokkaido, Japan: An inter-decadal and geographic comparison. *Marine Ecology* **38**: e12477, https://doi.org/10.1111/maec.12477.

Hastie, T. and Tibshirani, R. 1990. Generalized Additive Models. John Wiley and Sons, Inc.

Hillebrand, H., Donohue, I., Harpole, W.S., Hodapp, D., Kucera, M., Lewandowska, A.M., Merder, J., Montoya, J.M. and Freund, J.A. 2020. Thresholds for ecological responses to global change do not emerge from empirical data. *Nature Ecology and Evolution* **4**: 1502–1509, https://doi.org/10.1038/s41559-020-1256-9.

Holmes, E.E., Ward, E.J. and Wills, K. 2012. MARSS: Multivariate autoregressive state-space models for analyzing time-series data. *The R Journal* **4**: 11–19.

Hunsicker, M.E., Ward, E.J., Litzow, M.A., Anderson, S.C., Harvey, C.J., Field, J.C., Gao, J., Melin, S., Thompson, A.R. and Warzybok, P. 2022. Tracking and forecasting community responses to climate perturbations in the California Current Ecosystem. *PLOS Climate* **1**: e0000014, https://doi.org/10.1371/journal.pclm.0000014.

Jacox, M.G., Moore, A.M., Edwards, C.A. and Fiechter, J. 2014. Spatially resolved upwelling in the California Current System and its connections to climate variability. *Geophysical Research Letters* **41**: 3189–3196, https://doi.org/10.1002/2014GL059589.

Kuroda, H., Saito, T., Kaga, T., Takasuka, A., Kamimura, Y., Furuichi, S. and Nakanowatari, T. 2020. Unconventional sea surface temperature regime around Japan in the 2000s–2010s: Potential influences on major fisheries resources. *Frontiers in Marine Science* **7**: 574904, https://doi.org/10.3389/fmars.2020.574904

Large, S.I., Fay, G., Friedland, K.D. and Link, J.S. 2013. Defining trends and thresholds in responses of ecological indicators to fishing and environmental pressures. *ICES Journal of Marine Science* **70**: 755–767, https://doi.org/10.1093/icesjms/fst067.

Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Pell, A.N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C.L., Schneider, S.H. and Taylor, W.W. 2007. Complexity of coupled human and natural systems. *Science* **317**: 1513–1516, DOI: 10.1126/science.1144.

Marine Net Hokkaido. 2021. Search for fish catches and catch amounts by species and year. http://www.fishexp.hro.or.jp/marinedb/internetdb/fishdb/fish_year.asp.

Mason, J.G., Eurich, J.G., Lau, J.D., Battista, W., Free, C.M., Mills, K.E., Tokunaga, K., Zhao, L.Z., Dickey-Collas, M., Valle, M., Pecl, G.T., Cinner, J.E., McClanahan, T.R., Allison, E.H., Friedman, W.R., Silva, C., Yáñez, E., Barbieri, M.Á. and Kleisner, K. M. 2022. Attributes of climate resilience in fisheries: From theory to practice. *Fish and Fisheries* **23**: 522–544. https://doi.org/10.1111/faf.12630.

Peterson, W.T. and Miller, C.B. 1977. The seasonal cycle of zooplankton abundance and species composition along the central Oregon coast. *Fishery Bulletin* **75**: 717–724.

Ralston, S., Field, J.C. and Sakuma, K.M. 2015. Long-term variation in a central California pelagic forage assemblage. *Journal of Marine Systems* **146**: 26–37, https://doi.org/10.1016/j.jmarsys.2014.06.013.

Samhouri, J.F., Andrews, K.S., Fay, G., Harvey, C.J., Hazen, E.L., Hennessey, S.M., Holsman, K., Hunsicker, M.E., Large, S.I., Marshall, K.N., Stier, A.C., Tam, J.C. and Zador, S.G. 2017. Defining ecosystem thresholds for human activities and environmental pressures in the California Current. *Ecosphere* **8**: e01860, https://doi.org/10.1002/ecs2.1860.

Santora, J.A., Schroeder, I.D., Field, J.C., Wells, B.K. and Sydeman, W.J. 2014. Spatio-temporal dynamics of ocean conditions and forage taxa reveal regional structuring of seabird–prey relationships. *Ecological Applications* **24**: 1730–1747, https://doi.org/10.1890/13-1605.1.

Selkoe, K.A., Blenckner, T., Caldwell, M.R., Crowder, L.B., Erickson, A.L., Essington, T.E., Estes, J.A., Fujita, R.M., Halpern, B.S., Hunsicker, M.E., Kappel, C.V., Kelly, R.P., Kittinger, J.N., Levin, P.S., Lynham, J.M., Mach, M.E., Martone, R.G., Mease, L.A., Salomon, A.K., Samhouri, J.F., Scarborough, C., Stier, A.C., White, C. and Zedler, J. 2015. Principles for managing marine ecosystems prone to tipping points. *Ecosystem Health and Sustainability* **1**: 1–18, https://doi.org/10.1890/EHS14-0024.1.

Sydeman, W.J., Dedman, S., Garcia-Reyes, M., Thompson, S., Thayer, J.A., Bakun, A. and MacCall, A.D. 2020. Sixty-five years of northern anchovy population studies in the southern California current: a review and suggestion for sensible management. *ICES Journal of Marine Science* **77**: 486–499, doi: 10.1093/icesjms/fsaa004.

Trenbeth, K.E. and Fassullo, J.T. 2013. An apparent hiatus in global warming? *Earth's Future* **1**: 19–32, https://doi.org/10.1002/2013EF000165.

Ward, E.J., Anderson, S.C., Daminano, L.A., Hunsicker, M.E. and Litzow, M.A. 2019. Modeling regimes with extremes: the bayesdfa package for identifying and forecasting common trends and anomalies in multivariate time-series data. *The R Journal* **11**: 46–55.

6 Leading Indicators of Loss of Resilience and Ecosystem Change

6.1 Introduction

Traditional observing systems, including ship- and shore-based sampling, satellite-borne sensors, moorings, autonomous floats, and underwater vehicles are capable of monitoring a wide range of physical and environmental properties (Miloslavich *et al.*, 2018). This direct sampling is effective for understanding physical oceanographic processes. However, understanding how and when physical changes cascade through ecosystems and elicit biological responses remains difficult. Potential ecosystem responses include oceanographically-driven changes in ecosystem function, changes in the spatial distribution, abundance, and composition of the forage community, and changes in food web dynamics. These ecological factors influence trophic transfer, and in turn, can affect ecosystem productivity. While one can hypothesize how and when environmental changes (*e.g.*, a delay in upwelling or an increase in temperature) will affect an ecosystem more broadly, leading indicators, such as ecosystem sentinels (*i.e.*, species that can provide information about unobserved ecosystem components, Zacharias and Roff, 2001), can help identify when and where these broad-scale impacts have or are likely to occur, and identify thresholds or tipping points when physical processes translate to broad-scale implications for the ecosystem.

Biological taxa ranging from plankton to top predators have been proposed as potential elucidating or even leading indicators of ecosystem change in marine ecosystems (Boeing and Duffy-Anderson, 2008; Brodeur *et al.*, 2008; Racault *et al.*, 2017; Hazen *et al.*, 2019; Nielsen *et al.*, 2021). For example, zooplankton have short life cycles (weeks) and are closely associated with water masses. Thus, they respond quickly to both seasonal and event-scale changes in environmental conditions driven by shifts in ocean circulation and atmospheric forcing. Ichthyoplankton have narrower thermal tolerances than older life stages (Pörtner and Peck, 2010) and therefore, are more sensitive to fluctuations in ocean conditions and respond faster to environmental perturbations than adult fishes (Asch, 2015; Koslow *et al.*, 2017; Auth *et al.*, 2018; Goldstein *et al.*, 2019). These characteristics of zooplankton and ichthyoplankton, as well as their important role in the trophodynamics of marine pelagic ecosystems, make them effective sentinel taxa for ecosystem variability (Boeing and Duffy-Anderson, 2008; Brodeur *et al.*, 2008; Mackas and Beaugrand, 2010; Mackas *et al.*, 2012). As such, they are regularly monitored through various ocean observing systems and are used as indicators of ecosystem state in various marine ecosystems (Beaugrand, 2005; Peterson *et al.*, 2015; Gallo *et al.*, 2022; Ndah *et al.*, 2022).

Top predator-measured metrics have also been proposed as essential ocean variables that can contribute to the global ocean observing system (Miloslavich *et al.*, 2018). Several key characteristics are common to top predator taxa (*e.g.*, seabirds and marine mammals) that are well suited for use as ecosystem sentinels. These include 1) conspicuousness, 2) sensitivity to ecosystem processes and timeliness in their responses, and 3) ability to collect multiple indicators from a single individual or population that are informative about ecological processes over a range of spatial and temporal scales (Figs. 6.1 and

6.2). The relative importance of these characteristics will depend on the ecosystem process and time scale of interest. For example, detecting the implications of short-term climate variability may require multiple consecutive measurements over a relatively short timeframe, thus ideal indicators should be conspicuous and show an appropriately rapid response. In addition, measures of biodiversity (*e.g.*, taxonomic diversity, functional diversity and community composition) have been proposed as good leading indicators of ecosystem change because loss of diversity decreases ecosystem resilience which can cause dramatic ecosystem shifts (Mori *et al.*, 2013). Social drivers underlying ecosystem change have been explored less in the literature but they may also provide earlier indication of impending shifts (Hicks *et al.*, 2016).

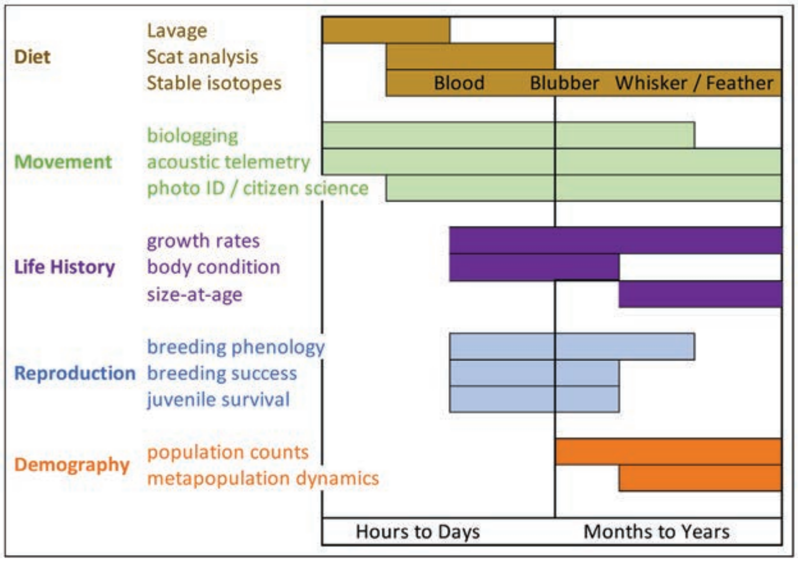


Fig. 6.1 Multiple time scales of data available from top predator sentinels that can give insight into multiple aspects of the ecosystem. From Hazen *et al*. (2019). Reproduced with permission of Creative Commons.

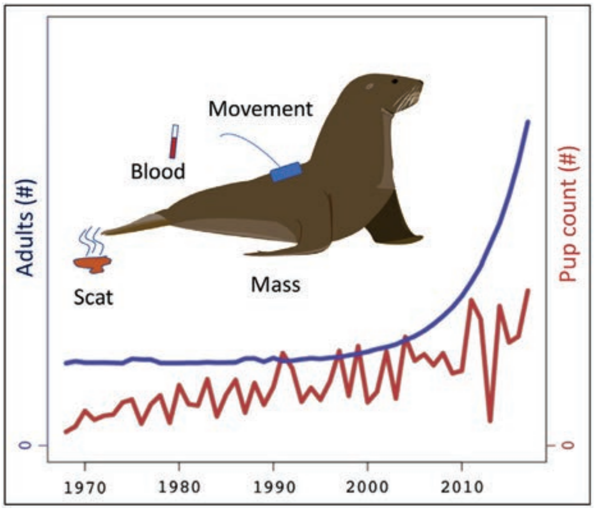


Fig. 6.2 Top predators can be sampled using multiple technologies that give insight into different aspects and time scales of ecosystem response. From Hazen *et al*. (2019). Reproduced with permission of Creative Commons.

6.2 Methodologies for identifying leading indicators of ecosystem change

The development and testing of methodological approaches for detecting early warning signs of ecosystem change have been the focus of myriad research efforts over the past few decades. For example, many studies have investigated whether the application of theoretical early warning indicators, statistical metrics of ecological resilience, datasets from empirical ecosystems, including lakes, seas, and open oceans could hold promise for informing natural resource management (Dakos *et al*., 2012, 2017; Litzow *et al*., 2013; Scheffer *et al*., 2015; Burthe *et al*., 2016; Gsell *et al*., 2016). These indicators essentially capture the 'critical slowing down' of degraded systems as they are about to become unstable and approach a critical transition or tipping point. This slowing down can be detected in the statistical properties of time series, such as increased temporal or spatial autocorrelation and variance in the system state (Scheffer *et al*., 2015). To date, there has been mixed success in applying early warning indicators to empirical systems (Burthe *et al*., 2016; Gsell *et al*., 2016), and they have been unreliable in ocean ecosystems (Litzow and Hunsicker, 2016). Given these outcomes, a multiple-methods approach for early detection of large ecosystem shifts that is tailored to local ecosystem characteristics and mechanistic understanding has been suggested for providing timely advice for management actions (Lindegren *et al*., 2012). In addition, other research efforts have been aimed at providing the earliest possible detection of an ecosystem that is already shifting to a different state. For example, multivariate statistical analyses, such as Dynamic Factor Analysis, are being used to synthesize information from multiple biological taxa that respond quickly to climate perturbations in an effort to develop an overall indicator of ecosystem state and to identify the probability of an ecosystem shifting to a previous or novel state (see TOR 3 and TOR 4; Ward *et al*., 2019, 2021; Litzow *et al*., 2020b; Hunsicker *et al*., 2022). Extensions of these analyses are also underway to provide reliable forecasts of ecosystem state one year in advance, based on future ocean conditions (Hunsicker *et al*., 2022).

6.3 Management relevant indicators derived from pressure–response relationships

While the pursuit of effective leading indicators or early detection of ecosystem change is ongoing, there are management-relevant indicators that have already been derived from significant pressure–response relationships (both linear and nonlinear), including anthropogenic and environmental pressures. For example, in Canada, relationships between both physical environmental and biological pressures and endangered northern abalone (*Haliotis kamtschatkana*) abundance have been used to improve abundance estimates (Hansen *et al*., 2020), which will be directly used by management to assess their current status in British Columbia. Environmental conditions in both freshwater and marine ecosystems are used to forecast returns of many stocks of both Sockeye and Pink salmon (Hyatt *et al*., 2020; DFO, 2021). To identify fishing opportunities and avoid overfishing, DFO Science provided pre-season forecasts of adult Fraser Sockeye salmon (*Oncorhynchus nerka*) arrival times in local waters and migration routes around Vancouver Island, based on the statistical relationships between migratory patterns and environmental variables (DFO, 2016). In addition, Xu *et al*. (2020) used boosted regression trees to link Fraser River watershed Chinook salmon growth rates to three environmental variables. Incorporating those environmental variables in salmon stock assessment models will improve science advice to fisheries management.

Likewise, in the southern area of Region 11, a suite of physical and biological indicators of ocean conditions experienced by out-migrating juvenile salmon are summarized annually in a 'stoplight table' (https://www.fisheries.noaa.gov/west-coast/science-data/ocean-ecosystem-indicators-pacific-salmon-marine-survival-northern) that can be used to predict returns of adult Chinook salmon (Burke *et al*., 2013). Evidence of thresholds in relationships of multiple environmental pressures and Chinook salmon forecast model performance could also be used to improve forecast models and to potentially anticipate and adjust management strategies to account for environmental conditions where forecast performance may be particularly poor (Satterthwaite *et al*., 2019). Strong relationships have been identified between ocean conditions and fish recruitment variability and productivity that can inform assessment models and management decision making for commercially important groundfish species (Tolimieri *et al*., 2018; Haltuch *et al*., 2020; Vestfals *et al*., in press). In addition, nowcasts of mammal marine distributions, based on observed ocean conditions, can help resource managers and users manage risks associated with fisheries bycatch and ship-strike (Hazen *et al*., 2017, 2018; Welch *et al*., 2019; Samhouri *et al*., 2021).

There are also examples of multiple indicators relevant to ecosystem-based management in North Pacific marine ecosystems stemming from WG 36 analyses. For instance, in the WCVI ecosystem, boreal copepod biomass anomalies were nonlinearly related to the timing of spring transition and southern copepod biomass anomalies were nonlinearly related to the PDO (Fig. 5.2). Copepod community composition can represent the amount of energy available to higher trophic levels, for example, boreal copepods have higher amounts of lipid than southern copepods and can therefore translate to more energy available to upper trophic levels. In the U.S. case study ecosystem, sea lion pup weights were nonlinearly related to basin-scale environmental indices such as the PDO (Table 5.2, Fig. 5.20). On the WCVI, the proportion of predators and trophic level of the surveyed community were also nonlinearly related to the PDO (Fig. 5.2). In addition to nonlinear relationships, several linear pressure–response relationships were identified that may inform management or single-species stock assessment models. For example, in marine areas around the Shiretoko Peninsula, there was a relationship between a human pressure DFA trend and an ecosystem response DFA trend (Fig. 5.4). In coastal waters around the Korean Peninsula, DFA trends indicate that squid catches and increases in croaker and crab catches were significantly correlated with nutrient concentrations and individual numbers of zooplankton (Figs. 5.5–5.7, Table 5.1).

6.4 Challenges in identifying leading indicators and thresholds

Identifying reliable leading indicators and thresholds of ecosystem change continues to be an important goal of many science and management plans. However, there are several challenges in doing so. For example, the absence or lack of adequate data on ecosystem responses to environmental and anthropogenic pressures can make these efforts difficult or even impossible. Ecosystem indicators investigated to date in the PICES regions and elsewhere may depend on data or time series availability. However, the efficacy of these indicators depends on whether the 'right' data are being collected at the 'right' scales to detect early signs of ecosystem change. A combination of interacting stressors is likely to produce nonlinear and threshold responses rather than a single causal factor; therefore, detection of ecosystem change may require data on a broad range of ecosystem variables (Huggett, 2005; Groffman *et al*., 2006). Also, environmental stressors may be operating at different scales, and the perception of an ecosystem functioning, in terms of indicators, may also be scale dependent (Heim *et al*., 2021).

6.5 Recommendations for future research

There are several avenues of research that may improve the detection and reliability of leading indicators and ecosystem thresholds for managing marine resources. Examining whether the statistical methods used to identify thresholds in pressure–response relationships in empirical systems is one of them. For example, some pressure–response relationships identified as nonlinear in the U.S. study system were subsequently identified as linear when the same analysis was updated using additional years of data (Samhouri *et al*., 2017; Hunsicker *et al*., unpublished). Simulation studies and sensitivity analyses could be useful for determining whether various methods used to identify ecological thresholds are reliable and to reveal circumstances in which they might not be. Simulation models based on ecosystem modeling frameworks might be particularly useful to detect and/or stress test indicators of ecosystem change and reference points (*e.g*., Fulton *et al*., 2005). More research is also needed on identifying the potential for nonstationary in pressure–response relationships and accounting for these dynamics in modeling efforts (Puerta *et al*., 2019; Litzow *et al*., 2020a, b; Malick *et al*., 2020). Nonstationary dynamics can change the usefulness of leading indicators and impact forecasting efforts (Wainwright, 2021). Process-based studies are key to improving our understanding of the mechanisms that might underlie nonstationary relationships and strengthening our abilities to anticipate or forecast ecosystem shifts. Lastly, but of critical importance, is the need to develop guidelines for how to frame these research efforts for managers so that we can move investigations of leading indicators and ecosystem thresholds from science activity into management action.

6.6 Literature cited

Asch, R.G. 2015. Climate change and decadal shifts in the phenology of larval fishes in the California Current ecosystem. *Proceedings of the National Academy of Sciences of the United States of America* **112**: E4065–E4074, https://doi.org/10.1073/pnas.14219 46112.

Auth, T., Daly, E., Brodeur, R. and Fisher, J. 2018. Phenological and distributional shifts in ichthyoplankton associated with recent warming in the northeast Pacific Ocean. *Global Change Biology* **24**: 259–272, https://doi.org/10.1111/gcb.13872.

Beaugrand, G. 2005. Monitoring pelagic ecosystems using plankton indicators. *ICES Journal of Marine Science* **62**: 333–338, https://doi.org/10.1016/j.icesjms.2005.01.002.

Boeing, W.J. and Duffy-Anderson, J.T. 2008. Ichthyoplankton dynamics and biodiversity in the Gulf of Alaska: Responses to environmental change. *Ecological Indicators* **8**: 292–302, https://doi.org/10.1016/j.ecoli nd.2007.03.002.

Brodeur, R.D., Peterson, W.T., Auth, T.D., Soulen, H.L., Parnel, M.M. and Emerson, A.A. 2008. Abundance and diversity of coastal fish larvae as indicators of recent changes in ocean and climate conditions in the Oregon upwelling zone. *Marine Ecology Progress Series* **366**: 187–202, https://doi.org/10.3354/meps0 7539.

Burke, B.J., Peterson, W.T., Beckman, B.R., Morgan, C., Daly, E.A. and Litz, M. 2013. Multivariate models of adult Pacific salmon returns. *PloS ONE* **8**: e54134–e54134, https://doi.org/10.1371/journal.pone.0054134.

Burthe, S.J., Henrys, P.A., Mackay, E.B., Spears, B.M., Campbell, R., Carvalho, L., Dudley, B., Gunn, I.D.M., Johns, D.G., Maberly, S.C., May, L., Newell, M.A., Wanless, S., Winfield, I.J., Thackeray, S.J., Daunt, F. and Allen, C. 2016. Do early warning indicators consistently predict nonlinear change in long-term ecological data? *The Journal of Applied Ecology* **53**: 666–676, https://doi.org/10.1111/1365-2664.12519.

Dakos, V., Carpenter, S., Brock, W., Ellison, A., Guttal, V., Ives, A., Kefi, S., Livina, V., Seekell, D., Nes, van, E.H. and Scheffer, M. 2012. Methods for detecting early warnings of critical transitions in time series illustrated using simulated ecological data. *PloS ONE* **7**: e41010–e41010, https://doi.org/10.1371/journal.pone.0041010.

Dakos, V., Glaser, S.M., Hsieh, C.-H. and Sugihara, G. 2017. Elevated nonlinearity as an indicator of shifts in the dynamics of populations under stress. *Journal of the Royal Society Interface* **14**: 20160845, https://doi.org/10.1098/rsif.2016.0845.

DFO (Fisheries and Oceans Canada). 2016. Run timing and diversion rate models for Fraser River sockeye. DFO Canadian Science Advisory Secretariat Science Advisory Report, 2016/008.

DFO. 2021. Pre-season run size forecasts for Fraser River sockeye (*Oncorhynchus nerka*) and Pink (*Oncorhynchus gorbuscha*) Salmon in 2021. DFO Canadian Science Advisory Secretariat Science Advisory Report 2021/038.

Fulton, E.A., Smith, A.D. and Punt, A.E. 2005. Which ecological indicators can robustly detect effects of fishing? *ICES Journal of Marine Science* **62**: 540–551, https://doi.org/10.1016/j.icesjms.2004.12.012.

Gallo, N.D., Bowlin, N.M., Thompson, A.T., Satterthwaite, E.V., Brady, B. and Semmens, B.X. 2022. Fisheries surveys are essential ocean observing programs in a time of global change: A synthesis of oceanographic and ecological data from U.S. West Coast fisheries surveys. *Frontiers in Marine Science* **9**: https://doi.org/10.3389/fmars.2022.757124.

Goldstein, E.D., Duffy-Anderson, J.T., Matarese, A.C. and Stockhausen, W.T. 2019. Larval fish assemblages in the eastern and western Gulf of Alaska: Patterns, drivers, and implications for connectivity. *Deep Sea Research II* **165**: 26–40, https://doi.org/10.1016/j.dsr2.2018.09.003.

Groffman, P.M., Baron, J.S., Blett, T., Gold, A.J., Goodman, I., Gunderson, L.H., Levinson, B. M., Palmer, M.A., Paerl, H.W., Peterson, G.D., Poff, N.L., Rejeski, D.W., Reynolds, J.F., Turner, M.G., Weathers, K.C. and Wiens, J. 2006. Ecological thresholds: The key to successful environmental management or an important concept with no practical application? *Ecosystems* **9**: 1–13, https://doi.org/10.1007/s10021-003-0142-z.

Gsell, A.S., Scharfenberger, U., Özkundakci, D., Walters, A., Hansson, L.-A., Janssen, A.B.G., Nõges, P., Reid, P.C., Schindler, D.E., Van Donk, E., Dakos, V. and Aian, R. 2016. Evaluating early-warning indicators of critical transitions in natural aquatic ecosystems. *Proceedings of the National Academy of Sciences of the United States of America* **113**: E8089–E8095, https://doi.org/10.1073/pnas.1608242113.

Haltuch, M.A., Tolimieri, N., Lee, Q. and Jacox, M.G. 2020. Oceanographic drivers of petrale sole recruitment in the California Current Ecosystem. *Fisheries Oceanography* **29**: 122–136, https://doi.org/10.1111/fog.12459.

Hansen, S.C., Obradovich, S.G., Rooper, C.N., Waddell, B.J., Nichol, L.M., MacNeill, S. and Barton, L.L. 2020. Identifying variables for standardization of the Northern Abalone (*Haliotis kamtschatkana*) index site surveys time series (1978–2018) based on survey methodology and environmental variability. Canadian Technical Report of Fisheries and Aquatic Sciences 3330: vii + 110 pp.

Hazen, E.L., Palacios, D.M., Forney, K.A., Howell, E.A., Becker, E., Hoover, A.L., Irvine, L., DeAngelis, M., Bograd, S.J., Mate, B.R., Bailey, H. and Singh, N. 2017. WhaleWatch: a dynamic management tool for predicting blue whale density in the California Current. *The Journal of Applied Ecology* **54**: 1415–1428, https://doi.org/10.1111/1365-2664.12820.

Hazen, E., Scales, K., Maxwell, S., Briscoe, D., Welch, H., Bograd, S., Baily, H., Benson, S., Eguchi, T., Dewar, H., Kohin, S., Costa, D.P., Crowder, L.B. and Lewison, R.L. 2018. A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. *Science Advances* **4:** http://dx.doi.org/10.1126/sciadv.aar3001.

Hazen, E.L., Abrahms, B., Brodie, S., Carroll, G., Jacox, M.G., Savoca, M.S., Scales, K.L., Sydeman, W.J. and Bograd, S.J. 2019. Marine top predators as climate and ecosystem sentinels. *Frontiers in Ecology and the Environment* **17**: 565–574, https://doi.org/10.1002/fee.2125.

Heim, K.C., Thorne, L.H., Warren, J.D., Link, J.S. and Nye, J.A. 2021. Marine ecosystem indicators are sensitive to ecosystem boundaries and spatial scale. *Ecological Indicators* **125**: 107522, https://doi.org/10.1016/j.ecolind.2021.107522.

Hicks, C.C., Crowder, L.B., Graham, N.A., Kittinger, J.N. and Cornu, E.L. 2016. Social drivers forewarn of marine regime shifts. *Frontiers in Ecology and the Environment* **14**: 252–260, https://doi.org/10.1002/fee.1284

Huggett, A.J. 2005. The concept and utility of 'ecological thresholds' in biodiversity conservation. *Biological Conservation* **124**: 301–310, https://doi.org/10.1016/j.biocon.2005.01.037.

Hunsicker, M.E., Ward, E.J., Litzow, M.A., Anderson, S.C., Harvey, C.J., Field, J.C., Gao, J., Melin, S., Thompson, A.R. and Warzybok, P. 2022. Tracking and forecasting community responses to climate perturbations in the California Current Ecosystem. *PLOS Climate* **1**: : e0000014, https://doi.org/10.1371/journal.pclm.0000014.

Hyatt, K.D., Stiff, H. and Stockwell, M.M. 2020. Impacts of the 2013-2016 marine heatwave on Barkley Sound Sockeye salmon, pp. 224–229 *in:* State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2019 *edited by* J.L. Boldt, A. Javorski, and P.C. Chandler, Canadian Technical Report of Fisheries and Aquatic Sciences 3377: x + 288 pp.

Koslow, J.A., McMonagle, H. and Watson, W. 2017. Influence of climate on the biodiversity and community structure of fishes in the southern California Current. *Marine Ecology Progress Series* **571**: 193–206, https://doi.org/10.3354/meps1 2095.

Lindegren, M., Dakos, V., Groger, J., Gardmark, A., Kornilovs, G., Otto, S. and Mollmann, C. 2012. Early detection of ecosystem regime shifts: A multiple method evaluation for management application. *PloS ONE* **7**: e38410, https://doi.org/10.1371/journal.pone.0038410.

Litzow, M.A. and Hunsicker, M.E. 2016. Early warning signals, nonlinearity, and signs of hysteresis in real ecosystems. *Ecosphere* **7**: e01614, https://doi.org/10.1002/ecs2.1614.

Litzow, M.A., Mueter, F.J. and Urban, J.D. 2013. Rising catch variability preceded historical fisheries collapses in Alaska. *Ecological Applications* **23**: 1475–1487, https://doi.org/10.1890/12-0670.1.

Litzow, M.A., Malick, M.J., Bond, N.A., Cunningham, C.J., Gosselin, J.L. and Ward, E.J. 2020a. Quantifying a novel climate through changes in PDO-climate and PDO-salmon relationships. *Geophysical Research Letters* **47**: e2020GL087972, https://doi.org/10.1029/2020GL087972.

Litzow, M.A., Hunsicker, M.E., Bond, N.A., Burke, B.J., Cunningham, C.J., Gosselin, J.L., Norton, E.L., Ward, E.J. and Zador, S.G.. 2020b. The changing physical and ecological meanings of North Pacific Ocean climate indices. *Proceedings of the National Academy of Sciences of the United States of America* **117**: 7665–7671, https://doi.org/10.1073/pnas.192126611.

Malick, M.J. 2020. Time-varying relationships between ocean conditions and sockeye salmon productivity. *Fisheries Oceanography* **29**: 265–275, https://doi.org/10.1111/fog.12469.

Mackas, D.L. and Beaugrand, G. 2010. Comparisons of zooplankton time series. *Journal of Marine Systems* **79**: 286–304, https://doi.org/10.1016/j.jmarsys.2008.11.030.

Mackas, D., Greve, W., Edwards, M., Chiba, S., Tadokoro, K., Eloire, D., Mazzocchi, M., Batten, S., Richardson, A., Johnson, C., Head, E., Conversi, A. and Peluso, T. 2012. Changing zooplankton seasonality in a changing ocean: Comparing time series of zooplankton phenology. *Progress in Oceanography* **97**: 31–62, https://doi.org/10.1016/j.pocean.2011.11.005

Miloslavich, P., Bax, N.J., Simmons, S.E., Klein, E., Appeltans, W., Aburto-Oropeza, O., Andersen Garcia, M., Batten, S.D., Benedetti-Cecchi, L., Checkley, D.M., Chiba, S., Duffy, J. E., Dunn, D.C., Fischer, A., Gunn, J., Kudela, R., Marsac, F., Muller-Karger, F.E., Obura, D. and Shin, Y. 2018. Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. *Global Change Biology* **24**: 2416–2433, https://doi.org/10.1111/gcb.14108.

Mori, A.S., Furukawa, T. and Sasaki, T. 2013. Response diversity determines the resilience of ecosystems to environmental change. *Biological Reviews of the Cambridge Philosophical Society* **88**: 349–364, https://doi.org/10.1111/brv.12004.

Ndah, A.B., Meunier, C.L., Kirstein, I.V., Göbel, J., Rönn, L. and Boersma, M. 2022. A systematic study of zooplankton-based indices of marine ecological change and water quality: Application to the European marine strategy framework Directive (MSFD). *Ecological Indicators* **135**: 108587, https://doi.org/10.1016/j.ecolind.2022.108587.

Nielsen, J.M., Rogers, L.A., Brodeur, R.D., Thompson, A.R., Auth, T.D., Deary, A.L., Duffy-Anderson, J.T., Galbraith, M., Koslow, J.A. and Perry, R.I. 2021. Responses of ichthyoplankton assemblages to the recent marine heatwave and previous climate fluctuations in several Northeast Pacific marine ecosystems. *Global Change Biology* **27**: 506–520, https://doi.org/10.1111/gcb.15415.

Peterson, W.T., Fisher, J.L, Peterson, J.O., Morgan, C.A., Burke, B.J. and Fresh, K.L. 2015. Applied fisheries oceanography: Ecosystem indicators of ocean conditions inform fisheries management in the California Current. *Oceanography* **27**:80–89, http://dx.doi.org/10.5670/oceanog.2014.88.

Pörtner, H.-O. and Peck, M.A. 2010. Climate change effects on fishes and fisheries: Towards a cause-and-effect understanding. *Journal of Fish Biology* **77**: 1745–1779, https://doi.org/10.1111/j.1095-8649.2010.02783.x.

Puerta, P., Ciannelli, L., Rykaczewski, R.R., Opiekun, M. and Litzow, M.A.. 2019. Do Gulf of Alaska fish and crustacean populations show synchronous non-stationary responses to climate? *Progress in Oceanography* **175**: 161–170, https://doi.org/10.1016/j.pocean.2019.04.002.

Racault, M.F., Platt, T., Sathyendranath, S., Ağirbaş, E., Martinez Vicente, V. and Brewin, R. 2014. Plankton indicators and ocean observing systems: support to the marine ecosystem state assessment. *Journal of Plankton Research* **36**: 621–629, https://doi.org/10.1093/plankt/fbu016.

Racault, M.F., Sathyendranath, S., Brewin, R.J.W., Raitsos, D.E., Jackson, T. and Platt T. 2017. Impact of El Niño variability on oceanic phytoplankton. *Frontiers in Marine Science* **4**: https://doi.org/10.3389/fmars.2017.00133.

Samhouri, J.F., Andrews, K.F., Fay, G., Harvey, C.J., Hazen, E.L., Hennessey, S.M., Holsman, K., Hunsicker, M.E., Large, S.I., Marshall, K.N., Stier, A.C., Tam, J.C. and Zador, S.G. 2017. Defining ecosystem thresholds for human activities and environmental pressures in the California Current. *Ecosphere* **8**: e01860. 10.1002/ecs2.1860.

Samhouri, J.F., Feist, B.E., Fisher, M.C., Liu, O., Woodman, S.M., Abrahms, B., Forney, K.A., Hazen, E.L., Lawson, D., Redfern, J. and Saez, L.E. 2021. Marine heatwave challenges solutions to human-wildlife conflict. *Proceedings of the Royal Society. B, Biological Sciences* **288**: 20211607, https://doi.org/10.1098/rspb.2021.1607.

Satterthwaite, W., Andrews, K.S., Burke, B.J., Gosselin, J.L., Greene, C.M., Harvey, C.J., Munsch, S.H., O'Farrell, M.R., Samhouri, J.F. and Sobocinski, K.L. 2020. Ecological thresholds in forecast performance for key United States West Coast Chinook salmon stocks. *ICES Journal of Marine Science* **77**: 1503–1515, https://doi.org/10.1093/icesjms/fsz189.

Scheffer, M., Carpenter, S.R., Dakos, V. and van Nes, E.H. 2015. Generic indicators of ecological resilience: Inferring the chance of a critical transition. *Annual Review of Ecology, Evolution, and Systematics* **46**: 145–167, https://doi.org/10.1146/annurev-ecolsys-112414-054242.

Tolimieri, N., Haltuch, M.A., Lee, Q., Jacox, M.G. and Bograd, S.J. 2018. Oceanographic drivers of sablefish recruitment in the California Current. *Fisheries Oceanography* **27**: 458–474, https://doi.org/10.1111/fog.12266.

Vestfals, C.D., Marshall, K.N., Tolimieri, N., Hunsicker, M.E., Berger, A.M., Taylor, I.G., Jacox, M.G. and Turley, B.D. Stage-specific drivers of Pacific hake (*Merluccius productus*) recruitment in the California Current Ecosystem. *Fisheries Oceanography*. In press.

Ward, E.J., Anderson, S.C., Daminano, L.A., Hunsicker, M.E. and Litzow, M.A. 2019. Modeling regimes with extremes: the bayesdfa package for identifying and forecasting common trends and anomalies in multivariate time-series data. *The R Journal* **11**: 46–55.

Ward, E.J., Anderson, S.C., Hunsicker, M.E. and Litzow, M.A. 2021. Smoothed dynamic factor analysis for identifying trends in multivariate time series. *Methods in Ecology and Evolution* **13**: 908–918, https://doi.org/10.1111/2041-210X.13788.

Wainwright, T.C. 2021. Ephemeral relationships in salmon forecasting: A cautionary tale. *Progress in Oceanography* **193**: 102522, https://doi.org/10.1016/j.pocean.2021.102522.

Welch, H., Hazen, E.L., Bograd, S.J., Jacox, M.G., Brodie, S., Robinson, D., Scales, K.L., Dewitt, L. and Lewison, R. 2019. Practical considerations for operationalizing dynamic management tools. *Journal of Applied Ecology* **56**: 459–469, https://doi.org/10.1111/1365-2664.13281.

Welch, H., Brodie, S., Jacox, M.G., Bograd, S.J. and Hazen, E.L. 2020. Decision-support tools for dynamic management. *Conservation Biology* **34**: 589–599, https://doi.org/10.1111/cobi.13417.

Xu, Y., Decker, A.S., Parken, C.K., Ritchie, L.M., Patterson, D.A. and Fu, C. 2020. Climate effects on size-at-age and growth rate of Chinook Salmon (*Oncorhynchus tshawytscha*) in the Fraser River, Canada. *Fisheries Oceanography* **29**: 381– 395, https://doi.org/10.1111/fog.12484.

Zacharias, M.A. and Roff, J.C. 2001. Use of focal species in marine conservation and management: a review and critique. *Aquatic Conservation* **11**: 59–76, https://doi.org/10.1002/aqc.429.

7 The Value in Developing Heuristic Models to Examine Pressures and Ecological Responses in Ocean Ecosystems

7.1 Introduction

Understanding and predicting marine ecosystem dynamics is challenging largely due to the multitude of environmental and anthropogenic pressures on target and non-target species and the complexities of their interactions. It is made even more challenging by the dynamic nature of the ocean environment. Heuristic models can be a useful tool for increasing the understanding of complex relationships between pressures and ecosystem responses and how they might inform management actions or outcomes. Such models are simplified representations of ecosystem structure and functioning and are constructed based on hypotheses about the causal relationships among several variables. In fishery and ocean ecosystem studies, heuristic models have been used to follow ecosystem changes in marine food webs, explore unintended consequences from management actions, and make linkages between climate change and marine ecosystems, and the humans that depend on them (Pollnac *et al*., 2015, 2019; Harvey *et al*., 2016).

For TOR 6, WG 36 aimed at developing heuristic models of pressures (climate forcing, fishing) and ecosystem responses using thresholds or reference points, based on WG analyses. Our goal was to demonstrate how indicators with defined thresholds could be useful for assessing ecosystem state and formulating responsive management strategies. However, the outcome of our analyses from TOR 4 precluded us from developing heuristic models for all ecosystems examined. For example, 1) single pressure–response relationships were not examined in all ecosystems, 2) of those where single pressure–response relationships were examined, a small number resulted in defined thresholds, and 3) the identified pressure–response relationships with defined thresholds did not always have clear links to management actions. Here, we provide two examples of heuristic models, for the U.S. (Fig. 7.1) and Korea (Fig. 7.2) case study regions, to illustrate how such models could be constructed and how they might be useful for making management decisions. This heuristic has also been used as a backbone for FUTURE (**F**orecasting and **U**nderstanding **T**rends, **U**ncertainty and **R**esponses of North Pacific Marine **E**cosystems), PICES' integrative science program, with Bograd *et al*. (2019) reviewing how changes in the physical system, such as marine heatwaves, translate to broader ecosystem processes.

7.2 Examples of heuristic models

7.2.1 U.S.A.

Marine heatwaves have highlighted the need for responsive ecosystem-based management for the North Pacific. Recent marine heatwaves, due to long-term warming trends and decreased surface mixing (Jacox *et al*., 2016), have resulted in increased sea surface temperatures (SSTs), causing more significant ecosystem impacts when the marine heatwaves move close to shore. These increased SSTs can displace species poleward (Pinsky *et al*., 2013), or towards the shore, to find refuge in cooler, upwelled waters. Warmer SSTs can lead to increased prevalence of harmful algal blooms whose toxins can have cascading ecosystem effects (Anderson *et al*., 2021). The 2014–2016 marine heatwave in the Northeast Pacific was named "the blob" because of its immensity and consequent ecosystem impacts. The toxins from harmful algal blooms extended from California to Washington, delaying the opening of Dungeness crab fishing (Santora *et al*., 2020). Consequently, foraging opportunities for recovering humpback whales were condensed inshore, putting them at increased risk of entanglement once the crab fishery opened (Santora *et al*., 2020). Since then, the Dungeness crab fishery has faced additional closures resulting in lost revenue and pressures on coastal fishing communities. Ultimately, if we can find thresholds in ecosystem state, *e.g.*, when warming waters are most likely to translate to unanticipated risks, we can better anticipate and react to changing ecosystem conditions to minimize impacts, and maximize sustainable uses of the ocean.

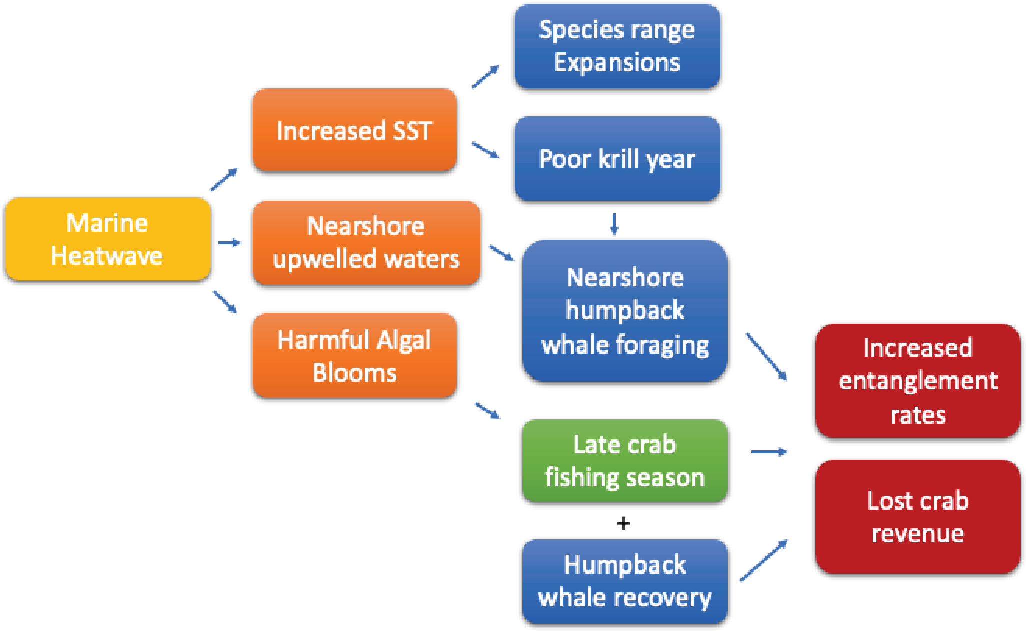


Fig. 7.1 Example of a heuristic model where a marine heatwave is the driver of marine ecosystem dynamics off the U.S. west coast.

7.2.2 Korea

In response to TOR 4, Dynamic Factor Analysis (DFA) was applied to extract common patterns in time series of the environment (N = 17), human pressures (N = 12), and ecosystem components (N = 6) for coastal waters around the Korean Peninsula during 2000–2016. DFA identified two common trends for environmental pressures, two common trends for the human pressures, and one common trend for the ecosystem indicators (Figs. 5.5–5.7). Trend 1 for the environmental pressures was predominant in climate indices (PDO, NINO3.4, MEI, NPGO) and water temperature (Fig. 5.5). This aspect suggests that the temperature changes around Korean Peninsula waters could be affected by changes in the North Pacific climate. However, Trend 1 for the climate indices was not significantly correlated with Trend 1 (squid, mysid shrimp, crab, croaker, and shrimp) and Trend 2 (anchovy and eel) for fish landings and Trend 1 for ecosystem response indicators (individual numbers of copepods, euphausiids, and chordates) (Table 5.1). On the other hand, Trend 2 for the environment pressures (NH_4-N, NO_2-N, DIN, DIP) was significantly correlated with Trend 1 and Trend 2 for fish landings and Trend 1 for ecosystem response indicators (Table 5.1). It seems that fishing and zooplankton are more likely to be affected by regional-scale environmental pressures in waters surrounding the Korean Peninsula.

The significant correlations among the common trends suggest a predictable relationship between environmental and human pressures and ecosystem response indicators for the Korean study system. The decreases in NH_4-N, NO_2-N, DIN, and DIP concentrations were correlated with reductions in individual numbers of copepods, euphausiids, and chordata (Figs. 5.5–5.7, Table 5.1). Decreases in squid catches and increases in croaker and crab catches were also correlated with decreases in nutrient concentrations and individual numbers of zooplankton. Furthermore, increases in anchovy catches were related to decreases in squid catches and increases in croaker, crab, and eel catches. Squid, croaker, and eel feed on anchovies (https://www.nifs.go.kr/frcenter/). It seems that these carnivorous fishes are in competition for prey and mutually affect each other. We summarize these correlations among nutrients, zooplankton, and fishes in Figure 7.2.

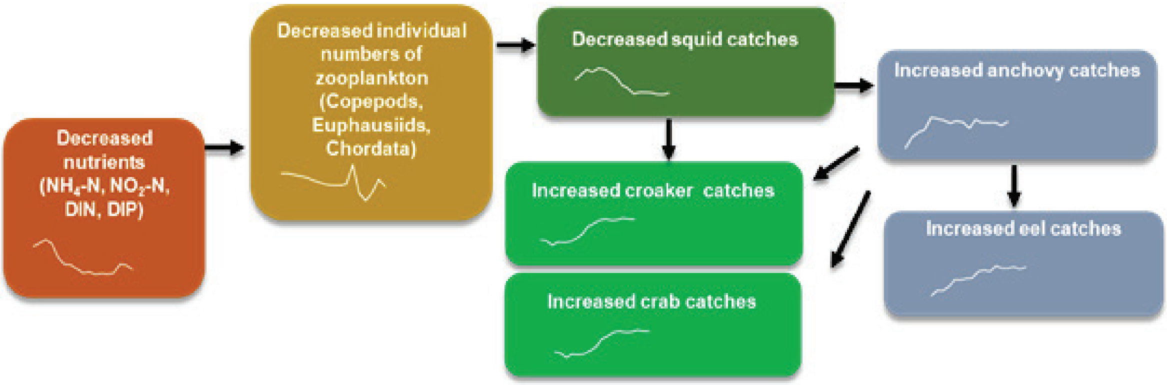


Fig. 7.2 Example of a heuristic model derived from correlations between environmental and human pressures and ecosystem response indicators in Korea's case study ecosystem (see Figures 5.5–5.7, Table 5.1).

According to a 2018 report provided by KSO (Korea Statistical Office, https://kosis.kr/eng), the annual catches of squid, anchovies, and mackerel have been increasing since the rise in temperature during the 1990s. These concurrent increasing trends suggest that fishing in Korea could be affected by changes in the physical environment, driven by climate change. However, in our analysis, we did not find a significant correlation between the common trends of climate indices and fishing (Table 5.1). The common trends for the fish landings and ecosystem indicators were derived from the annual means calculated over all the regions of the study area within Regions 19, 20, and 21. However, the fishing grounds of squid, croaker, anchovy are found in different parts of these bioregions (http://www.nifs.go.kr/). If common trends for the climate indices and fishing in each region are examined, we may identify stronger relationships that lend to predicting ecosystem responses by climate and environmental pressures. Furthermore, we used only chlorophyll-a and zooplankton data for ecological response indicators due to the absence of long-term monitoring data of fish stocks. To understand more clearly and to quantify ecosystem responses to climate and environmental pressures in waters around the Korean Peninsula, scientists and the Korean government need to obtain more fish stock data.

7.3 Recommendations for future research

As environmental, human and ecological time series lengthen and become more readily available, continued efforts to examine pressure–response relationships will enable the development of similar types of heuristic models. Those relationships that may have clear links to management actions should be prioritized. These efforts would help support the development of heuristic models, regardless if the identified relationships are linear or nonlinear. In addition, this information could be used to develop qualitative networks models (QNM, Melbourne-Thomas *et al*., 2012) or to inform quantitative network models, such as structural equation models (Malaeb *et al*., 2000; Kim and Park, 2013, 2017; Pollnac *et al*., 2015, 2019) to assess ecosystem linkages and dynamics. For example, QNM are a useful tool for conducting dynamic simulations of conceptual or heuristic models and evaluating how perturbations might affect different components of an ecosystem as well as management strategies (Harvey *et al*., 2016; Sobocinski *et al*., 2018; Forget *et al*., 2020). They are also well suited for data-poor systems where precise quantitative relationships among different stressors and ecological components are unknown (Reum *et al*., 2015). All of these modeling approaches may serve as valuable tools for supporting ecosystem-based approaches to the management of marine resources in PICES member countries.

7.4 Literature cited

Anderson, D.M., Fensin, E., Gobler, C.J., Hoeglund, A.E., Hubbard, K.A., Kulis, D.M., Landsberg, J.H., Lefebvre, K.A., Provoost, P.R., Richlen, M.L., Smith, J.L., Solow, A.R. and Trainer, V.L. 2021. Marine harmful algal blooms (HABs) in the United States: History, current status and future trends. *Harmful Algae* **102**: 101975, https://doi.org/10.1016/j.hal.2021.101975.

Bograd, S.J., Kang, S., Di Lorenzo, E., Horii, T., Katugin, O.N., King, J.R., Lobanov, V.B., Makino, M., Na, G., Perry, I.R., Qiao, F., Rykaczewski, R.R., Saito, H., Therriault, T.W., Yoo, S. and Batchelder, H. 2019. Developing a social–ecological–environmental system framework to address climate change impacts in the North Pacific. *Frontiers in Marine Science* **6**: 333, https://doi.org/10.3389/fmars.2019.00333.

Forget, N.L., Duplisea, D.E., Sardenne, F. and McKindsey, C.W. 2020. Using qualitative network models to assess the influence of mussel culture on ecosystem dynamics. *Ecological Modelling* **430**: 109070, https://doi.org/10.1016/j.ecolmodel.2020.109070.

Harvey, C.J., Reum, J., Poe, M., William, G.D. and Kim, S. 2016. Using conceptual models and qualitative network models to advance integrative assessments of marine ecosystems. *Coastal Management* **44**: 486–503, https://doi.org/10.1080/08920753.2016.1208881.

Jacox, M.G., Hazen, E.L., Zaba, K.D., Rudnick, D.L., Edwards, C.A., Moore, A.M. and Bograd, S.J. 2016. Impacts of the 2015–2016 El Niño on the California Current System: Early assessment and comparison to past events. *Geophysical Research Letters* **43**: 7072–7080, https://doi.org/10.1002/2016GL069716.

Kim, J. and Park, J. 2013. A statistical model for computing causal relationships to assess changes in a marine environment. *Journal of Coastal Research* **65**(sp1): 980–985, https://doi.org/10.2112/SI65-166.1.

Kim, J. and Park, J. 2017. Bayesian structural equation modeling for coastal management: The case of the Saemangeum coast of Korea for water quality improvements. *Ocean and Coastal Management* **136**: 120–132, https://doi.org/10.1016/j.ocecoaman.2016.10.014.

Pinsky, M.L., Worm, B., Fogarty, M.J., Sarmiento, J.L. and Levin, S.A. 2013. Marine taxa track local climate velocities. *Science* **341**: 1239–1242, DOI: 10.1126/science.1239352.

Melbourne-Thomas, J., Wotherspoon, S., Raymond, B. and Constable, A. 2012. Comprehensive evaluation of model uncertainty in qualitative network analyses. *Ecological Monographs* **82**: 505–519, https://doi.org/10.1890/12-0207.1.

Malaeb, Z.A., Summers, J.K. and Pugesek, B.H. 2000. Using structural equation modeling to investigate relationships among ecological variables. *Environmental and Ecological Statistics* **7**: 93–111, https://doi.org/10.1023/A:1009662930292.

Reum, J.C.P., McDonald, P. S., Ferriss, B.E., Farrell, D.M., Harvey, C.J. and Levin, P.S. 2015. Qualitative network models in support of ecosystem approaches to bivalve aquaculture. *ICES Journal of Marine Science* **72**: 2278–2288, https://doi.org/10.1093/icesjms/fsv119.

Pollnac, R., Christie, P., Cinner, J.E., Dalton, T., Daw, T.M., Forrester, G.E., Graham, N.J. and McClanahan, T.R.2015. Marine reserves as linked social-ecological systems. *Proceedings of the National Academy of Sciences of the United States of America* **107**:18262–18265, https://doi.org/10.1073/pnas.0908266107.

Pollnac, R.B., Carothers, C., Seara, T. and Poggie, J.J. 2019. Evaluating impacts of marine governance on human communities: Testing aspects of a human impact assessment model. *Environmental Impact Assessment Review* **77**: 174–181, https://doi.org/10.1016/j.eiar.2019.02.001.

Santora, J.A., Mantua, N.J., Schroeder, I.D., Field, J.C., Hazen, E.L., Bograd, S.J., Sydeman, W.J., Wells, B.K., Calambokidis, J., Saez, L., Lawson, D. and Forney, K.A. 2020. Habitat compression and ecosystem shifts as potential links between marine heatwave and record whale entanglements. *Nature Communications* **11**: 536, https://doi.org/10.1038/s41467-019-14215-w.

Sobocinski, K.L., Greene, C.M. and Schmidt, M.W. 2018. Using a qualitative model to explore the impacts of ecosystem and anthropogenic drivers upon declining marine survival in Pacific salmon. *Environmental Conservation* **45**: 278–290, https://doi.org/10.1017/S0376892918000073.

Appendix 1

WG 36 Terms of Reference

WG 36 term: 2016–2019
Extended 1 year to 2020
Parent Committee: FUTURE SSC

1. Outline each country's mission, goals, and governmental science plans that point to the establishment of reference points across PICES member nations, and identify those that are comparable.

2. Summarize 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. This will build upon indicators identified via WG 19, WG 28, S-HD and WG 35 (NPESR3). Determine a subset (or not) of ecosystems and indicators that will be the focus of WG activities.

3. Summarize and select previous methods for determining thresholds (both non-linear and societal limits) in ecosystem indicators. This would include statistical and objective-based approaches.

4. Determine shapes or functional forms of pressure–response relationships from available datasets, and quantify thresholds to identify potential ecosystem reference points.

5. Identify ecosystem components that respond earliest to changes in biophysical drivers and could potentially serve as leading indicators of loss of resilience and ecosystem change.

6. Develop a "heuristic model" to examine drivers (climate forcing, fishing) and ecosystem response using selected ecosystem reference points for member nations.

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Appendix 3

Member Country Considerations of WG 28’s Recommended List of Indicators for Use Analyses by WG 36

Theme and Sub-theme	Indicator*	Canada	China	Japan	Korea	Russia	USA
Climate	**ENSO (Multivariate ENSO Index MEI; Oceanic Nino Index ONI)**	X	X	X	YES	X	X
	Pacific Decadal Oscillation (PDO)	X	X	X	YES	X	X
	North Pacific Gyre Oscillation Index (NPGO)	X	X	X	YES	X	X
	Aleutian Low Pressure Index (ALPI)				help from US or CAN		
	North Pacific Index (NPI)				help from US or CAN		
	Southern Oscillation Index (SOI)				help from US or CAN		
	Arctic Oscillation index				help from US or CAN		

Theme and Sub-theme	**Indicator***	**Canada**	**China**	**Japan**	**Korea**	**Russia**	**USA**
Physical Environment	**Sea Surface Temperature (SST) averages by season (D,J,F for W)**	Average for N. California Current (by survey)	X	X	Yellow and East seas	NOAA datasets	California Current
	Sea Level Pressure (SLP) anomaly averaged by season	will ask	will ask	will ask	will ask	average anomaly (and gradients)	average anomaly (and gradients)
	Seasonal projections of SST from national multi-model ensemble						
	Winter maximum sea ice area or extent	NA	NA	X	NA	sea ice concentrations	Kirstin will bring some data
	Freshwater discharge	NA	Yangtze, Yellow river discharge, will ask	for some major rivers, yes	major rivers	Amur River, will ask	X, David Hill and Rob Suryan to ask for GoA
	Upwelling (strength and/or timing)	X					X
	Transport (currents)						
Chemical Environment	**Nitrate**	will ask	X	will ask	coastal only	not long time series	X
	Phosphate				coastal only		
	Silicate				coastal only		
	pH	will ask	X	will ask	coastal only	not long time series	X, but short
	Dissolved oxygen	will ask	X	will ask	Yellow and East seas	not long time series	X

Theme and Sub-theme	Indicator*	Canada	China	Japan	Korea	Russia	USA
Contaminants	**Polychlorinated Biphenyls (PCBs)**	short time series	will ask	will ask	coastal only	coastal	coastal
	Persistent organic pollutants (POPs)	short time series	will ask	will ask	coastal only	coastal	coastal
	Total mercury	short time series	will ask	will ask	coastal only	coastal	coastal
	Tributylin (TBT)			will ask	coastal only		
	Toxics in biota (selected species)			for some species yes	mussels, oysters		
	Swimming beach closures for coliform bacteria contamination			for some beach, yes	NA		
Biological Environment/ Ecosystem Structure	**Harmful Algal Bloom area or frequency (HABs)**	NA for chosen ecosystem	short time series (red tide, green tide)	X	coastal only	X but rare event	X
	Habitat-forming species biomass				NA		
	Spawning Stock Biomass (SSB of selected species)	X	NA	X	will ask	X when published	X
	Mean individual fish weight			X	will ask		
	Mean age at first maturation (for selected species)			X	will ask		
	Mean length at first maturity (for selected species)			X	will ask		
	Distribution range (of selected species)			X	NA		
	Slope of size spectrum	in progress	from publications, will ask	X	in progress	could be done	groundfish survey data

Theme and Sub-theme	Indicator*	Canada	China	Japan	Korea	Russia	USA
Biological Environment/ Biodiversity	**Species richness**	X	X	X	short time series	X (but not used)	X (juveniles)
	Taxonomic diversity	X	X	will ask	short time series	X (but not used)	X (juveniles)
	Number of taxa representing 80% of biomass	X	X	will ask	short time series	X (needs to be calculated)	X (needs to be calculated)
Biological Environment/ Food web energy flows	**Chlorophyll-a**	X (satellite)	X (survey and satellite)	will ask	survey (coastal) satellite	X (satellite)	X (satellite)
	Crustacean plankton biomass	X	X (some species)	will ask	short time series	X	X
	Gelatinous plankton biomass (or volume)	X	X	will ask	short time series	X	X
	Cephalopod biomass				NA		
	Small pelagic fish biomass	X (modeled?)	X from publication	X	NA	will ask, to be calculated	X
	Demersal fish biomass	X (modeled?)	X from publication	X	NA	will ask, to be calculated	X
	Piscivorous fish biomass	X (modeled?)	X from publication	X	NA	will ask, to be calculated	X
	Nekton (at trophic level >3) biomass				NA		
	Top predator biomass,	X (modeled?)	X from publication	X	NA	NA	X
	Seabird breeding success				will ask		
	Seabird abundance (selected species)				will ask		
	Total primary production				satellite-based model		
	Primary production needed to support fisheries removals				NA		
	Crustacean zooplankton secondary production				NA		

Theme and Sub-theme	Indicator*	Canada	China	Japan	Korea	Russia	USA
Biological Environment/ Ecosystem resilience	Mean number of interactions per node				NA		
	Mean trophic links per species				NA		
	Diet diversity index				NA		
Exploitation of Living Marine Resources/ Fishing	**Total landings**	X	will ask	X	Yellow and East seas	X from publication	X
	Mean trophic level of landings	X	will ask	X	Yellow and East seas	X (selected species)	X
	Taxonomic diversity of landings	X	will ask	X	Yellow and East seas	NA (no variability)	X
	Landings (biomass) of selected species	X	will ask	X	Yellow and East seas	X from NPESR	X
Exploitation of Living Marine Resources/ Aquaculture	Aquaculture production (vertebrates, invertebrates)				coastal only		
Social and Economic/ Fishing effort	Annual number of vessels that fish				Yellow and East seas		
	Number of days per calendar/fishing year the fishery is open				NA		
	Annual total number of days spent fishing (“fishing days”)				NA		
	Catch per unit of effort by gear and target fishery				NA		
	Numbers of commercial fishers	will ask	X	X	YES	will ask (likely can be calculated)	X (will ask)
	Number of fish processing plants				will ask		
	Per capita consumption of seafood				YES		

Theme and Sub-theme	Indicator*	Canada	China	Japan	Korea	Russia	USA
Social and Economic/ Landings revenue	Annual total ex-vessel revenue				NA		
	Average price (selected species)				NA		
	Revenue per fishing trip				NA		
	Revenue per fishing day				NA		
	Value and amounts of seafood exports and imports	will ask	X	X	YES	X, will ask	X (will ask)
Social and Economic/ other marine activities	Shipping				YES		
	Hydrocarbon-related activities				NA		
	Coastal engineering/length of shoreline hardening				will ask		
Additional considerations/ Top priorities from WG 35 NPESR and HD committee	Quantity and value of catches and landings of seaweeds, fish, shellfish, and other invertebrates from inside and outside national EEZs	will ask	X	X	YES	X, will ask	X (will ask)
	Quantity and value of mariculture of seaweeds, fish, shellfish, and other invertebrates	will ask	aggregated by quantity, not necessarily value	X	YES	will ask	X (will ask)
	Number and power of fishing vessels by gear type, length, and tonnage	aggregated only	gear type, tonnage	X	NA	NA	X (will ask)
	Catch per unit effort (CPUE) by gear type and target fishery	aggregated only	X by target fishery	?	NA	NA	X (will ask)
	Employment in commercial fishing	will ask	X	X	YES	will ask (likely can be calculated)	X (will ask)
	Coastal population	will ask	will ask	X	YES	will ask	will ask

* Member country considerations of PICES Working Group on *Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors* (WG 28) recommended list of indicators for use analyses. Indicators in bold are WG 28-recommended 'as a core set' of indicators. PICES member countries noted if time series data were available for each indicator ("X") and noted additional details or if data would be requested. This was an initial screening and was refined for inclusion in analyses.

Appendix 4

Overview Article on Commercial Fish Abundance in the Far Eastern Seas and Adjacent Pacific Ocean in *Trudy VNIRO*

The dynamics of the abundance of commercial fish in the Far Eastern Seas and adjacent areas of the open part of the Pacific Ocean and the factors influencing it[3]

A.V. Datsky[1], *V.V. Kulik*[2], *S.A. Datskaya*[3]

[1] Central Office of the Russian Research Institute of Fisheries and Oceanography (FSBSI «VNIRO»), Moscow
[2] Pacific Branch of the Russian Research Institute of Fisheries and Oceanography («TINRO»), Vladivostok
[3] Moscow State University named after M.V. Lomonosov (Moscow State University), Moscow

Abstract

In order to identify the effect of solar activity cycles and other environmental factors on the state of stocks of commercial fish species in the Far Eastern seas and the adjacent water area of the northwestern Pacific Ocean, long-term data on biomass and catch of 28 and 38 groups, respectively, were analyzed. The strength of the relationship between environmental factors and the abundance of fish was measured through the maximum information coefficient and was estimated both without a shift in the series and with a shift of the potential predictor to the past up to 5 years. The research results revealed significant relationships in the impact of solar energy on the abundance of the majority (21 stocks out of 28 for biomass and 26 stocks out of 38 for catch) of commercial fish. Among other environmental factors that have a decisive effect on the abundance of aquatic organisms, water temperature, ice cover, phytoplankton bloom and biomass of various fractions of zooplankton are noted. Abiotic factors are most susceptible to fish in the early stages of development. Peak biomass values of fish, mainly with a frequency of 3-5 and 8-13 years, formed the generation of high numbers, accounting for about 24% of the analyzed generations (data from 380 generations of 27 stocks were used). Due to the regional influence of heliogeophysical and other factors in the dynamics of the abundance of fish of

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[3] *Trudy VNIRO* **186**(4): 31–77, https://doi.org/10.36038/2307-3497-2021-186-31-77

different population groups of the same species, there is a distinct cyclicality in the formation of their abundance. The method for predicting catches used in this work by taking into account the interaction of heliophysical and other environmental factors and the revealed patterns in the frequency of formation of the biomass of population groups and species will increase the efficiency of using the raw material base of marine fish in the study area.

Appendix 5

FUTURE's Research Theme Questions Addressed by WG 36

FUTURE's research theme questions addressed through WG 36, and specifically TOR 4 and TOR 6, are highlighted in bold font.

1. What determines an ecosystem's intrinsic resilience and vulnerability to natural and anthropogenic forcing?
    - 1.1. What are the important physical, chemical and biological processes that underlie the structure and function of ecosystems?
    - **1.2. How might changing physical, chemical and biological processes cause alterations to ecosystem structure and function?**
    - 1.3. How do changes in ecosystem affect the relationships between ecosystem components?
    - **1.4. How might changes in ecosystem structure and function affect an ecosystem's resilience or vulnerability to natural and anthropogenic forcing?**
    - **1.5. What thresholds**, buffers and amplifiers **are associated with maintaining ecosystem resilience?**
    - 1.6. What do the answers to the above sub-questions imply about the ability to predict future states of ecosystems and how they might respond to natural and anthropogenic forcing?

2. How do ecosystems respond to natural and anthropogenic forcing, and how might they change in the future?
    - **2.1. How has the important physical, chemical and biological processes changed, how are they changing, and how might they change as a result of climate change and human activities?**
    - **2.2. What factors might be mediating changes in the physical, chemical and biological processes?**
    - **2.3. How does physical forcing, including climate variability and climate change, affect the processes underlying ecosystem structure and function?**
    - **2.4. How do human uses of marine resources affect the processes underlying ecosystem structure and function?**

- 2.5. How are human uses of marine resources affected by changes in ecosystem structure and function?
- **2.6. How can understanding of these ecosystem processes and relationships, as addressed in the preceding sub-questions, be used to forecast ecosystem response?**
- 2.7. What are the consequences of projected climate changes for the ecosystems and their goods and services?

3. How do human activities affect coastal ecosystems and how are societies affected by changes in these ecosystems?
   - 3.1. What are the dominant anthropogenic pressures in coastal marine ecosystems and how are they changing?
   - 3.2. How are these anthropogenic pressures and climate forcings, including sea level rise, affecting nearshore and coastal ecosystems and their interactions with offshore and terrestrial systems?
   - 3.3. How do multiple anthropogenic stressors interact to alter the structure and function of the systems, and what are the cumulative effects?
   - 3.4. What will be the consequences of projected coastal ecosystem changes and what is the predictability and uncertainty of forecasted changes?
   - 3.5. How can we effectively use our understanding of coastal ecosystem processes and mechanisms to identify the nature and causes of ecosystem changes and to develop strategies for sustainable use?

Appendix 6

Session/Workshop Summaries and Meeting Reports from Past Annual and Inter-sessional Meetings Related to WG 36

PICES-2017, Vladivostok, Russia

4th International Symposium on "*The Effects of Climate Change on the World's Oceans*", Washington, DC, USA, 2018

ICES ASC 2018, Hamburg, Germany

PICES-2018, Yokohama, Japan

PICES-2019, Victoria, Canada

PICES-2020, Virtual

PICES-2017

September 22–October 1, 2017, Vladivostok, Russia

Excerpted from:

Summary of Scientific Sessions and Workshops at PICES-2017

FUTURE Topic Session (S3)
Below and beyond maximum sustainable yield: Ecosystem reference points

Co-Convenors: *Elliot L. Hazen (USA), Jennifer Boldt (Canada), Robert Blasiak (Japan), Mary Hunsicker (USA)*

Invited Speaker: *Robert Blasiak (University of Tokyo, Japan)*

Background

PICES SG/WG-CERP was tasked with identifying ecosystem reference points that would integrate across committees to achieve FUTURE goals and missions. This topic review session examined a) examples of ecosystem reference points that have been established, and b) methodologies for calculating ecosystem reference points from driver–pressure relationships across PICES ecosystems. The goal of this topic session was to bring together experts from physical, biological, and human dimensions to explore past and future approaches to understand how ecosystem management have and can best set reference points that deal with ecological and societal goals. Reference points for fisheries management are generally determined under a single set of environmental conditions with a single species focus. Almost all forms of resource management rely on reference points in order to manage a species (*e.g.*, BMSY, Potential Biological Removal, and Yield per Recruit). However, ecosystem reference points that have been developed have largely focused on additive relationships but more attention is needed on setting reference points in relation to ecosystem functioning such as climatic forcing and predator–prey relationships. One such example, maximum ecosystem yield (MEY) in the Gulf of Alaska and Bering Sea provides an umbrella on total catch, but still does not account for intraspecific dynamics or climate forcing. The Topic Session involved participation from multiple PICES committees and focused on reviewing examples of ecosystem reference points and methods for defining reference points that have been used internationally.

Summary of presentations

Invited speaker, Dr. Robert Blasiak, gave a talk on "*Towards common ecosystem reference points for North Pacific ecosystems*" during the well-attended Tuesday morning Plenary Session. Dr. Blasiak's topic covered reference point terminology, matching reference points to policy commitments, recent work in reference points, and human dimensions. He pointed out that ecosystem reference points are challenging, for example, management objectives for ecosystems are not always well defined, involve a diverse set of stake holders, and can encompass flora, fauna, abiotic conditions, and target and non-target species. Societal objectives and human dimensions are a key element towards setting goals in identifying appropriate reference points. Societal objectives and social systems, however, are in as much change, if not more, as our ecological systems. Dr. Blasiak's talk was an excellent example of needed connections between biophysical indicators and human dimensions.

Topic Session S3 continued after the Plenary Session and was well attended by over 40 participants. Dr. James Thorson gave a presentation on "*Time varying processes in stock assessment: A bridge to ecosystem-based reference points*". He pointed out several reasons why stock assessment output should be used as ecosystem reference points: ecosystem advice can be compared among ecosystems; stock assessments are ubiquitous worldwide, and they have a strong link to management. Two questions to address when using assessments are: (1) How sensitive are assessments to unmodeled processes and (2) how sensitive are management targets to changing productivity? Dr. Thorson discussed different approaches that can help prioritize which processes are important, such as elasticity analysis to look at a single parameter to see how it affects Fmsy or meta-analysis to compare stocks within a given region to look for synchronous changes.

Dr. Ian Perry provided an overview of WG 28 on *Developing Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors*. Dr. Perry reviewed WG 28 outcomes and recommendations. WG 28 not able to propose a comprehensive indicator; instead reviewed indicators, frameworks to select them, and identified common pressures on North Pacific ecosystems. Suites of indicators vary with region (coastal, open), or objectives or pressures, and WG 28 identified a core set of indicators and a toolbox of others. WG 28 developed quantitative methods for assessing potential impacts of stressors and identifying which pressures were most important. Dr. Perry also pointed out that risk diagrams (exposure *vs* sensitivity) may be useful to assess with defining references points.

Ms. Jung-Hyun Lim gave a presentation on the estimation of potential yield in the Korean waters of the East China Sea. Given decreased catches in Korean waters during 1970–2016, she compared different approaches to estimating potential yield of the ecosystem. Ms. Lim compared potential yield estimated using standardized surplus production models (holistic approach) and an ecosystem modeling approach. Estimates of potential yield were surprisingly similar between the two methods. However, each approach had strengths and weaknesses and in conclusion she recommended using holistic approaches.

Dr. Elliott Hazen presented Dr. Mary Hunsicker's talk on "*Characterizing driver-response relationships and defining ecological thresholds in large marine ecosystems*". He pointed out that many ecosystems have experienced regime shifts, with the main drivers being climate change, harvest, and eutrophication. In pelagic systems, highly nonlinear relationships are common and thus may have detectable thresholds.

After the oral presentations, there was a valuable discussion among Session S3 participants and attendees. It was argued that in order to forecast future states of ecosystem indicators, there is a need to understand the mechanisms underlying changes in indicators. Environmental "rules" may change, therefore, multiple approaches (statistical and numerical) may be needed. Dr. George Sugihara's work may be another useful method that could be used to look for non-linearities in indicators. There is good information on target species but not as much is known about nontarget species (such as small forage species). Long-term process monitoring studies are important to address this gap in ecosystem metrics.

There was some discussion about how to provide advice to managers. One suggestion was that social economic analyses integrate many aspects of ecosystems (social, economic, cultural, science) and provide a package that puts ecosystem aspects into context for human impacts and can bridge the gap to managers. It was also noted that perhaps management processes need to be more dynamic. If there are nonlinear responses to an environmental driver, such as the PDO, the PDO cannot be managed, so to make the linkage to management, the total allowable catch, for example, could be reduced under poor environmental conditions. Ensuring transfer of science to management may differ greatly among PICES member countries, which is likely a charge that the Working Group on *Common Ecosystem Reference Points across PICES Member Countries* (WG 36) will need to address as well.

List of papers

Oral presentations

Towards common ecosystem reference points for North Pacific ecosystems (Plenary)
Robert Blasiak

Time-varying processes in stock assessment: A bridge to ecosystem-based reference points
James T. Thorson

Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors: A summary PICES Working Group 28
R. Ian Perry, Motomitsu Takahashi, Jennifer Boldt, and members of WG 28

A study on the estimation of the potential yield in the Korean waters of the East China Sea
Jung Hyun Lim, Hee Joong Kang, Hyun A Kim, Young Il Seo and Chang-Ik Zhang

Characterizing driver-response relationships and defining ecological thresholds in large marine ecosystems
Mary E. Hunsicker, Jameal F. Samhouri and Carrie V. Kappel

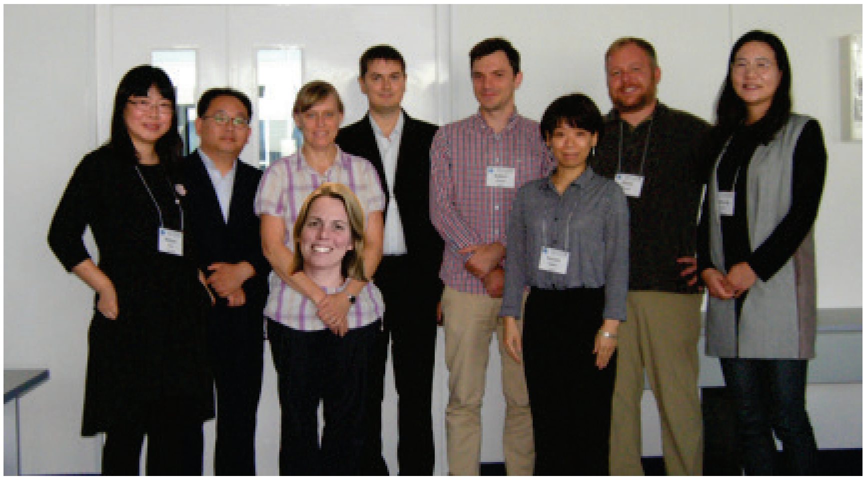
Poster presentations

The application of Argo profile data and innovative methods in fisheries sciences
Peng Lian, Tao Tian, S.J. Joung

Report of Working Group *Common Ecosystem Reference Points across PICES Member Countries*

The Working Group on *Common Ecosystem Reference Points across PICES Member Countries* (WG 36) met from 9:00 to 17:30 h on September 22, 2017 in Vladivostok, Russia, under the chairmanship of Drs. Mary Hunsicker (USA) and Xiujuan Shan (China). The meeting objectives of this first were to review WG 36 TORs (WG deliverables), discuss and summarize WG 36 contributions to FUTURE, discuss indicators and reference points that are important to respective countries and ecosystems, identify action items, develop a work plan and timeline, and discuss cooperation with the other WGs and organizations.

The participants at this meeting are listed in ***WG 36 Endnote 1***. The agenda for this meeting is presented in ***WG 36 Endnote 2***.



Participants of the first meeting of WG 36 at PICES-2017, Vladivostok, Russia. Left to right: Xiujuan Shan, Sangchoul Yi, Mary Hunsicker, Jennifer Boldt, Vladimir Kulik, Robert Blasiak, Kazumi Wakita, Elliott Hazen, Sukyung Kang.

AGENDA ITEM 1

Welcome and WG member introductions

The WG 36 Co-Chairs welcomed members and working group members introduced themselves. Dr. Hunsicker participated via phone.

AGENDA ITEM 2

Review SG-CERP’s report

Dr. Hunsicker provided an overview of the report from the Study Group on *Common Ecosystem Reference Points across PICES Member Countries* (SG-CERP). SG-CERP was supported by

FUTURE, MONITOR, and S-HD and addressed Objective 1.1 of the FUTURE Science Plan to understand what determines "an ecosystem's intrinsic resilience and vulnerability to natural and anthropogenic forcing." Managing ecosystems under a changing climate requires flexibility to facilitate resilient ecosystems for ecological and societal goals. This creates a need for dynamic reference points that reflect a dynamic marine environment and a coupled social-ecological system. Can we develop common ecosystem reference points that incorporate both societal need and climatic variability? How do ecosystem reference points compare among PICES member countries?

SG-CERP members discussed the need for ecosystem reference points and drafted:

1. A Working Group proposal to advance this work through the lifetime of the FUTURE program, including terms of references and deliverables,
2. A Workshop proposal for the 2017 Inter-sessional Science Board meeting (did not occur because membership was still being determined for the WG),
3. Topic Session proposal for PICES-2017 in Vladivostok (S3: *Below and beyond maximum sustainable yield: Ecosystem reference points*),
4. A schematic of where the proposed WG fits in with other PICES expert groups and with FUTURE,
5. A timeline for activities and deliverables for the WG,
6. A table of methods for detecting non-linearities in time series relationships,
7. A table of previous indicator work, including sources for ecosystem indicators, indicator recommendations, and data availability.

AGENDA ITEM 3
Review of WG 36 Terms of Reference

WG 36 members reviewed the TORs for the WG (***WG 36 Endnote 3***).

AGENDA ITEM 4
WG 36 contributions to FUTURE

Dr. Hunsicker reported on WG 36 contributions to FUTURE, and potential collaborations with other WGs. Products from WG 36 will help address some of the goals of FUTURE, such as understanding how marine ecosystems in the North Pacific respond to climate change and human activities. In particular, WG 36 will help address FUTURE's research theme question: "How do ecosystems respond to natural and anthropogenic forcing, and how might they change in the future?" WG 36 will help address FUTURE linkages from ecosystem processes to marine ecosystems and between marine ecosystems and human systems (Figure 1).

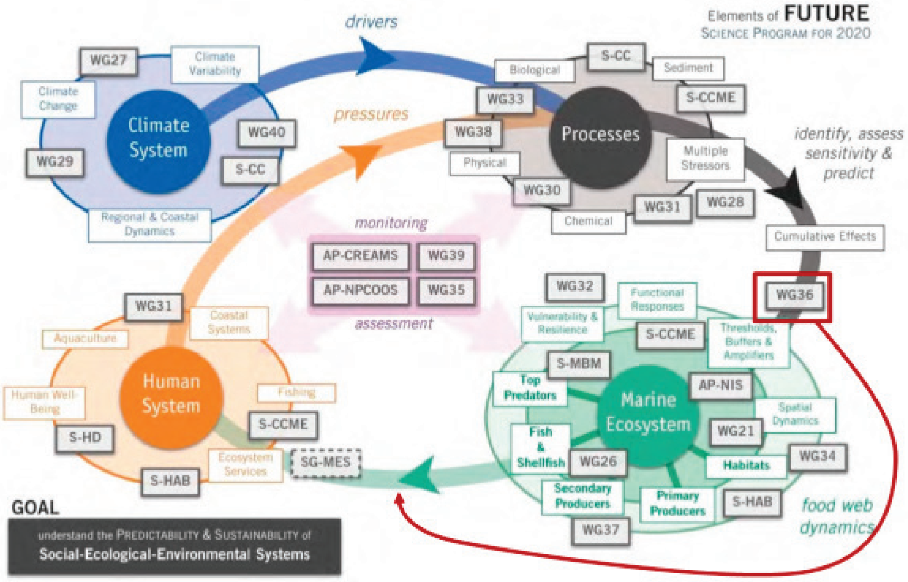


Figure 1 Schematic showing where WG 36 products fit into the FUTURE science program.

AGENDA ITEM 5

Presentations on indicators, reference points, and topics important to respective countries/ study ecosystems and relevant to the WG activities

WG members provided brief, informal presentations on indicators, reference points, and topics that are important to their respective countries/study ecosystems and relevant to the WG activities.

Some of the main points arising from these presentations and follow-up discussions are the following.

- Some important references were identified, including:
  - Monnereau, I., Mahon, R., McConney, P., Nurse, L., Turner, R., Valles, H. 2017. The impact of methodological choices on the outcome of national-level climate change vulnerability assessments: An example from the global fisheries sector. *Fish and Fisheries* 1–15. DOI: 10.1111/faf.12199. Monnerau *et al*. (2017) identified shortcomings in methodological decisions behind vulnerability work such as inconsistent representation among countries belonging to each group, use of socio-economic indicators not scaled to population size, use of a small number of indicators, and lack of accounting for potential redundancy among indicators.
  - Cheung, W.W.L., Pitcher, T.J., Pauly, D. 2005. A fuzzy logic expert system to estimate intrinsic extinction vulnerabilities of marine fishes to fishing. *Biological Conservation* 124: 97–111. Cheung *et al*. (2005) and Cheung and Jones (in press) used fuzzy logic to deal with data gaps and differences in data quality (using a series of “if/then” statements).
  - Wakita *et al*. 2014. Human utility of marine ecosystem services and behavioural intentions for marine conservation in Japan. *Marine Policy* 46: 53–60. This study showed that people’s perception of marine ecosystem services would be diverse based on their way of living and it would affect behavioural intentions for marine conservation.

- Participants discussed what indicators should be examined. Members suggested that the WG could start with some of the indicators recommended by WG 28 (*Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors*) and WG 19 (*Ecosystem-based Management Science and its Application to the North Pacific*), such as biomass of fish by group or community. Discussion points included:
  - Species richness would be difficult to calculate across surveys.
  - Access to some data is limited in different member countries. Publically available data will sometimes provide a different understanding than data that are used in decision making.
  - WG 36 could coordinate with WG 35 (WG-NPESR3) to get data time series, or at least metadata for indicators.
  - One option could be to select one indicator per objective.
  - Indicator selection varies by ecosystem, major pressures, experts involved.
  - Do we need to select a species/objective that is important to all countries?
  - We could examine a couple common indicators across all ecosystems and also include additional indicators that are important for individual ecosystems.
  - Perhaps consider including migratory species shared among countries.

- Participants discussed methodologies for assessing non-linear responses of indicators. The main points were:
  - When comparing different methodologies to detecting nonlinear responses of indicators, General Additive Model (GAM) results are more easily interpreted compared to gradient forest approach.
  - One limitation of GAMs is that they do not work well if there are missing data, and the data time series has to be fairly long.
  - Not many indicators examined so far have a clear threshold.
  - One con of specified functional forms is that you have to know form beforehand
  - GAMs and Gradient forest don't rely on knowing functional form.
  - Nonlinear time series analysis needs a lot of data.
  - Change-point analysis is easy to run.
  - Rodionov's STARS analysis may be better than other change point analyses because it provides a test of significance and behaves better at the end of the time series. STARS has an excel add-on; we could look for R code.
  - Structural equation modeling, which doesn't require a known functional form, is being explored for the California Current's Integrated Ecosystem Assessments (IEA), for use after thresholds have been detected. How the model is structured is important.
  - Second derivative and GAM methodologies are very similar.
  - Gradient forest is used to look for changes in variance – which is somewhat similar to change point analysis.
  - R code is available for GAMs and second derivatives.
  - Gradient forest could be examined for a couple of time series.
  - A GitHub repository could be used to share code.

AGENDA ITEMS 6 TO 11

Action items, work plan/timeline, and meetings for 2017/2018

WG 36 members discussed action items and developed a work plan, and a schedule for meetings during 2017/2018.

- Participants discussed and identified tasks for WG members for TORs 1–3.

  TOR 1: Outline each member country's mission, goals, government science plans and write a summary for the first TOR.

  - Summarize government science plans

    Action item: Each country can likely pull together information for this TOR; the focus would be on fisheries; a variety of ministries in each country would have to be consulted.

    Action item: Dr. Hunsicker to write a template or write the U.S. description so others can follow.
  - Afterwards, WG members could compare among descriptions to identify comparable areas.

  TOR 2: Previous PICES WG 28 and WG 19 tables of data availability provide information for this TOR.

  - The WG will re-visit these tables once we identify/update list of indicators.
  - Determine a subset of indicators: discuss the best method to do this; review objectives or indicators in the excel spreadsheet.
  - Members to review these indicators and determine which are most important for their systems and identify which ones have data that would be easily accessible within the next 6 months and are long enough so that the WG can do analyses on these.
  - Can we do this within the next couple months so that the WG can do analyses on them at the inter-sessional workshop?
  - Members discussed which ecosystems should be examined. There are the NPESR-identified ecosystems that could be used (region numbers); there are individuals that are responsible for each LME. The WG could use data from the NPESR if it matches what was contributed to NPESR.
  - NPFC/PICES group – can WG 36 link to them? Regions 18 and 23 – there are data for Pacific saury with the NPFC. NPFC would be a useful source of data for a couple of species. A WG on jack mackerel will meet in Vladivostok this year.

    Action item: Dr. Kulik to look into data availability from the NPFC.
  - There is no representation from Alaska in WG 36, but the WG could invite someone for the inter-sessional workshop, since they have long time series.

    Action item: members to think about other ideas in terms of how we decide on focal ecosystems.
  - Difficult for some members to identify which indicators are important for their region, perhaps a step-wise approach would be best. For example, the Bering Sea has good biological data coverage. We may have some ecosystems with multiple indicators (*e.g.*, Bering Sea) and others will have fewer indicators, but perhaps indicators in common with the Bering Sea, so comparisons could be made across multiple ecosystems.

    Action: Dr. Hunsicker to send an example and develop this over the next couple of months.

    Action: Dr. Hazen to ask S-MBM for top predators data.

  TOR 3: Potential methods the WG could use.

    Action item: Dr. Hunsicker to add pros and cons (including time series length requirements, if the method can handle data gaps; interpretability, *etc*.) to the methodology table and add other methods (*e.g.*, papers that Dr. Blasiak introduced), include references in the table.

  - WG to continue to think about this, but TORs 1 and 2 are a higher priority.

    Action item: Dr. Hazen to set up a GitHub repository to share code for methods.

    Action item: Dr. Hazen to assemble data sets before the inter-sessional workshop.

- WG members wrote a proposal for an inter-sessional workshop (see ***WG 36 Endnote 4***):
  - Options include:
    - 4th International Climate Change Symposium in Washington, DC, June 4–8, 2018,
    - Transitional Areas Conference in La Paz, Mexico, April 24–26, 2018.
  - The climate change symposium is a priority because we could get input from Scott Large, IndiSeas people.

- Members discussed PICES-2018:
  - No Topic Session was proposed,
  - 1-day business meeting was requested,
  - The Co-Chairs prepared a proposal for a workshop (see ***WG 36 Endnote 5***). This would be a continuation of the Inter-sessional workshop, where we could potentially start analyses for leading indicators (TOR 5) "Identify ecosystem components that respond earliest to changes in biophysical drivers and could potentially serve as leading indicators of loss of resilience and ecosystem change."
  - It was suggested that the WG request another member from Canada.
  - WG 36 should coordinate with S-MBM, WG-NPESR3, and look to better coordinate with HD, and, in year 2 or 3, with WG 40.

- Members developed a PowerPoint presentation report to FUTURE SSC
  Action: Dr. Boldt to draft meeting report and send to the Co-Chairs for edits.

WG 36 Endnote 1

WG 36 participation list

Members

Jennifer Boldt (Canada)
Robert Blasiak (Japan)
Elliott Hazen (USA)
Mary Hunsicker (USA, Co-Chair)*
Vladimir Kulik (Russia)
Xiujuan Shan (China, Co-Chair)
Kazumi Wakita (Japan)
Sangchoul Yi (Korea)

Members unable to attend

China: Yanbin Gu, Yan Jin
Japan: Mitsutaku Makino

Observers

Steven Bograd (USA, FUTURE SSC, SB, POC)
Sukyung Kang (Korea, FUTURE)

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*Participated remotely

WG 36 Endnote 2

WG 36 meeting agenda

1. Welcome and WG member introductions
2. Review SG-CERP's report
3. Review WG 36 TORs (WG deliverables)
4. Discuss and summarize WG 36 contributions to FUTURE
5. Brief, informal presentations on indicators, reference points, and topics that are important to respective countries/study ecosystems and relevant to the WG activities

6. Identify action items, develop work plan/timeline, and schedule meetings for 2017/2018
7. Discuss cooperation with the other WGs and organizations, for example, ICES
8. Draft proposal for an inter-sessional workshop in 2018
9. Draft proposals for a workshop and a topic session at PICES-2018
10. Discuss other potential proposal ideas for priority projects and activities with financial and policy implications
11. Review main highlights for the Co-Chairs' report to the FUTURE SSC

WG 36 Endnote 3

WG 36 Terms of Reference

1. Outline each country's mission, goals, and governmental science plans that point to the establishment of reference points across PICES member nations, and identify those that are comparable. (Intersessional / Yr1);
2. Summarize 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. This will build upon indicators identified *via* WG 19, WG 28, S-HD and WG 35 (NPESR-3). Determine a subset (or not) of ecosystems and indicators that will be the focus of WG activities. (Intersessional / Yr 1);
3. Summarize and select previous methods for determining thresholds (both non-linear and societal limits) in ecosystem indicators. This would include statistical and objective-based approaches (Intersessional / Yr 1);
4. Determine shapes or functional forms of driver–response relationships from available datasets, and quantify thresholds to identify potential ecosystem reference points. (Yr 2);
5. Identify ecosystem components that respond earliest to changes in biophysical drivers and could potentially serve as leading indicators of loss of resilience and ecosystem change. (Yr 3);
6. Develop a "heuristic model" to examine drivers (climate forcing, fishing) and ecosystem response using selected ecosystem reference points for member nations. (Yr 3);
7. Publish final report.

WG 36 Endnote 4

Proposal for an inter-sessional workshop on *"Quantifying thresholds in driver-response relationships to identify reference points"* in conjunction with the 4th International Symposium on *"The effects of climate change on the world's oceans"* in 2018

Duration: 2 days

Convenors: Xiujuan Shan (China), Mary Hunsicker (USA) Jennifer Boldt (Canada), Elliott Hazen (USA)

Suggested Invited Speakers: Yunne-Jai Shin (France), Lynne Shannon (South Africa), Jameal Samhouri (USA), Scott Large (Denmark/ICES)

Marine ecosystems are influenced by dynamic atmospheric and oceanographic drivers and human activities. An open question is whether biological responses within the ecosystems are linear or nonlinear in relation to climatic forcing variables or the abundance of other species. Strong nonlinearities indicate the existence of thresholds beyond which small changes in a climatic variable or species abundance cause large responses in another ecosystem component. Crossing ecological thresholds can alter or redistribute ecosystem benefits to humans and thereby have important socioeconomic consequences. Thus, knowledge of where these thresholds exist is valuable for determining target or limit reference points to prevent ecosystem components from tipping into undesirable states. TOR 4 of WG 36 CERP is to 'determine shapes or functional forms of driver–response relationships from available datasets, and quantify thresholds to identify potential ecosystem reference points'. The proposed workshop is a key step for achieving this goal and for establishing a strong foundation for TOR 5, 'identifying ecosystem components that respond earliest to changes in biophysical drivers and could potentially serve as leading indicators of loss of resilience and ecosystem change'. In addition, having the proposed workshop at the joint ICES/PICES meeting provides an excellent opportunity to develop a cooperation or partnership between these two organizations to advance the science of thresholds and leading indicators of ecosystem change. The specific objectives of the workshop are to: 1) Review results from TORs 1–3, specifically the focal ecosystems and indicators identified for our WG (TOR 2), the available data sets (TOR 2), and the methods selected for identifying thresholds in the ecosystem indicators (TOR 3). 2) Develop or refine previous R code via GifHub that is generalizable for identifying nonlinearities and thresholds in driver–response relationships in the focal ecosystems. 3) Apply analyses to focal ecosystems and indicators and summarize/compare findings. 4) Review and summarize methods for identifying leading indicators of ecosystem change in marine ecosystems to lay the foundation for TOR 4. 5) Review similar efforts from ICES working groups and discuss potential strategies for facilitating a partnership between ICES and PICES, *e.g.* joint working group.

WG 36 Endnote 5

Proposal for a Workshop on *"Identifying common reference points and leading indicators of ecosystem change"* at PICES-2018

Convenors: Xiujuan Shan (China), Mary Hunsicker (USA), Vladimir Kulik (Russia)

Duration: 1 day

Suggested Invited Speakers: Gavin Fay (USA), Steve Munch (USA), Jin Gao (USA), Beth Fulton (Australia), Michael Litzow (USA)

Abrupt nonlinear change in ecosystem structure and function can dramatically alter human-derived benefits from the system and can have negative impacts on people's livelihoods and well-being. A growing number of driver–response relationships in marine ecosystems are being identified as strongly nonlinear, indicating that they are potentially prone to inflection points and threshold dynamics. Better knowledge of where such thresholds occur can advance our ability to anticipate future conditions and critically inform what management actions can maximize ecological, social or economic benefits. Moreover, thresholds common across analogous systems can be used to develop robust sets of reference points to prevent ecosystem components from tipping into undesirable states. A major goal of WG 36 CERP is to 'determine shapes or functional forms of driver–response relationships from available datasets, and quantify thresholds to identify potential ecosystem reference points' in North Pacific ecosystems (TOR 4). The proposed workshop is an important step for completing this goal and for making comparisons among the focal ecosystems selected for WG 36 activities. The workshop will also allow WG 36 to make progress in 'identifying ecosystem components that respond earliest to changes in biophysical drivers and could potentially serve as leading indicators of loss of resilience and ecosystem change' (TOR 5). In addition, the proposed workshop will give WG 36 members an opportunity to work together to ensure that the methods and R code generated for the WG activities can be easily used by PICES member nations as well as other nations to identify potential target or limit reference points and early warning signs of ecosystem change. The specific objectives of the workshop are to: 1) Conduct analyses for TOR 4 to 'determine shapes or functional forms of driver–response relationships from available datasets, and quantify thresholds to identify potential ecosystem reference points' in North Pacific ecosystems. 2) Identify differences and commonalities among thresholds / ecosystem reference points in the focal ecosystems of WG 36 activities. 3) Select common methods for system-wide comparisons to identify leading indicators of ecosystems. 4) Develop, test and share R code via shared GitHub repository that is generalizable for other ecosystems. 5) If time allows, begin applying leading indicator analyses to focal ecosystems of PICES member nations (TOR 5).

4th International Symposium on
"The Effects of Climate Change on the World's Oceans"
June 4–8, 2018, Washington, DC, USA

W11: Quantifying thresholds in driver-response relationships to identify reference points PICES Working Group 36 (CERP) workshop, June 3, 9:00/W11-Invited

Quantifying critical points in ecological indicator responses to fishing and the environment

Scott Large, NOAA Fisheries, Northwest Fisheries Science Center, USA. E-mail: scott.large@noaa.gov

Ecosystem-based fisheries management (EBFM) is a more holistic management strategy that concurrently addresses human, ecological, and environmental factors influencing living marine resources and evaluates these considerations collectively on a system level. Ecological indicators seek to develop decision criteria for EBFM as keyed to quantifiable attributes of ecosystem status. For EBFM, indicator reference points associated with management action need to be quantified, analogous to single species decision criteria (*e.g.*, BMSY). Ecological indicator thresholds would in principle capture responses to both fishing and environmental pressures. Theoretical and quantitative methods have been developed to assign decision criteria to ecological indicators' response to human-use pressures; yet few efforts have established decision criteria in response to the combined influence of human-use and environmental pressures. Here, we seek to identify ecological thresholds at which a small change in fishing and environmental pressure results in an abrupt change in ecosystem status. We applied multiple analytical techniques including bivariate generalized additive threshold models and gradient forest models to determine more broadly (*i.e.*, with global and national representation) if ecological indicators have common inflection points in response to fishing and environmental pressures. Our findings highlight levels of pressure where the magnitude of indicator response might differ from our expectations.

ICES ASC 2018
June 4–8, 2018
Hamburg, Germany

ICES/PICES Theme Session Q
Sustainability thresholds and ecosystem functioning: the selection, calculation, and use of reference points in fishery management

Conveners: Daniel R. Goethel (USA), Henrik Sparholt (Denmark), Aaron M. Berger (USA), Xiujuan Shan (China)

Fishery management systems rely on defining biological reference points, which serve as a basis for setting fishing limits and targets and population sizes. These values govern the establishment of harvest specifications and are used to determine whether a stock's biomass is too low (overfished) and whether fishing intensity is too high (overfishing occurring). In addition, reference points can be critical to harvest rules and management when they contain pre-specified policy measures to be implemented when excessive harvests or depleted biomass occur relative to reference levels. Despite management being reliant on reference points, there are challenges and uncertainties surrounding the choice and calculation of points or proxies and using them in management/policy.

For instance, equilibrium population assumptions underlying the calculation of many reference points are challenged by spatial and temporal variation due to density-dependent mechanisms (recruitment, growth, maturity, and mortality), climate change, variable management and fishing practices, predator-prey dynamics, and myriad other factors. Assuming equilibrium in the presence of regime shifts may limit the reliability and robustness of static reference points, and it remains uncertain whether these changes should be accounted for in a stock management plan.

Multispecies and ecosystem-level reference points often provide a different view of sustainable harvest levels, because single species approaches do not account for the various trade-offs and uses at the system level. For example, single species FMSY management paradigms form the basis of policy advice provided by ICES (and many countries), but ignore ecosystem aspects (such as carrying capacity and species interactions). Ignoring ecosystem dynamics often leads to FMSY approaches being biased and possibly impeding stock rebuilding initiatives and achievement of MSY. There has been increasing exploration of ecosystem dynamics and indicators that could be used as part of a holistic approach to integrated ecosystem assessment. The basis of management decisions in the coming years must be robust and adaptable in order to deal with the changing environment and complexities of multi-sector resource use.

This session will explore best practices and new approaches to calculating and selecting reference points in fishery management. Research and case studies on new approaches and best practices that ensure reference points support sustainable fishery management given complex ecosystems, communities, and management aims are welcome.

PICES-2018

October 25–November 4, 2018, Yokohama, Japan

Excerpted from:

Summary of Scientific Sessions and Workshops at PICES-2018

FUTURE Workshop (W5)
Identifying common reference points and leading indicators of ecosystem change

Convenors: *Mary Hunsicker (USA), Xiujuan Shan (China), Vladimir Kulik (Russia)*

Invited Speaker:
Caihong Fu (DFO, Canada)

Background

Abrupt nonlinear change in ecosystem structure and function can dramatically alter human-derived benefits from the system and can have negative impacts on people's livelihoods and well-being. A growing number of driver–response relationships in marine ecosystems are being identified as strongly nonlinear, indicating that they are potentially prone to inflection points and threshold dynamics. Better knowledge of where such thresholds occur can advance our ability to anticipate future conditions and critically inform what management actions can maximize ecological, social or economic benefits. Moreover, thresholds common across analogous systems can be used to develop robust sets of reference points to prevent ecosystem components from tipping into undesirable states. A major goal of the Working Group on *Common Ecosystem Reference Points across PICES Member Countries* (WG 36/WG-CERP) is to 'determine shapes or functional forms of driver–response relationships from available datasets, and quantify thresholds to identify potential ecosystem reference points' in North Pacific ecosystems (TOR 4). This workshop was an important step for completing this goal and for making comparisons among the focal ecosystems selected for WG 36 activities. The workshop also allowed WG 36 to make progress in 'identifying ecosystem components that respond earliest to changes in biophysical drivers and could potentially serve as leading indicators of loss of resilience and ecosystem change' (TOR 5). In addition, the workshop gave WG 36 members an opportunity to work together to ensure that the methods and R code generated for the WG activities could be easily used by PICES member countries as well as other nations to identify potential target or limit reference points and early warning signs of ecosystem change. The specific objectives of the workshop were to: 1) Conduct analyses for TOR 4 to 'determine shapes or functional forms of driver–response relationships from available datasets, and quantify thresholds to identify potential ecosystem reference points' in North Pacific ecosystems; 2) Identify differences and commonalities among thresholds/ ecosystem reference points in the focal ecosystems of WG 36 activities; 3) Select common methods for system-wide comparisons to identify leading indicators of ecosystems; 4) Develop, test and share R code via shared GitHub repository that is generalizable for other ecosystems; 5) Begin applying leading indicator analyses to focal ecosystems of PICES member countries (TOR 5).

Summary of presentations

WG 36 held a workshop (W5) on October 25, 2018 in Yokohama, Japan. It was chaired by Siujuan Shan and Vladimir Kulik. Mary Hunsicker participated remotely. The main objective of the workshop was to familiarize all WG members with the R programming language and the R scripts needed to run analyses to complete TOR 4 (Determine shapes or functional forms of driver–response relationships from available datasets, and quantify thresholds to identify potential ecosystem reference points).

Invited speaker, Caihong Fu (Canada), provided a talk on her research with Indicators for the Seas (IndiSeas). She summarized research conducted by the two phases of IndiSeas (IndiSea1 and IndiSeas2). Research conducted as part of IndiSeas1 resulted in the evaluation of the ecological status of marine ecosystems relative to fishing. One lesson learned was that it is difficult to distinguish between fishing and environmental effects. For IndiSeas2, climate, biodiversity, and human dimensions indicators were also examined. Dr. Fu conducted model-based simulations to test indicator behavior and performance under controlled environmental conditions and compared these across models, ecosystems, and fishing strategies to account for different sources of uncertainty. Dr. Fu also applied a variety of methods to look for nonlinearities and identify inflection points in time series. She pointed out the challenge of identifying thresholds, because inflection points do not necessarily reflect ecosystem tipping points.

Lisha Guan could not attend the workshop but she provided a talk (given by Xiujuan Shan) on indicators used in China. She summarized the main indicators used to assess the state of marine ecosystems. Physical indicators often used in China include, for example, chlorophyll-a, dissolved inorganic nitrogen and phosphate, rate of denitrification and nitrification, pH, dissolved oxygen, and others. Ecological indicators included, for example, growth rate, age or size at maturity, natural mortality, mean size or age, diet composition, survey-based relative abundance index, abundance of surveyed community, mean length in surveyed community, and others. She summarized results from a case study examining nine fish and shrimp species in the Yellow Sea. As part of this case study, she examined the spatial correlation between encounter probabilities and between positive catch rates for predators and competitors.

Workshop participants had several questions for each speaker and there was a lively discussion about the indicators that were used in the presenters’ analyses.

For the workshop, members built a GitHub repository that includes three test scripts and a test dataset from the California Current that were tested at the Yokohama PICES Meeting. Elliott Hazen led the workshop participants through an R tutorial and reviewed the R code and documentation (on GitHub). Each member country was able to try some if not all the code on data from the U.S portion of the California Current from Samhouri *et al*. 2017. The workshop environment enabled members to help each other with issues and troubleshooting. The GitHub repository created for WG 36 (https://github.com/elhazen/WG-36) includes:

1. Test data – “coast-wide data for reference points.csv”.
2. Dynamic Factor Analysis code - “DFA code v2.0_ELH.R” that will create plots and create a clean dataset that will be used in the next two scripts.
3. Single factor Generalized Additive Model code “Single_Driver_ResponseGAM_v2.R” – GAM and inflections to identify non-linear thresholds.
4. Gradient Forest Analysis code – “gradientForestAnalysis.R” – a multi-factor regression approach to identify non-linear thresholds.
5. INDperform package – “IndicatorPerformancePackage.R” – A method for testing redundancy and utility of indicators presented by Saskia Otto at the ECCWO4 W11.

The workshop participants also discussed examining the “minerva” package that Vladimir Kulik has explored and introduced. This would allow looking into the effects of multiple indicators.

Workshop participants discussed observations, issues, and preliminary results from the R tutorial. Most if not all of the WG members were able to install RStudio, run R code on the California Current time series and reproduce results from the Samhouri *et al.* 2017 paper. Some members were able to apply the analyses to data sets from their own nations as well. From the discussion the participants listed several conclusions and outlined next steps.

Canada: Jennifer Boldt ran the R code for a single-driver and response on IndiSeas indicators and no significant responses between the short list of IndiSeas indicators were found. The list of indicators to be used in her analysis is being expanded to include more of the WG 28 (*Development of Ecosystem Indicators to Characterize Ecosystem Responses to Multiple Stressors*) recommended indicators and to update the time series. One consideration in moving forward with WG analyses is the issue of spatial scale, for example, large-scale climate forcing indicators *vs*. regional survey data that may miss some species *vs*. point estimate data.

China: For the China’s preliminary analyses, Xiujaun Shan successfully ran the R code using total landings as a proxy for human activities, and different taxa landings as the ecological indicators. The NOI, NPGO, PDO were included as the oceanographic indicators. More indicators will be added following the meeting.

Korea: From the Korean side, RStudio and R code were successfully installed and loaded. Preliminarily, the R code was run with temperature and chlorophyll-a in surface coastal waters in Korea retrieved monthly from MODIS satellite from 2002 to 2014. There is no distinct relationship between them. One concern is the availability of long-term data in Korean waters, especially regarding ecological aspects. Most ecological data, such as biodiversity, biomass, and population structure of marine mammals have been obtained temporarily in short term, such as 1 or 2 years. There are various fishery data on landings and model-derived potential landings of mackerel. Next steps include analyzing relationships between indicators suggested by WG 28, including human and climate pressures, and environmental and ecological variables.

Russia: The relationship between marine trophic level (MTI) and catches of dominant objects of fishing in the Russian part of the Region 19 were checked using the R code. There was no significant inflection point found, but the best model was the GAM (thin-plate regression spline over catches). From previous preliminary cross-correlation studies it is known that the strongest effect of catches on the MTI in this case can be found after 3 years. After shifting MTI 3 years forward and rerunning the code the relationship became linear and significantly negative ($r = -0.7$, $p < 0.001$). Obviously, inflection points could not be found again. We will need more time to check other possible relationships between submitted ETSOs for NPESR3.

U.S. west coast: Many of the driver–response relationships have been tested and presented by Samhouri *et al*. 2017 (both GAMs and Gradient Forest Analysis). The next steps for U.S. members are to the expand the GAM and Gradient Forest Analysis using a broader set of indicators, *i.e.*, those indicators suggested by WG 28, and to apply DFA and INDperform to the regional data sets.

From the discussion the participants raised several issues that require further thought and deliberation:

- Some members ran analyses using independently developed code and found that responses to individual pressures were sometimes different than the shape of the same response to multiple indicators. For example, a response to a single driver may be nonlinear, but the response became linear when two drivers were considered.
- Responses to drivers may be lagged.
- How to account for interaction terms and their combinations? This question may need to be considered for each ecosystem. Gradient forest method is appropriate for this (for multiple responses and drivers) and we should pay attention to this.
- Spatial scale of indicators is important to consider (*e.g.*, pollution indicators have different spatial scale than other indicators, such as fishery indicators).
- Multiple other statistical analyses (*e.g.*, factor analysis, MDS, *etc*.) may be worth examining.

From the discussion the participants also outlined next steps:

- Members will continue to collate and update indicators (from the WG 28 list); document indicators, time series, and rationale for the drivers–responses selected;
- Members will carry out analyses on their ecosystems using the R code;
- One of the WG members will review Samhouri *et al*. (2017);
- WG members agreed on the need for regular deadlines, updates, and meetings to keep up momentum on analyses (in addition to an inter-sessional workshop).

From left: Eko Siswanto, Suzan Yeh, Chi-lu Sun, Alekandr Zavolokin, Jennifer Fisher, Mary Hunsicker (by phone), Steve Teo, Gerard DiNardo, Xiujuan Shan, Vladimir Kulik, Jennifer Boldt, Jackie King, Jongseong Ryu, Elliott Hazen, Sukyung Kang, Caihong Fu, Barbara Muhling

List of papers

Oral presentation

Marine ecosystem responses to anthropogenic and environmental pressures: Linear or nonlinear?
Caihong Fu

Report of Working Group *Common Ecosystem Reference Points across PICES Member Countries*

The Working Group on *Common Ecosystem Reference Points across PICES Member Countries* (WG 36) held its second meeting from 9:00 to 17:30 h on October 26, 2018 in Yokohama, Japan. The meeting was co-chaired by Dr. Xiujuan Shan (China), and Dr. Mary Hunsicker (USA) participated remotely. Dr. Shan who welcomed members and participants to the meeting (***WG 36 Endnote 1***) where self-introductions were made. The agenda for the meeting is presented in ***WG 36 Endnote 2***.

Participants of the second meeting of WG 36 at PICES-2018, Yokohama, Japan. Left to right: Xiujuan Shan, Sukyung Kang, Vladimir Kulik, Elliott Hazen, Robert Suryan, Jennifer Boldt, Jongseong Ryu. Missing from photo: Mary Hunsicker who participated by phone.

AGENDA ITEMS 2–4
Review WG 36 terms of reference, activities, progress, action items

WG members reviewed and discussed progress on WG 36 terms of reference (TORs):

1. TOR 1 is drafted by most member countries (excluding Russia); however, all members need to add one to two paragraphs on the research that has been done/is being done in his/her country that is relevant to ecosystem-based fishery management (EBFM) research and reference points.

Action: Members to revise TOR 1 and send to Drs. Hunsicker and Shan.

2. For TOR 2 (identifying core and optional indicators), a couple of notes were made about some indicators: 1) for temperature, raw data should be used, so a common baseline time period does not have to be established, 2) satellite data would be useful because of the broad spatial coverage, and 3) time series for analyses need to be longer than ~15 years.

Actions:

- Members to review the list of indicators and check off those indicators that they have (or double check the list if this was done during the business meeting);

- Jennifer Boldt to contact WG 35 (WG-NPSER3) to see what data are available for indicators;
- Rob Suryan and Elliott Hazen to check with Section on *Marine Birds and Mammals* on availability of diet and reproductive success data;

3. For TOR 3 (comparison of methodologies), we are in the process of drafting a paper that presents the pros and cons of methodologies for identifying thresholds and reference points.

Actions:

- Members to add strengths and weaknesses to the table and send to Dr. Hunsicker;
- Vladimir Kulik to add Minerva to the table with strengths and weaknesses outlined.

4. TOR 4 is still ongoing. WG members have made progress in terms of running R code. To keep the momentum going will require regular and frequent communication among members.

Actions:

- Members to run code and update indicator lists as needed;
- Dr. Hunsicker to email members in early December to indicate how coding and analyses are going, and to send out frequent and regular emails (every 2 months) to check in with members; potentially have phone/internet meetings.

5. TORs 5 and 6 have not been addressed yet. The proposed topic session for PICES-2019 on identifying thresholds and leading indicators (***WG 36 Endnote 3***) could help us move towards TOR 5. In addition, over the next year WG members will continue to discuss the possibility of a one-year extension for our WG.

WG members reviewed related efforts and activities, including:

- 2-day Workshop (W11) on “*Quantifying thresholds in driver-response relationships to identify reference points*” at PICES/ICES/IOC/FAO 4th International Symposium on “*Effects of climate change on the world’s oceans*” (ECCWO-4) in Washington, D.C., June 2018 (Co-Convenors: Mary Hunsicker, Robert Blasiak, Elliott Hazen, Jennifer Boldt, and Xiujuan Shan);
- Theme Session ICES/PICES Theme session Q on “*Sustainability thresholds and ecosystem functioning: the selection, calculation, and use of reference points in fishery management*” (PICES Convenor: Xiujuan Shan) at the ICES ASC 2018 in Hamburg, Germany.

AGENDA ITEM 5

Working group proposal

WG members revised WG 36 TORs for a joint PICES/ICES WG-CERP and submitted to the FUTURE SSC and ICES leadership. The FUTURE SSC presented the request to Science Board which recommended that WG 36 complete its TORs and final report before submitting a new working group proposal to be joint with ICES. WG members will continue to discuss the possibility of a joint ICES/PICES WG and how to align new efforts with ICES WG CERP. The first meeting of the ICES WG CERP will be held at the 2019 ICES Annual Science Conference.

WG 36 Endnote 1

WG 36 participation list

<u>Members</u>

Jennifer Boldt (Canada)
Vladimir Kulik (Russia)
Elliott Hazen (USA)
Mary Hunsicker (USA, Co-Chair)*
Jongseong Ryu (Korea)
Xiujuan Shan (China, Co-Chair)

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*Participated remotely

<u>Members unable to attend</u>

China: Yanbin Gu
Japan: Mitsutaku Makino, Kazumi Wakita
Korea: Sangchoul Yi

<u>Observer</u>

Sukyung Kang (Korea, FUTURE)
Robert Suryan (USA)

WG 36 Endnote 2

WG 36 meeting agenda

1. Welcome and WG member introductions
2. Review WG 36 TORs (WG deliverables)
3. Review of WG 36 activities and progress on TORs and related efforts
4. Identify action items and develop work plan/timeline
5. Decide on workshops, topic sessions and training course and draft proposals
6. Review main highlights for the co-chairs' report to the FUTURE SSC
7. If extra time, work on TORs

WG 36 Endnote 3

Proposal for a Topic Session on "*Identifying thresholds and potential leading indicators of ecosystem change: the role of ecosystem indicators in ecosystem-based management*" at PICES-2019

Co-sponsor: ICES (potentially)
Duration: 1 day

Convenors: Elliott Hazen (USA), Xiujuan Shan (China), Mary Hunsicker (USA), Jennifer Boldt (Canada)

Suggested Invited Speakers: Vladimir Kulik (Russia), Saskia Otto (ICES/Germany), Jamie Tam (Canada), Jeongsong Ryu (Korea)

Abrupt nonlinear change in ecosystem structure and function can dramatically alter human-derived benefits from the system and can have negative impacts on people's livelihoods and well-being. A growing number of driver–response relationships in marine ecosystems are being identified as strongly nonlinear, indicating that they are potentially prone to inflection points and threshold dynamics. Better knowledge of where such thresholds occur can advance our ability to anticipate future conditions and critically inform what management actions can maximize ecological, social or economic benefits. Moreover, thresholds common across analogous systems can be used to develop robust sets of reference points to prevent ecosystem components from tipping into undesirable states. We are interested in presentations on ecosystem indicators and thresholds, leading indicators of loss of resilience and ecosystem change, and the future of indicators, such as novel indicators from socio-ecological systems and examples of how indicators have been used in management. Transdisciplinary presentations are encouraged.

PICES-2019

October 16–27, Victoria, Canada

Excerpted from:

Summary of Scientific Sessions and Workshops at PICES-2019

FUTURE Topic Session (S6)

Identifying thresholds and potential leading indicators of ecosystem change: The role of ecosystem indicators in ecosystem-based management

Convenors: *Elliott Hazen (USA), Xiujuan Shan (China), Mary Hunsicker (USA), Jennifer Boldt (Canada)*

Invited Speakers:
Saskia A. Otto (Institute of Marine Ecosystem and Fishery Science (IMF) Center for Earth System Research and Sustainability (CEN) University of Hamburg)

Background

Abrupt nonlinear change in ecosystem structure and function can dramatically alter human-derived benefits from the ecosystem and can have negative impacts on people's livelihoods and well-being. A growing number of driver–response relationships in marine ecosystems are being identified as strongly nonlinear, indicating that they are potentially prone to inflection points and threshold dynamics. Better knowledge of where such thresholds occur might advance our ability to anticipate future conditions and critically inform what management actions can maximize ecological, social or economic benefits. Moreover, thresholds common across analogous systems can be used to develop robust reference points to prevent ecosystem components from tipping into undesirable states. This session invited presentations on ecosystem indicators and thresholds, leading indicators of loss of resilience and ecosystem change, and the future of indicators, such as novel indicators from socioecological systems and examples of how indicators have been used in management.

Summary of presentations

This topic session was well attended, with active participation from attendees.

Dr. Saskia Otto gave an invited talk titled "*How can we develop suitable indicators to inform management of ecosystems under multiple pressures*". She noted that despite advancement in the science of ecosystem indicators, relationships to pressures are frequently unclear as links can be obscured by environmental change, data limitations, food web dynamics, or non-linear and cumulative effects of multiple pressures. She explained that developing a set of meaningful indicators calls for iterative indicator validations, accounting for natural processes and for trade-offs between management objectives, to enable learning and setting target levels and action thresholds in an adaptive manner. She highlighted the R package INDperform to assist with screening and validating the performance of indicators, which could improve the indicator's usefulness in a management context.

Dr. Philina English's presentation assessed the degree to which changes in distributions of groundfish populations can be explained by locality-specific climate velocities—the distance and direction of movement required to maintain similar climatic conditions through time. She constructed geostatistical spatiotemporal fish density models and compared them to local climate velocity predictions. These models will help anticipate changes in species interactions and fishing pressures.

Dr. Dan Liu examined changing patterns in piscivorous fishes in relation to biotic and abiotic drivers such as sea surface temperature (SST), and particularly the dynamics of their prey assemblage. She found step-changes in small pelagic and prey species. Significant correlations were found both in piscivorous fishes and prey assemblage with SST. She found that impacts of changes in fishing effort were greater than climate variability on catches.

Dr. David Kimmel's talk titled "*Zooplankton abundance trends and patterns in the Shelikof Strait, western Gulf of Alaska 1990-2017*" described shifting phenology impacts on the match–mismatch between zooplankton and their predators. He examined trends in zooplankton abundance and environmental conditions in the Gulf of Alaska over time. A novel finding of his research was that the change in abundance of several species appears to reflect a shift in phenology related to temperature effects on development rate.

Dr. Jason Link gave a talk titled "*Evidence for ecosystem overfishing in North Pacific marine ecosystems*". He presented novel indices of ecosystem overfishing (EOF), providing a brief summary and theoretical background of each, with thresholds. Index values were estimated for all the major large marine ecosystems in the North Pacific. From these he showed that there has indeed been EOF at points in time in many of these marine ecosystems. He also demonstrated that had we been monitoring EOF indicators, we would have detected major changes to fish and fisheries earlier than what we actually did by monitoring on a stock-by-stock basis. He concluded by posing recommendations of these EOF thresholds moving forward to detect and avoid any drastic changes to North Pacific fisheries systems.

Dr. Kelly Andrews investigated forecast performances for key California/Oregon ocean fishery stocks and high priority stocks of prey for endangered southern resident killer whales. He explored how well environmental indices explained variation in forecast performance, and tested for nonlinearities and thresholds. His results suggest environmental influences on preseason forecasts may create biases that unwittingly render salmon fisheries management more or less conservative, and therefore warrant further study and consideration.

Dr. Michael Litzow described how the physical and ecological conditions mapping onto the Pacific Decadal Oscillation index (PDO) and North Pacific Gyre Oscillation index (NPGO) have changed over multi-decadal time scales. These changes apparently began around a 1988/89 North Pacific climate shift that was marked by abrupt Northeast Pacific warming and declining temporal variance in the Aleutian Low, a leading atmospheric driver of the PDO. Dr. Litzow concluded that we cannot assume that relationships with the PDO and NPGO are stationary, and he recommended that primary environmental indicators are used when relating ecological to environmental conditions.

Dr. Stephanie Green gave a talk titled "*Traits-based tools to account for the effect of shifting predator-prey interactions on the distributions of tunas under climate change*". She outlined an initiative that seeks to address this gap by using insights into species' foraging and anti-predation traits to incorporate the effect of climate-mediated range shifts on predator–prey interactions. She described the framework for this approach, and illustrated the process by which it has been applied to model the distribution of tunas and their prey in the California Current system.

Dr. Natasha Hardy looked at albacore tuna as ecosystem samplers/indicators of ecosystem change. She tested whether key behavioural and morphological traits of prey have shaped the prey selection process for albacore tuna in NE Pacific food webs under past climatic conditions, using trait-based analytical tools. Traits of prey included body shape, habitat position and diel migration, refuge/avoidance behaviour, and physical defenses. She highlighted how this approach could be used to forecast the strength of predator–prey interactions as species' ranges shift under climate change in the NE Pacific.

Dr. David Costalago described the pathways and connections between plankton food web components, the seasonal development of these pathways and their spatial variation in the Strait of Georgia. He examined the bottom-up hypothesis that the quality of food is driving Chinook salmon survival. He used fatty acid (FA) biomarkers, stable isotope analyses, and the ratio of essential FAs to examine Chinook salmon prey quality. Dr. Costalago found that zooplankton nutritional quality varies seasonally and spatially, providing different quality of food for outmigrating salmon.

Kym Jacobson examined copepod metrics as indicators of regional ocean conditions. In a case study, she used cold-water and warm-water copepod biomass at one station to see how well it represented broader regional patterns. She quantified the spatial coherence of copepod biomass and identified regional and basin-scale environmental drivers of copepod distributions. Her results showed evidence of similarities in copepod biomass at one station (NH05) compared to other sampling stations of similar depths. The main drivers of copepod distribution included deep temperature, station depth, and the PDO.

At the end of the Session, attendees discussed scale issues. For example, the data requirements for trait-based analyses (taxonomic detail, life history stages, data types) were discussed. It was noted that life history stages of both predators and prey have different traits and there is work underway to address this. Another discussion point regarding scale was the comparison of ICES and PICES communities. Participants discussed how ICES was able to acquire and develop indicators from member nations. It was noted that it was a process that developed over time with various initiatives. For example, regional conventions (*e.g.*, HELCOM) with frameworks required indicators and the Marine Strategy Framework Directive (MSFD) brought more people together with varying expertise, leading to the adoption of novel approaches. Participants agreed that the exchange of ideas between organizations such as PICES and ICES should be supported, since it leads to innovative approaches to assessing marine ecosystems.

List of papers

Oral presentations

How can we develop suitable indicators to inform management of ecosystems under multiple pressure? (Plenary)
Saskia A. Otto

Are Canadian Pacific groundfishes shifting their distribution in response to local climate velocities?
Philina A. English, Sean C. Anderson, Eric J. Ward, Brendan M. Connors, Andrew M. Edwards, Robyn E. Forrest, Karen L. Hunter, Christopher N. Rooper

Identifying drivers and their thresholds for piscivorous fishes in the exploited China Seas under climate change
Dan Liu, Yongjun Tian, Caihong Fu, Shuyang Ma, Jianchao Li, Peng Sun, Zhenjiang Ye and Shijie Zhou

Zooplankton abundance trends and patterns in the Shelikof Strait, western Gulf of Alaska 1990-2017
David Kimmel

Evidence for ecosystem overfishing in North Pacific marine ecosystems
Jason S. Link

Ecological thresholds in forecast performance for key United States West Coast Chinook salmon stocks
William H. Satterthwaite, Kelly S. Andrews, Brian J. Burke, Jennifer L. Gosselin, Correigh M. Greene, Chris J. Harvey, Stuart H. Munsch, Michael R. O'Farrell, Jameal F. Samhouri and Kathryn L. Sobocinski

The changing physical and ecological meanings of North Pacific Ocean climate indices
Michael Litzow, Mary Hunsicker, Nicholas Bond, Brian Burke, Curry Cunningham, Jennifer Gosselin, Emily Norton, Eric Ward and Stephani Zador

Traits-based tools to account for the effect of shifting predator-prey interactions on the distributions of ocean species under climate change
Stephanie J. Green, Natasha A. Hardy, Michael Jacox, Elliott L. Hazen, Steven J. Bograd, Larry B. Crowder

Trait-based modeling for albacore tuna predator-prey interactions under climate change in the NE Pacific
Natasha Hardy, Elliott Hazen, Michael Jacox, Steven Bograd, Larry B. Crowder, Stephanie J. Green

Dynamics of the planktonic food-web of the Strait of Georgia (northeast Pacific) and implications for zooplanktivorous fish
David Costalago, Brian P. V. Hunt, Chrys Neville, Ian Perry, Kelly Young and Ian Forster

Characterizing spatial coherence of copepods as regional indicators in the Northern California Current
Michael J. Dumelle, Jesse F. Lamb, Kym C. Jacobson, Mary E. Hunsicker, Cheryl A. Morgan, Brian J. Burke, and William T. Peterson

Poster presentation

Using phytoplankton community index to assess water quality improvement in Hong Kong
Kedong Yin and Jianzhang He

FUTURE Workshop (W13)
Common ecosystem reference points

Convenors: *Jennifer Boldt (Canada), Vladimir Kulik (Russia), Elliott Hazen (USA), Xiujuan Shan (China), Mary Hunsicker (USA), Jongseong Ryu (Korea)*

Invited Speaker:
Kirstin Holsman (NOAA Alaska Fisheries Research Center, Seattle, USA)

Background

WG 36 on *Common Ecosystem Reference Points across PICES Member Countries* is addressing PICES' FUTURE science program's research theme question: "How do ecosystems respond to natural and anthropogenic forcing, and how might they change in the future?" Strong nonlinearities in marine ecosystems indicate the existence of thresholds beyond which small changes in pressure variables can cause large responses in other ecosystem components. Better knowledge of where thresholds occur can advance our ability to anticipate future conditions and critically inform what management actions can maximize ecological, social or economic benefits. Moreover, thresholds common across analogous systems can be used to develop robust sets of reference points to prevent ecosystems from shifting into undesirable states. The purpose of this workshop was to finalize WG 36 TOR-4: "Determine shapes or functional forms of driver–response relationships from available datasets, and quantify thresholds to identify potential ecosystem reference points". WG 36 convened a workshop at PICES-2018 for which members built a GitHub repository. This GitHub repository includes R code for single pressure GAMs, dynamic factor analyses (DFA), and gradient forest approaches. Participants from each PICES member nation ran the R code on a California Current dataset, and then expanded analyses to country-specific indicators. The Working Group met intersessionally in 2019 to advance progress on TOR-4, and to be more prepared to complete the full set of objectives of the WG at the hands-on practical workshop at PICES-2019. The practical workshop was for WG 36 members and other interested participants to (1) compare results of the threshold quantification analyses, (2) refine the analyses based on group feedback, (3) examine model diagnostics (4) complete additional analyses using gradient forest and DFA approaches, (5) identify next steps, and (6) document the analyses completed and the R code used.

Summary of presentations

PICES Workshop 13 on "*Common ecosystem reference points*" was convened on October 17, 2019. The workshop was well attended with participants actively discussing thresholds and techniques for programming. Workshop conveners welcomed participants, participants introduced themselves, and the agenda was reviewed. Jennifer Boldt reviewed WG 36 Terms of Reference (TOR), the timeline for accomplishing TORs, how this work fits into the PICES Science Program (FUTURE), WG 36 membership, completed WG 36 activities and reports, and the goals of the workshop.

Invited talk
An invited talk was given by Kirstin Holsman titled "*Beyond singular driver-response tipping points and thresholds, recent examples and emerging approaches*". She began with the definition of tipping points as defined in the IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels (IPCC SR1.5): "Tipping points refer to critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system, often with an understanding that the change is irreversible." She then summarized current research and examples of multivariate threshold studies. For example, she highlighted studies that 1) identified principles for managing ecosystems that are prone to tipping points and noted that management actions can change tipping points, 2) showed within year ecosystem sampling /monitoring increases the detectability of reaching thresholds, and 3) there is a need for adaptive thresholds. Leading indications that tell managers when an ecosystem is approaching a tipping point may include deterioration of autocorrelation, increased variance, increased synchrony (asynchrony among communities stabilizes ecosystem function of metacommunities), and declines in spatial heterogeneity. Finally, Dr. Holsman identified potential future approaches to advance our understanding of multivariate thresholds that would be relevant for the working group.

Discussion
Dr. Holsman then led a discussion on multivariate thresholds and potential next steps in WG 36's analyses and future analyses. Workshop participants first identified some science and management questions important to this topic.

Science and management questions:

1. Can we do simulation work based on an heuristic model and real data to help identify tipping points better? This could be *via* tools such as qualitative network models or mental models.
2. How long does a data set need to be to determine tipping points?
3. Can cryptic tipping points be revealed through multivariate approaches? The caveat being that long time series are likely needed for this approach.
4. How can we clearly communicate multivariate thresholds to management?
5. Can we make modeled tipping points contingent on management or state to get at dynamic tipping points?

6. What are the temporal and spatial resolution needs for surveys to identify tipping points? Lack of heterogeneity may be an indicator of an approaching tipping point; therefore, if surveys are not conducted at a fine enough spatial or temporal resolution, this may affect our ability to predict tipping points. When a tipping point is approached, that may be an indication that funds should be directed to monitoring (*e.g.*, Selkoe *et al*. 2015).

Workshop participants discussed these questions and then formulated questions to be addressed in WG 36 analyses (potentially a manuscript) and in future analyses:

1. **How do changes in sampling frequency and spatial scale influence the ability to detect tipping points? Can intensified sampling near a tipping point help identify it?**
2. **How do social and ecological tipping points differ?**
3. How can we identify dynamic (those that change depending on environmental state) and multivariate tipping points?
4. **What if social hysteresis is strong (*e.g.*, new state is desired state)? When an ecosystem gets to a new state how hard is it to get back? Or, in some cases, if it's too difficult or expensive to change the current state, do we settle for the current state?**
5. What are some early warning indicators and how do they perform, *e.g.*, changes in variance, synchrony/asynchrony, heterogeneity, change in trend?

Questions 1, 2, and 4 are the questions that WG 36 will work towards answering within the next year and Questions 3 and 5 can be addressed in future analyses.

ICES Working Group

Dr. Mary Hunsicker provided a summary of the ICES Working Group on Common Ecosystem Reference Points. Their TORs are similar to those of WG 36 and the timeline of the ICES WG is 2019–2021. Their first meeting was convened in September 2019, the next meeting will be convened in November 2020, and their final meeting will be convened in 2021. During the September meeting, participants were able to address some of their Terms of Reference. Dr. Hunsicker pointed out a valuable online tool, ICES SharePoint, that enables ICES Working Group members to share electronic files. This sort of tool would be valuable for the PICES community.

WG 36 TOR discussion

WG 36 members then discussed how they will address TORs 5 and 6. It was decided that TOR 5 could include a case study and not necessarily all ecosystems. In addition, the potential manuscript that was discussed (noted below for TOR 3, including the use of simulated data) could address this TOR.

A conceptual diagram/mental model could address TOR 6 and could include social indicators (not necessarily quantitatively).

For TOR 3, WG 36 members are working on a methods review paper. It was suggested that this manuscript would be strengthened with simulations that Dr. Saskia Otto (ICES) can include. Dr. Hunsicker will share a link to Dr. Otto's work with WG 36 members.

WG 36 members discussed the need for a 1-year extension to finish the final report.

Regional analyses

WG 36 members then provided updates on their regional analyses. All member countries have made progress on analyses; some members needed to complete some steps of analyses, others requested input on results interpretation. There was discussion of additional analyses that could be done (*e.g.*, Bayes DFA).

Work session

Dr. Hunsicker asked members to update the excel table of the list of indicators that each member country has for analyses.

The attendees broke out into subgroups:

1. Individuals working on analyses with the help of other members,
2. Individuals outlining a potential manuscript that was discussed in the morning,
3. Individuals writing an outline for the final report.

Summary

Overall, the W13 workshop objectives were accomplished. Members made significant progress on modeling and result interpretation, developed an outline for a manuscript, and wrote an outline for the final report. Additional R training might be useful to improve PICES member countries' capabilities in future code-dependent efforts.

Workshop 13 participants. Back row, left to right: Sukyung Kang, Shion Takemura, Jackie King, Aleksandr Zavolokin, Kirstin Holsman, Elliott Hazen, Tom Okey, JongSeong Ryu, Vladimir Kulik; Front row, left to right: Kazumi Wakita, Mary Hunsicker, Jennifer Boldt.

List of attendees

Name	Affiliation	Country
Joanna Strzelecki	CSIRO	Australia
Jennifer Boldt*	DFO	Canada
Jackie King**	DFO	Canada
Tom Okey*	School of Environmental Studies/Ocean Integrity Research	Canada
Zengjie Jiang	Yellow Sea Fisheries Research Institute, CAFS	China
Shion Takemura*	National Research Institute of Fisheries Science, FRA	Japan
Kazumi Wakita*	Tokai University	Japan
Sukyung Kang	NIFS	Korea
Jongseong Ryu*	Anyang University	Korea
Vladimir Kulik*	TINRO	Russia
Elliott Hazen*	NOAA/SFSC/NMFS	USA
Kirstin Holsman*	NOAA/AFSC/NMFS	USA
Mary Hunsicker*	NOAA/NFSC/NMFS	USA

**indicates interest in participating in drafting manuscript*
*** indicates interest in R code developed*

List of papers

Oral presentations

Beyond singular driver-response tipping points and thresholds, recent examples and emerging approaches. (Invited)
Kirstin Holsman

Report of Working Group *Common Ecosystem Reference Points across PICES Member Countries*

The Working Group on *Common Ecosystem Reference Points across PICES Member Countries* (WG 36) held its meeting on October 18, 2019 in Victoria, Canada. The participants at the meeting are listed in ***WG 36 Endnote 1*** and the meeting agenda is presented in ***WG 36 Endnote 2***. WG 36 Co-Chair, Dr. Mary Hunsicker welcomed everyone to the meeting.

WG 36 meeting participants at PICES-2019, Victoria, Canada. Clockwise, from top: Elliott Hazen, Vladimir Kulik, Mary Hunsicker, Jennifer Boldt, Jongseong Ryu, Shion Takemura.

AGENDA ITEM 2
Overview of WG accomplishments to date

WG members presented their individual accomplishments on ToRs since the previous workshop and business meeting.

AGENDA ITEMS 3 AND 4
Overview of expectations for WG final report and draft outline

WG members reviewed and revised a draft of the final WG report. The WG plans to organize the report according to the ToRs, with a general introduction and conclusions/recommendations bookending the report. The WG also assigned section leads and timelines for completing different sections of the report.

AGENDA ITEM 5
Future meetings, sessions, publication

The WG submitted a proposal for a topic session at PICES-2020 (***WG 36 Endnote 3***).

The WG also discussed proposing a workshop (possibly for the 2021 Annual Meeting) on collaborative coding and science. WG 36 is depending heavily on the programming language R which is a programming language and free software environment for statistical computing and graphics supported by the R Foundation for Statistical Computing, and is entirely open source. The R language is widely used among scientists, statisticians, and data miners for exploring data and conducting statistical and data analysis. There has been a substantial increase in the popularity of R since its first release in 2000.

Our WG found that sharing of R-code and R-programming skills was paramount to the success of our efforts. As such, we have developed a shared code library *via* GitHub that has been available and accessed by members of the WG.

AGENDA ITEM 6

Workshop and meeting reports

WG members drafted and submitted the following reports and proposals:

- MS Powerpoint slides to FUTURE documenting the group's activities to date,
- Activity report to FUTURE,
- Topic Session proposal to Science Board (PICES-2020; ***WG 36 Endnote 3***),
- Workshop (W13: *Common Ecosystem Reference Points*) summary to the Secretariat (PICES-2019),
- Request to FUTURE SSC/Science Board for a 1-year extension to complete WG ToRs and final report.

In additional activities, WG members continued to work on their analyses for ToR 4 (Determine shapes or functional forms of driver–response relationships from available datasets, and quantify thresholds to identify potential ecosystem reference points). Jennifer Boldt and Elliott Hazen are assisting members with R code and interpretation of model results.

AGENDA ITEM 7

Other business

WG 36 requests Dr. Shion Takemura (Japan) to replace Dr. Mitsutaku Makino who has stepped down as member.

WG 36 Endnote 1

WG 36 participation list

Members

Mary Hunsicker (USA, Co-Chair)
Jennifer Boldt (Canada)
Vladimir Kulik (Russia)
Elliott Hazen (USA)
Jongseong Ryu (Korea)

Members unable to attend

China: Yanbin Gu, Xiujuan Shan (Co-Chair)
Japan: Robert Blasiak, Mitsutaku Makino, Kazumi Wakita
Korea: Sangchoul Yi

Observer

Shion Takemura (Japan)

WG 36 Endnote 2

WG 36 meeting agenda

1. Welcome and sign in
2. Overview of WG accomplishments to date and goals for business meeting
3. Overview of expectations for WG final report and deadline
4. Draft outline for final WG report
5. Planning for future meetings, sessions, publication
6. Write up workshop and business meeting reports
7. Other business

WG 36 Endnote 3

Proposal for a Topic Session on *"Managing for pathways of resilience in a changing climate: recent examples and emerging approaches"* at PICES-2020

Duration: 1 day

Convenors: Xiujuan Shan (China), Kirstin Holsman (USA), Jennifer Boldt (Canada), Mary Hunsicker, (USA)

Suggested Invited Speakers: Angelica Peña (Canada), Shin-ichi Ito (Japan), Manu Di Lorenzo (USA), Anne Solomon (Canada; SES; potential Keynote), Lisa Pfeiffer (economics; USA), Christoph Heinze (U. Bergen, EU tipping points project)

Climate change and compounding anthropogenic pressures pose a risk to marine social-ecological systems. Of increasing concern is the potential for systems to rapidly shift (often irreversibly) to new states in response to pressures. In some cases, such shifts can occur abruptly without much warning, despite years of mounting pressure and apparent system resilience. These nonlinear inflection points in pressure–response relationship, – *i.e*., "tipping points" –, are defined by the IPCC SR15 as "critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system, often with an understanding that the change is irreversible." Identifying singular or compound, nonlinear, or contextual tipping points is of paramount importance to the IPCC as the likelihood of crossing tipping points increases with atmospheric carbon, climate instability, and ecological sensitivity, posing a significant risk for ecological and human wellbeing. Tools and methods for managing systems prone to tipping points are important for national, regional, and local resource management and climate adaptation. While identifying tipping points is challenging, there are multiple recent approaches that advance this objective, especially in terms of multivariate tipping points. We propose a topic session that will 1) explore emergent tools and approaches for identifying multivariate thresholds and tipping points, 2) explore existing and potential social and ecological tipping points and responses, and 3) review approaches for managing systems prone to tipping points. This topic session will bring together international experts from oceanographic, ecological, and social sciences to compare methodologies and synergies across systems. Of particular focus will be methods to promote adaptation and resilience to climate change in marine systems increasingly being pushed towards extremes and tipping points.

PICES-2020
Virtual Annual Meeting

Report of Working Group *Common Ecosystem Reference Points across PICES Member Countries*

The Working Group on *Common Ecosystem Reference Points across PICES Member Countries* (WG 36) held a virtual business meeting on September 15, 2020 at PICES-2020. The participants at the business meeting are listed in *WG 36 Endnote 1*. The agenda for the meeting is presented in *WG 36 Endnote 2*. The objectives of the meeting were to 1) discuss and summarize progress on WG 36 ToRs to date, 2) identify action items and develop revised timeline for the final report, and 3) discuss ideas for follow-up work and PICES working groups. WG 36 Co-Chair, Dr. Mary Hunsicker (USA), welcomed Working Group members and observers to the meeting.

Participants of the fourth meeting of WG 36, at PICES-2020. Top, left to right: Jennifer Boldt, Elliott Hazen, Mary Hunsicker; second row, left to right: Jongseong Ryu, Shion Takemura, Steven Bograd; third row, left to right: Jackie King, Vladimir Kulik, Kazumi Wakita; bottom row: Sonia Batten and Hal Batchelder.

AGENDA ITEM 2

Overview of WG 36 final report

WG 36 requested its parent, FUTURE SSC, for an extension for the report deadline, as progress has been delayed due to the impacts of COVID-19. This request was granted and will be presented at the Science Board meeting for approval. The WG aims to complete and submit the final report to the FUTURE SSC by March 31, 2021.

AGENDA ITEMS 3–6

Discussion of Terms of Reference

WG members reviewed progress on all ToRs. A full draft of ToR 1 is complete with contributions from all member countries. Jennifer Boldt provided an update on ToR 2, and WG members reported on their individual progress and plans for completing their contributions to this ToR. Mary Hunsicker provided updates on ToRs 3 and 4. She and other group members summarized their progress to date on regional analyses, outlined their plans for completing these analyses, and identified actions items and timelines to finish these ToRs.

The WG members also discussed ideas for modifying ToRs 5 and 6 for the final report based on ToR 4 results to date and new knowledge on leading indicators of ecosystem shifts. With helpful input from our FUTURE SSC liaison, Jackie King, the WG members have devised a plan for how to address these ToRs to ensure our efforts are worthwhile and can be completed in a timely manner. The WG members will flesh out these ideas over the coming weeks.

The WG is using Google Drive and Dropbox to organize materials and text for the final report.

AGENDA ITEM 7

Plan for future meetings and sessions

FUTURE SSC Co-Chair, Steven Bograd, informed meeting participants of a joint meeting between multiple FUTURE WGs that was held during PICES-2019 in Victoria, Canada. This meeting led to the development of a workshop proposal on climate extremes, the mechanisms and forcing of extremes on ocean ecosystems, and their impacts on biology and human services (titled "*The social-ecological-environmental dynamics of climate extremes in Pacific coastal systems*"). The session was approved at PICES-2019 but deferred to the 2021 PICES Annual Meeting due to COVID-19. In addition, WG 40 recently discussed proposing a new working group on climate extremes and suggested that one aspect would be predictability of extremes (*e.g.*, Marine Heatwaves) or predictability of response. This new working group could provide a good mechanism for integrating WGs 36, 40, and 41. The FUTURE SSC will discuss the potential for this working group during their meeting in October 2020. Dr. Bograd will follow up with our WG following their meeting and will help facilitate a discussion among members from WGs 36, 40, and 41 about pursuing a new study group or working group.

AGENDA ITEM 8

Reports

WG 36 members drafted and submitted the following reports and proposals:

- MS Powerpoint slides to FUTURE documenting the group's activities to date;
- Request for a 6-month extension to complete WG ToRs and final report.

WG 36 Endnote 1

WG 36 participation list

<u>Members</u>

Mary Hunsicker (USA, Co-Chair)
Jennifer Boldt (Canada)
Vladimir Kulik (Russia)
Elliott Hazen (USA)
Jongseong Ryu (Korea)
Shion Takemura (Japan)

Kazumi Wakita (Japan)

<u>Members unable to attend</u>

China: Yanbin Gu, Xiujuan Shan
Japan: Robert Blasiak
Korea: Sangchoul Yi

<u>Observers</u>

Steven Bograd (USA, FUTURE SSC Co-Chair)
Jackie King (Canada, FUTURE)
Sonia Batten (PICES)
Harold (Hal) Batchelder (PICES)

WG 36 Endnote 2

WG 36 meeting agenda

1. Welcome; goals for business meeting
2. Overview of WG final report to date
3. Discussion about ToR 2 – updates from member nations
4. ToR 3 update; discussion about ToR 4 – updates from member nations
5. Discussion about ToRs 5 and 6 and suggested changes
6. Discuss next steps and timelines for completing ToRs and final report
7. Discuss next steps for future related work and PICES working groups
8. Write up business meeting report and create slides for FUTURE SSC meeting

Appendix 7

PICES Press Article Related to WG 36

ECCWO-4 Workshop on "*Quantifying thresholds in driver-response relationships to identify reference points*"

by Robert Blasiak, Jennifer Boldt, Elliott Hazen, Mary Hunsicker and Xiujuan Shan

Participants of Workshop 11 at the 4th International Symposium on "The effects of climate change on the world's oceans" in Washington, DC. Workshop convenors (and authors of this article) are Robert Blasiak (fifth from left), Xiujuan Shan (sixth from left), Elliott Hazen (kneeling), Mary Hunsicker and Jennifer Boldt (right hand side of photo, front).

How are conditions in marine ecosystems shaped by diverse sets of dynamic atmospheric and oceanographic drivers? Which responses within these systems are linear in nature, and which are nonlinear? Is it possible to identify thresholds beyond which small changes in one variable can have large impacts on others? Where do human dimensions and all the associated drivers fit into this? And how can PICES member countries identify relevant ecosystem reference points and utilize these to avoid undesirable management outcomes?

These and many other questions were the basis for the 2-day PICES WG 36 workshop (W11) on "*Quantifying thresholds in driver-response relationships to identify reference points*" at the 4th International Symposium on "*The effects of climate change on the world's oceans*", June 2–3, 2018 in Washington, DC. The workshop aimed to:

1. Specifically identify focal ecosystems and indicators for the Working Group, collect available data sets from PICES member countries, select methods for identifying thresholds in the ecosystem indicators, and apply analyses to focal ecosystems and indicators;
2. Review and learn from similar efforts from other organizations such as ICES working groups and IndiSeas;
3. Identify potential partnerships between PICES and other organizations to advance the science of thresholds and leading indicators of ecosystem change.

With these broad aims, the first day of the workshop was designated as a closed session aimed at making progress towards achieving WG 36's terms of reference. The morning session began with presentations by representatives from PICES member countries focused on each country's mission, goals and governmental science plans related to the establishment of reference points. In addition, Lynne Shannon (University of Cape Town, South Africa) provided an overview of the IndiSeas project's approach to identifying common ecosystem indicators across various marine ecosystems, along with Dr. Kelly Ortega Cisneros (Rhodes University, South Africa) and Scott Large (NOAA Fisheries, USA). In the afternoon, WG 36 participants provided datasets, time series data, and programming scripts that enabled some initial analyses aimed at identifying thresholds in driver-response relationships, with assistance from Scott Large.

The open workshop on the second day was well attended, and filled with excellent presentations and lively discussions. It provided an excellent opportunity for the PICES Working Group to engage with members of other research communities, including ICES and IndiSeas. An introductory presentation about WG 36 was provided by WG Co-Chair. Mary Hunsicker (NOAA Fisheries, USA).

Scott Large delivered an invited presentation on "*Quantifying critical points in ecological indicator responses to fishing and the environment*". He gave an overview of how we can move from driver-response relationships to identifying ecosystem thresholds to inform management. Among other things, he emphasized the complexities involved with assessing the multiple indicators interacting within an n-space, and subsequently communicating the outcomes of such assessments.

Additional presentations were delivered by Caihong Fu, Gro van der Meeren, Saskia Otto, and Kirstin Holsman. Common threads among all the presentations included the challenges and value of identifying the most relevant and applicable ecosystem reference points in different regions. Speakers emphasized the need for effective ways of communicating the science and uncertainty inherent to such analyses and feeding this into decision-making processes.

Caihong Fu (Department of Fisheries and Oceans, Canada) talked about ecosystem-level biological reference points under varying climate and ecosystem states. She and her collaborators, including Yunne-Jai Shin (UMR MARBEC, France), are planning to use the individual-based model OSMOSE (Object-oriented Simulator of Marine biOdiverSity Exploitation) to identify more effective indicators of ecosystem change and thresholds, and to develop optimal ecosystem-level fishing strategies that are adaptive to changing environment and ecosystem conditions.

Gro van der Meeren (Institute of Marine Research, Norway) presented an overview of common ecosystems from the perspective of the Barents, Norwegian and North seas ecosystems. Indicators and thresholds have been identified for all of these systems and are mostly linked to climate change. Two take-home messages from her presentation are: 1) ecosystem state and trends are reported by natural scientists but the advice often lacks inclusion of legal, social or economic research and 2) global assessments of indicators and thresholds need to include local expertise involved in regional ecosystem assessments.

Saskia Otto (University of Hamburg, Germany) presented the status of indicators and thresholds in the Baltic Sea. Saskia first presented a summary of the latest HOLAS (Holistic Assessment) report by HELCOM (Helsinki Commission) and gave an overview of how the Ecological Quality Ratio is used within a holistic assessment to determine environmental status. She also gave an overview of an R package that she has developed (INDperform), which can be used to: 1) validate ecological state indicators, 2) select a suite of complimentary and well performing indicators and 3) assess the current state of the system in comparison to a reference period (Otto *et al*., 2018). This R package is a potential resource for WG 36 and may provide a foundation for future analyses.

Kirstin Holsman (NOAA Fisheries, USA) was the final presenter in our workshop and she gave a comprehensive overview of indicators and thresholds from the perspective of Alaska ecosystems. She described how ecological and human dimension indicators are incorporated within the Alaska Ecosystem Considerations Report and Integrated Ecosystem Reports and gave examples of how the Alaska Fisheries Science Center (AFSC) is trying to make ecosystem thresholds more operational. She also explained the North Pacific Fishery Management Council Process where the ecosystem status report is presented prior to AFSC stock assessments. She emphasized the value in having a presentation on ecosystem information timed together with the stock assessment for management uptake.

The workshop concluded with strong interest and discussions among the participants about future collaborations. The coming months will see stronger links between researchers engaged in studying ecosystem reference points and thresholds in the North Atlantic and North Pacific.

Dr. Robert Blasiak (robert.blasiak@su.se) is a Research Scientist at the Stockholm Resilience Centre (Stockholm University) and a visiting Research Scientist at the Graduate School of Agriculture and Life Sciences (The University of Tokyo). His research interests include biodiversity in areas beyond national jurisdiction, vulnerability of communities to climate change impacts on fisheries, and the emergence of conflict and cooperation in management of ocean resources. In PICES, he is a member of Working Group 36 on Common Ecosystem Reference Points across PICES Member Countries.

Dr. Jennifer Boldt (Jennifer.Boldt@dfo-mpo.gc.ca) is Research Scientist at the Pacific Biological Station, Fisheries and Oceans Canada. Her research interests are pelagic forage fish ecology, including responses to biological and environmental drivers, and ecosystem indicators and assessments. In PICES, she chairs the MONITOR Committee and is a member of Working Group 36 on Common Ecosystem Reference Points across PICES Member Countries.

Dr. Elliott Hazen (Elliott.hazen@noaa.gov) is a Research Ecologist at NOAA Fisheries Southwest Fisheries Science Center. His research interests include 1) Species Ecology, Movement, and Distribution: How do ocean species use both ocean features and prey landscapes to migrate and forage? 2) Foraging Theory and Behavior: How does prey mediate fine scale foraging ecology and behavioral plasticity of rorqual whales? 3) Climate Variability and Climate Change: How is climate change expected to change pelagic ecosystems and the people that depend on them? Elliott is a member of the PICES WG 36 on Common Ecosystem Reference Points and the Section on Marine Birds and Mammals.

Dr. Mary Hunsicker (mary.hunsicker@noaa.gov) is a Research Ecologist at NOAA Fisheries Northwest Fisheries Science Center. Her research interests include elucidating nonlinear dynamics and thresholds in relationships between climate and human drivers and ecological responses; testing the utility of early warning indicators to reliably detect abrupt shifts in marine ecosystems; and understanding the influence of environmental variables on species distributions and interactions. Mary is the Co-Chair of PICES WG 36 on Common Ecosystem Reference Points.

Dr. Xiujuan Shan (shanxj@ysfri.ac.cn) is a Professor at the Yellow Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences, and the Deputy-Director of Key Laboratory for Sustainable Utilization of Marine Fishery Resources, Ministry of Agriculture. Her research is focused mainly on fish stock assessment, fish biodiversity and the dynamics of marine ecosystem, particularly in the Bohai and Yellow Sea ecosystem, as well as projections of climate change on fisheries in China. She is the group leader of FISH STOCK task in UNDP/GEF project "Yellow Sea Large Marine Ecosystem". She also serves as the Co-Chair of PICES WG 36 on Common Ecosystem Reference Points across PICES Member Countries and is a member of China SCOR Committee.