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Quo Vadimus

Lessons learned from the PICES FUTURE Program on development of an interdisciplinary international science program to advance ocean sustainability

Shion Takemura [1,*,†], Hanna Na [2], Jennifer L. Boldt [3], Steven J. Bograd [4], Daisuke Hasegawa [5], Karen L. Hunter [3], Sukyung Kang [6], Oleg N. Katugin [7], Saeseul Kim [8], Vyacheslav B. Lobanov [9], Emanuele Di Lorenzo [10], Mackenzie Mazur [3], Hitomi Oyaizu [1], Fangli Qiao [11], Ryan R. Rykaczewski [12], Erin V. Satterthwaite [13], Seongbong Seo [14], Chengjun Sun [11], Thomas W. Therriault [3], Mitsutaku Makino [15,†]

[1]Japan Fisheries Research and Education Agency, Yokohama, Kanagawa, 2368648, Japan
[2]School of Earth and Environmental Sciences, Seoul National University, Seoul, 08826, Republic of Korea
[3]Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, BC, V9T 6N7, Canada
[4]NOAA Southwest Fisheries Science Center, Monterey, CA, 93940, United States
[5]Japan Fisheries Research and Education Agency, Shiogama, Miyagi, 9850001, Japan
[6]National Institute of Fisheries Science, Busan, 46083, Republic of Korea
[7]Pacific branch of the Russian Federal Research Institute of Fisheries and Oceanography, Vladivostok, Primorsky Kray, 690091, Russia
[8]PICES Secretariat, Sidney, BC, V8L 4B2, Canada
[9]V.I. Il'ichev Pacific Oceanological Institute, Vladivostok, Primorsky Kray, 690041, Russia
[10]Department of Earth, Environmental, and Planetary Sciences, Brown University, Providence, RI, 02912, United States
[11]First Institute of Oceanography, Ministry of Natural Resources, Qingdao, 266061, China
[12]NOAA Pacific Islands Fisheries Science Center, Honolulu, HI, 96818, United States
[13]California Sea Grant and CalCOFI, Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, 92093, United States
[14]Korea Institute of Ocean Science and Technology, Busan, 49111, Republic of Korea
[15]Atmosphere and Ocean Research Institute, The University of Tokyo, Chiba, 2770882, Japan

*Corresponding author. Japan Fisheries Research and Education Agency, Yokohama, Kanagawa, 2368648, Japan. E-mail: takemura_shion01@fra.go.jp
†equal authorship

Abstract

Interdisciplinary international science programs that combine environmental, ecological, and social research are pivotal in advancing ocean sustainability by integrating diverse expertise and fostering collaboration across borders. We examine the evolution and accomplishments of the North Pacific Marine Science Organization's (PICES) Forecasting and Understanding Trends, Uncertainty and Responses of North Pacific Ecosystems (FUTURE) Program, designed to understand and communicate the future of North Pacific ecosystems under various natural and anthropogenic forces. The program's unique application of the North Pacific Social-Ecological-Environmental Systems (SEES) framework has aimed to facilitate interdisciplinary collaboration and enhance our comprehension of ecosystem responses to climate variability. Through a combination of systematic review and quantitative text analysis of research outputs, we evaluate the program's success in addressing its scientific objectives, and identify key areas for future research. Our findings highlight significant shifts in PICES' research focus over time, evolving from basic marine science to applied ecosystem management. We also discuss the challenges faced in understanding ecosystem resilience, the impact of human activities, and the effectiveness of interdisciplinary approaches in advancing ocean sustainability. The lessons learned from the first two phases of the FUTURE Program (2010–2020) provide valuable insights for planning and executing large-scale international science initiatives aimed at enhancing ocean sustainability and addressing global climate variability.

Keywords: ocean sustainability; interdisciplinary; PICES FUTURE Program; ecosystem resilience; SEES framework; environmental change; human dimension

Introduction

Marine environments are shaped by the interplay between natural processes and human activities in space and time, so envisioning them as integrated social-ecological systems is vital to ensure that we holistically understand and manage them in their entirety. Additionally, oceans transcend national boundaries, so international collaboration, as facilitated by organizations like the North Pacific Marine Science Organization (PICES), enhances our ability to understand and develop effective strategies to address complex global challenges by combining and integrating expertise and resources.

Review of FUTURE science plan and SEES approach

PICES was established in 1992 "to promote and coordinate marine scientific research in order to advance scientific knowledge" (PICES Convention Article III). Researchers from six member countries (Canada, Japan, People's

Republic of China, Republic of Korea, the Russian Federation, and the United States of America) conduct scientific activities organized by discipline-based permanent committees. These committees include the Biological Oceanography Committee (BIO), the Fishery Science Committee (FIS), the Marine Environmental Quality Committee (MEQ), and the Physical Oceanography and Climate Committee (POC), all established in 1992; the Technical Committee on Monitoring (MONITOR), established in 2004; the Technical Committee on Data Exchange (TCODE), established in 2005; and the Human Dimensions Committee (HD), established in 2016. The overall activities are guided by the Science Board (scientific aspect), Finance and Administration Committee (resource aspect), and the Governing Council (governance aspect) (Tjossem 2017).

PICES established its first flagship science program, "Climate Change and Carrying Capacity" (CCCC; 1995–2009) to promote, coordinate, integrate, and synthesize interdisciplinary studies linking climate change and variability to physical conditions and ecosystem structure and function in the North Pacific and its adjacent marginal seas. The CCCC Program was an international research program in PICES, positioned as a regional program in the North Pacific under the Global Ocean Ecosystem Dynamics (GLOBEC) Program initiated by SCOR and UNESCO-IOC in 1991 (Hargreaves 1996). The CCCC Program focused on resolving how climate variability and change affects ecosystem structure and the productivity of key biological species at all trophic levels in the subarctic Pacific Ocean. Perry et al. (2002) assessed that the CCCC Program, beyond its initial objective of developing and coordinating research activities under the GLOBEC umbrella (e.g. Chavez et al. 2008), achieved its goal of stimulating and integrating programs on climate change and marine ecosystems in the North Pacific. On the other hand, they noted that the CCCC Program had not effectively initiated joint research with PICES' own observational programs on how changes in ocean conditions affect the lower and upper trophic levels, and that this remains a challenge. Perry et al. (2002) posited several questions to guide the evolution of the CCCC Program and PICES science: Are the structure and function of the North Pacific marine ecosystems different now than they were 200 years ago? Considering the significant declines in marine mammal populations, what has happened to the "excess production" that used to fuel these large upper trophic level populations? What can we learn from these changes that will help us understand the future of the North Pacific and its ecosystems in relation to climate change?

In October 2009, PICES's second flagship science program, "Forecasting and Understanding Trends, Uncertainty, and Responses of North Pacific Marine Ecosystems" (FUTURE) was launched, building on the knowledge and experience of the CCCC Program. While the CCCC Program emphasized climate change and impacts, FUTURE focuses on societal concerns arising from potential threats to North Pacific ecosystems (FUTURE Science Plan). In addition, the FUTURE Program differs from the CCCC Program in that it is a PICES-led program rather than a specific, global, or international research initiative. The ultimate goal of FUTURE is to understand and communicate the future of North Pacific ecosystems and the potential impacts from and on human use. This cornerstone initiative involving its member countries and associated entities (https://meetings.pices.int/Members/Scientific-Programs/FUTURE) is centered around three major scientific questions: (1) What determines an ecosystem's intrinsic resilience and vulnerability to natural and anthropogenic forcing?; (2) How do ecosystems respond to natural and anthropogenic forcing, and how might they change in the future?; and (3) How do human activities affect coastal ecosystems and how are societies affected by changes in these ecosystems? (see Appendix 1). FUTURE has two overriding objectives that when achieved will not only benefit PICES member countries but also marine science more broadly. These objectives are: (1) to increase understanding of climatic and anthropogenic impacts and consequences on North Pacific marine ecosystems, with continued leadership at the frontier and cutting-edge marine science; and (2) to develop activities that include interpretation, clarity of presentation, peer review, dissemination, and evaluation of ecosystem data products (e.g. status reports, outlooks, forecasts), and establish a process for engaging interested institutions and other recipients (e.g. intergovernmental science and management organizations). FUTURE aims to achieve its mission by developing an investigative framework that bridges various disciplinary perspectives spanning the marine and social sciences. This framework is essential for a thorough comprehension of marine ecosystem fluctuations across the North Pacific, their anthropogenic and environmental drivers, and their consequent effects on coastal marine resources, communities, and populations. The complexity of these interactions, which are often nonlinear and span diverse spatial and temporal dimensions, poses challenges to managing shared and cross-border environmental issues.

The investigative framework central to FUTURE is the North Pacific Social-Ecological-Environmental System (SEES) Framework that was developed by PICES researchers in consultation with the PICES community (Fig. 1, Bograd et al. 2019). This scalable and adaptable framework is instrumental in comprehensively understanding the interplay between the Climate System, Marine Processes, the Marine Ecosystem, and the Human System (Fig. 1) with specific scientific activities carried out by PICES Expert Groups (Study Groups, Working Groups, Advisory Panels). FUTURE has used the SEES framework to help guide the composition and activities of PICES expert groups so that the overarching structure of PICES leads to a more complete and integrated understanding of North Pacific marine ecosystems. Specifically, this framework facilitates understanding key strengths, gaps, and potential synergies across the PICES Expert Groups, allowing FUTURE to be responsive to the emerging needs of the organization and its member countries. At the heart of this framework is the emphasis on integrated, long-term, and sustained monitoring and assessment across all components of the system, including environmental, ecological, and social. This approach is pivotal in uncovering interactions across different disciplinary dimensions, thereby enhancing our understanding of large-scale ecosystem changes and their consequent impacts (Fig. 1).

Objectives

Our primary objective is to identify research topics and monitor changes in research activities in PICES through time. We assess how PICES science has evolved over time, beginning with the first flagship Science Program, CCCC (1995–2009), and continuing through the initial phases of the FUTURE Program (Phase I: 2010–2015, Phase II: 2016–2020). If PICES has advanced the integration of marine science disciplines to enhance our understanding of the structure and function of marine ecosystems, we hypothesize that this will be reflected

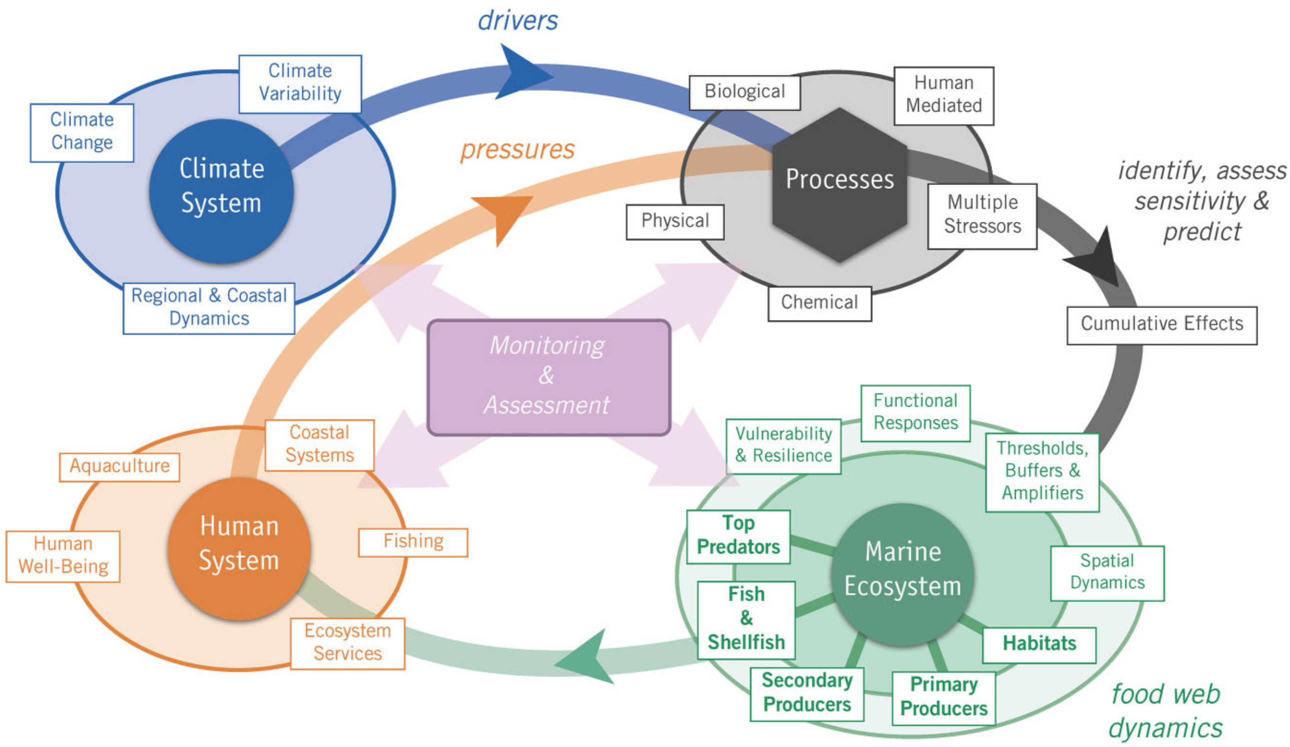

Figure 1. FUTURE SEES framework (Source: re-publish Fig. 1 © Bograd, Kang, Di Lorenzo, Horii, Katugin, King, Lobanov, Makino, Na, Perry, Qiao, Rykaczewski, Saito, Therriault, Yoo, and Batchelder (2019)/CC BY-4.0). Arrows show potential and realized connections between disciplinary components of PICES science. Mapping PICES expert groups onto the SEES diagram facilitates cross-discipline collaborations and identifies topics requiring additional investment.

in more interdisciplinary activities and outputs addressing the broader research questions of overarching programs. To test this hypothesis, we utilize two analytical approaches. The first is a quantitative text analysis based on text from all abstracts submitted to the PICES Annual Meetings from 1993 to 2019. The second approach is a systematic review based on the development and analysis of a FUTURE Product Matrix, which summarizes the scientific products (literature and meetings) produced during Phase II of the FUTURE Program, and how they address the science questions outlined in the original FUTURE Science Plan (Appendix 1).

The quantitative text analysis provides insight into whether the thematic focus or interdisciplinarity of the scientific products produced by PICES groups has changed over time and assesses if the change was responsive to the guidance offered by the flagship science program as it has evolved from CCCC through the second phase of FUTURE. The CCCC had an emphasis on understanding the coupling between atmospheric and oceanographic processes, their impact on the production of major living marine resources, and how they respond to climate change on time scales of seasons to centuries (Hargreaves 1996). With the implementation of the FUTURE Science Program in 2010, the scientific themes included a more explicit focus on resolving how interactions among processes influence ecosystem composition, structure, and function. Additionally, this understanding can improve the management of coastal ecosystems and increase sustainability. The systematic review provides insight into whether the evolution towards fostering a more comprehensive understanding of the interplay between the climate system, ocean and ecosystem processes, as well as the human systems, as exemplified by the SEES framework, was facilitated by the FUTURE Program.

Materials and methods

Review of methodologies for evaluating research activities of the FUTURE Program

In the field of conservation ecology, a "systematic review" has been proposed as a framework for evaluating the effectiveness of research activities related to biodiversity conservation (Pullin and Stewart 2006). A systematic review is a methodology that systematically evaluates the relevant literature in response to pre-specified questions (Pullin and Stewart 2006). For example, in marine science, this approach has been applied to evaluate the status and issues of research activities such as sea turtle conservation (Rees et al. 2016), marine debris (Bucci et al. 2020), and Ecological Niche Models and Species Distribution Models in marine environments (Melo-Merino et al. 2020). The SEES approach, in identifying collaborative and interdisciplinary PICES scientific activities as well as critical gaps in the scientific enterprise, provides a framework for interpreting the results of our analyses. For example, PICES has a long history of activities related to the marine ecosystem sphere but has only recently started major activities in the human system sphere, which should be reflected in the analyses.

In addition, recent innovations in natural language processing techniques (AI-driven technology in addition to the human-driven technology of the past) and personal computers have also focused attention on approaches that use text analysis as a methodology to quantitatively identify changes in research topics (Asatani et al. 2023). Quantitative text analysis is a methodology for producing insights and knowledge about historical events and current realities based on understanding and uncovering patterns and trends in the occurrence frequency of words in large textual data sets (Nielbo et al. 2024). These approaches, such as various software like NVIVO and traditional discourse analysis, have long existed but can now be accelerated and broadened through the use of AI. In the field of marine sciences, quantitative text analysis has been applied to policy documents (Yang et al. 2022, Sugimoto et al. 2023, Zhu et al. 2023), newspapers (Keller and Wyles 2021), and various other forms of textual information. Quantitative text analysis is a suitable methodology for understanding how research topics have changed over time from the establishment of PICES to the present.

Quantitative text analysis

We obtained PDF documents of abstracts from PICES Annual Meetings published from 1993 to 2019 on the PICES webpage (https://meetings.pices.int/publications/book-of-abstracts). These documents were converted into text files and compiled into a database by abstract ID, year of publication, and abstract text (see Supplementary Table S2 for details of abstract book statistics for each year). FUTURE Phase II ended in 2020; however, we used data up to 2019 because the PICES Annual Meetings were held online in 2020 and 2021 due to the COVID-19 pandemic. This resulted in a low number of presentations that may have biased the data. The start of the UN Decade of Ocean Science for Sustainable Development (UNDOS) in 2021 also triggered significant changes in PICES research activities, which will be discussed in Section "Discussion."

The text of the abstracts compiled in the database was decomposed into words, and nouns were extracted using spacyr version 1.3.0 (Benoit and Matsuo 2018), a natural language processing package in R. However, the frequency of occurrence of the raw data cannot ignore the impact of year-to-year changes in the number of abstracts due to variations in the volume of the PICES Annual Meeting abstract book from year to year. Therefore, the probability of occurrence (number of occurrences per 1000 words) for each year was calculated for each word by weighting the number of occurrences of the noun in the abstract book for each year by the total number of occurrences of the word as a whole. In this study, we used the top 100 keywords in terms of cumulative probability of occurrence, which is the sum of the probability of occurrence per year for 27 years. The extracted nouns were removed from the analysis preliminarily, as were nouns related to time, units, verbal meaning, and research methodology (see Supplementary Table S3 for details on the 100 nouns and excluded words used in the analysis).

In this study, we tabulated the probability of word occurrence by publication year to identify differences in word occurrence patterns among the publication years of abstract books from 1993 to 2019. Correspondence analysis was then performed to calculate and display the similarity of word-to-word occurrence trends over 27 years among abstract books by year on two dimensions based on X-squared distance. The correspondence analysis was performed using the FactoMineR package in R (Husson and Josse 2007 et al. 2007). To understand the evolution of PICES scientific research during the first PICES Science Program (CCCC) and the FUTURE Program, we compared the scores of the two dimensions from the results of correspondence analysis for 100 keywords in abstract books by year of publication, program (CCCC or FUTURE), and location of the PICES Annual Meeting (Western or Eastern North Pacific). Finally, we selected five keywords from each of the bottom 33%, middle 33%, and top 33% of Dimension 1 (DIM1) scores of correspondence analysis, resulting in a total of 15 keywords out of 100. We then compared the time-series change patterns in the probability of occurrence of each keyword.

Creation of the FUTURE product matrix

In an alternative, complementary approach, PICES publications were reviewed to identify which of the 18 PICES FUTURE sub-questions (Appendix 1) were addressed during FUTURE. References identified and examined included peer-reviewed papers published by PICES participants (e.g. expert group members), PICES Special Publications, and PICES Scientific Reports (i.e. final reports from PICES' Expert Groups) published during the period of FUTURE Phases I and II (i.e. 2010–2020, see Appendix 2) (Peer-reviewed Papers—PICES—North Pacific Marine Science Organization). We counted the number of references containing information that would help to answer each of the 18 sub-questions. Each special journal publication (with multiple papers) was counted as one reference. If the reference alluded to a question, but did not provide answers, it was not counted. To ensure consistent results, initially, four people each reviewed the same four reports to identify the sub-questions that were addressed. The four reviewers discussed and resolved any differences in results and agreed upon a standard procedure for evaluating the remaining references. Once the procedure was standardized, one person reviewed all remaining references. Since each main question has a different number of sub-questions, the % of references that address each of FUTURE's three main questions were compared, and the number of references per sub-question was examined.

Results

Integrative SEES approach facilitated interdisciplinary work

Figure 2 shows the top and bottom 10 keywords for Dimension 1 (DIM1) and Dimension 2 (DIM2) scores in the two-dimensional plot obtained by correspondence analysis (A and B), along with the time series changes in research keywords from 1993 to 2019 in PICES (C). The explanatory power of DIM1 was 29.39%, while that of DIM2 was 9.53%. Focusing on the DIM1 score (Fig. 2a), the bottom five keywords were composed of words related to basic (and specific) marine science, especially oceanography (e.g. sardine, zone, layer, circulation, current, etc.). On the other hand, the top five keywords consisted of words related to applied (and holistic) ocean science (management, habitat, climate, ecosystem, community, etc.). Focusing on the DIM2 score (Fig. 2b), the bottom five keywords consisted of words related to fisheries research (age, salmon, pollock, habitat, shelf, etc.), while the top five keywords consisted of words related to marine environmental research (cell, bloom, ice, phytoplankton, chlorophyll, etc.).

Focusing on the time-series changes of the research keywords (Fig. 2c), we observed a statistically significant trend for DIM1 ($R^2 = 0.898$, $P < 0.001$) to increase over time from lower scores (basic research) to higher scores (applied research). However, we did not observe a significant trend for DIM2 ($R^2 = 0.038$, $P = 0.849$) in increasing over time from higher scores (marine environmental research) to lower scores

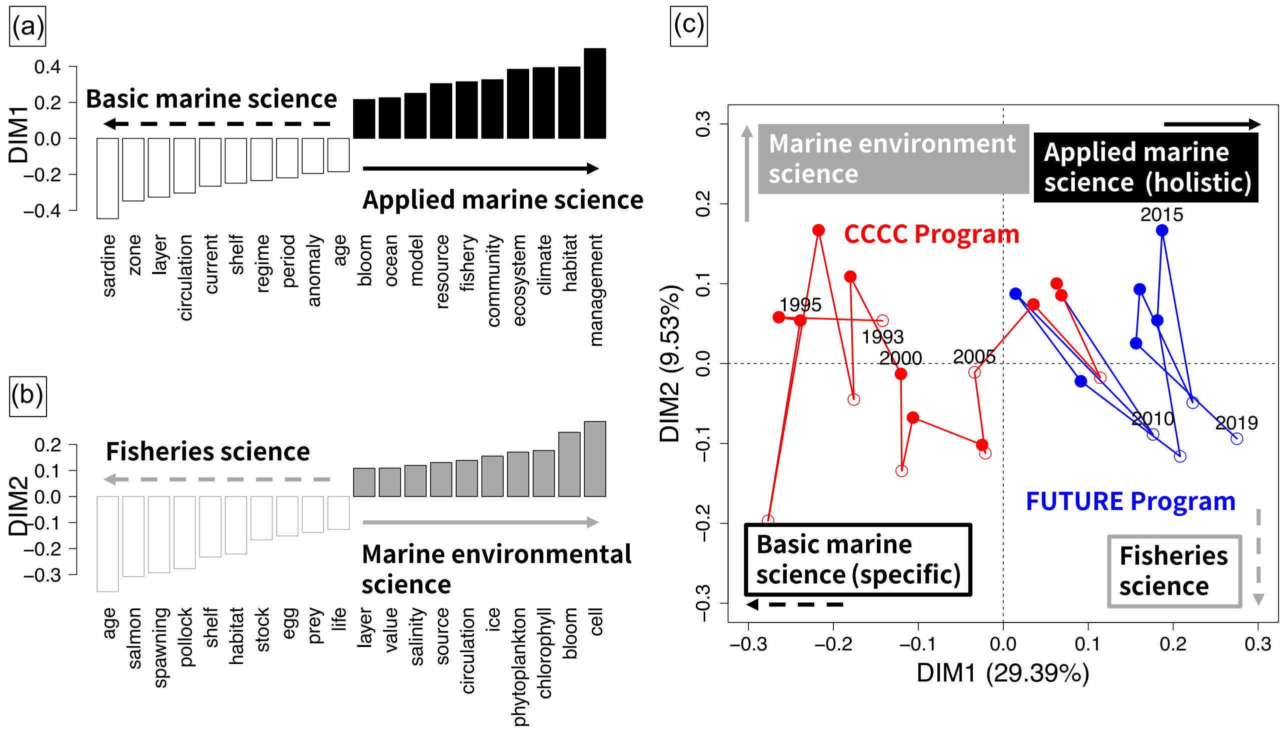

Figure 2. Results from correspondence analysis of text from PICES Annual Meeting abstracts during 1993–2019. (a) Top and bottom 10 keywords of DIM1. (b) Top and bottom 10 keywords of DIM2. (c) Changes in research themes in PICES over time. The colors of the lines indicate the different programs that were active during the year of publication of the abstract book (red: CCCC Program, blue: FUTURE Program). The different circles indicate the location of the Annual Meeting in the year of publication of the abstract book (filled circles: western North Pacific, open circles: eastern North Pacific).

(fisheries research). Focusing on the research programs conducted in the year the abstract was published, the CCCC Program (until 2009) was positioned with a lower DIM1 score (indicating more basic research), whereas the FUTURE Program (since 2010) was placed with a higher DIM1 score (indicating more applied research). DIM1 scores were significantly different between these two programs ($P < 0.001$; Wilcoxon rank sum exact test), while DIM2 scores were not significantly different ($P = 1$; Wilcoxon rank sum exact test). On the other hand, focusing on the location of the Annual Meeting in the year the abstract was published, the eastern side of the North Pacific had lower scores in fisheries research, while the western side had higher scores in marine environmental research (Fig. 2c). DIM2 scores differed significantly between Annual Meeting locations ($P < 0.001$; Wilcoxon rank sum exact test), but no significant differences were found for DIM1 scores ($P = 0.5765$; Wilcoxon rank sum exact test). Therefore, there are small year-to-year changes in research themes between "fisheries science" and "marine environmental science" depending on the location of the PICES Annual Meetings. Over the 27 years, it has been confirmed that the key themes have gradually shifted from "basic marine science" to "applied marine science." These results suggest that the research keywords of the abstracts have changed according to longer-term trends rather than short-term year-to-year changes in the research themes of the annual meetings.

Figure 3 shows the change over time in the probability of occurrence of representative keywords. Keywords with low DIM1 values (rank > 66%) were related to the accumulation of observed data. These keywords had a high probability of occurrence in the 1990s but a low probability of occurrence from the 2000s onwards (Fig. 3, top row). Keywords with moderate DIM1 scores ($33 > \text{rank} \geq 66\%$) are related to the understanding of mechanisms from physical, chemical, biological, and oceanographic perspectives. Most of these had a high probability of occurrence in the 1990s and early 2000s, while the probability of occurrence remained the same or decreased in the late 2000s and 2010s (middle row of Fig. 3). Keywords with high DIM1 scores ($\text{rank} \leq 33\%$) were those related to ecosystem management. Most of these keywords tended to have a low probability of occurrence before 2010 and a sharp increase in probability of occurrence after 2010 (bottom row of Fig. 3). Thus, from 1993 to 2019, PICES research topics shifted in emphasis from accumulating observational data and understanding mechanisms of physical-biological interactions (CCCC Program) towards a stronger focus on applications of marine ecosystem research (FUTURE Program). See Table S3 for details on the ranking of the 100 words by DIM1 score.

Summary of product matrix results

There was a total of 60 PICES references that explicitly addressed FUTURE's science questions during 2010–2020. This included 35 published special issues within scientific journals (293 scientific papers within these), 22 PICES Scientific Reports, and three PICES Special Publications (Supplementary Table S1). Generally, after 2014, there was an increase in the number of references that addressed the three main FUTURE questions (Fig. 4). The % of references that explicitly addressed the three main questions was relatively constant over time, except in 2011 and 2014, when the percentage addressing question 1 (Q1: What determines an ecosystem's intrinsic resilience and vulnerability to natural and

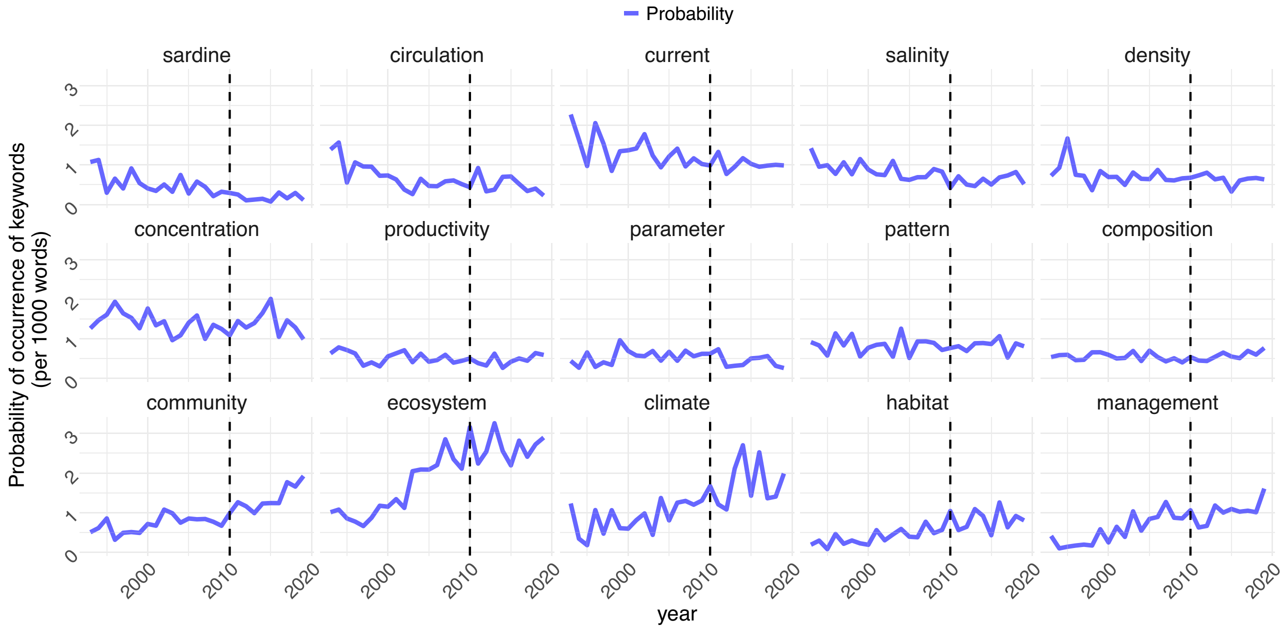

Figure 3. The probability of occurrence of representative keywords changes over time. The probability is the frequency of occurrence of each keyword in a given year weighted by the total frequency of occurrence in that year. The dashed line denotes the beginning of the first phase of the FUTURE Program in 2010. Keywords in the top row have a Dim1 score rank in the bottom 33% (rank > 66%); keywords in the middle row have a Dim1 score rank in the middle 33% (33 > rank ≥ 66%); and keywords in the bottom row have a Dim1 score rank in the top 33% (rank ≤ 33%). See Supplementary Table S3 for Dim1 scores for 100 keywords.

anthropogenic forcing?) was lower (Fig. 4). The lowest percentage of references addressed question 3 (Q3: How do human activities affect coastal ecosystems and how are societies affected by changes in these ecosystems?) (Fig. 4). Each reference addressed between 1 and 11 of the FUTURE sub-questions (Supplementary Table S1). Each sub-question was addressed by between 2 and 44 references (Fig. 5). The number of references was lowest for sub-questions 1.4 (How might changes in ecosystem structure and function affect an ecosystem's resilience or vulnerability to natural and anthropogenic forcing?) and 1.5 (What thresholds, buffers, and amplifiers are associated with maintaining ecosystem resilience?) (2 each) and highest for sub-question 1.2 (How might changing physical, chemical, and biological processes cause alterations to ecosystem structure and function?) (44; Fig. 5). Other questions that had relatively low reference counts included 1.6 and 3.3.

Although the references addressing the three main FUTURE questions have generally increased since the end of Phase I (2014), question 3 showed the overall lowest percentage of references compared to the others (Fig. 4). The least addressed sub-question under question 3 was 3.3, "How do multiple anthropogenic stressors interact to alter the structure and function of the systems, and what are the cumulative effects?," which is associated with one of FUTURE's primary aims of better incorporating humans in the system and ultimately led to the establishment of the Human Dimensions Committee in 2017.

The least addressed sub-questions were 1.4 and 1.5, which include the concept of ecosystem resilience, i.e. how resilience to natural and anthropogenic forcing is affected by changes to the ecosystem; and what thresholds, buffers, and amplifiers are associated with maintaining resilience. Other questions that had relatively low reference counts included 1.6, which is associated with the concept of predicting the future.

Discussion

How has FUTURE accomplished its scientific objectives

Both the text analysis and product matrix demonstrate a significant shift in PICES research themes since the implementation of the FUTURE Program. There has been a transition from collaborative efforts aimed at describing individual components of the North Pacific ecosystems to a more integrative characterization of ecosystem properties and responses. This shift is evident in both the correspondence analysis and change in keywords over time, and suggests FUTURE has made PICES science more interdisciplinary and potentially more useful to member countries and stakeholders.

This expansion of PICES science can be attributed to both organizational structure and the interdisciplinary approach driven by the FUTURE Program. Furthermore, PICES expert groups are structured around a variety of disciplinary topics with the aim of achieving both geographical and gender balance. The Annual Meetings rotate among the six Member Countries and also reflect the scientific interests and societal needs of each region, ensuring diversity of topics, as shown on the y-axis (DIM2) in Fig. 2c. Of course, PICES faced many difficulties such as the COVID-19 pandemic and budgetary constraints, but meeting regularly at Annual Meetings and continuously building interpersonal relations and communication is the foundation of integrated research.

The FUTURE Science Plan set ambitious objectives and science questions as an integrated Science Program. In order to address these science questions, as Bograd et al. (2019) explained, the SEES approach was developed to provide a more holistic understanding of marine ecosystems that include human stressors and responses. The SEES Schematic has been utilized as a boundary object (Star and Griesemar 1989), allowing researchers from wide-ranging disciplines to

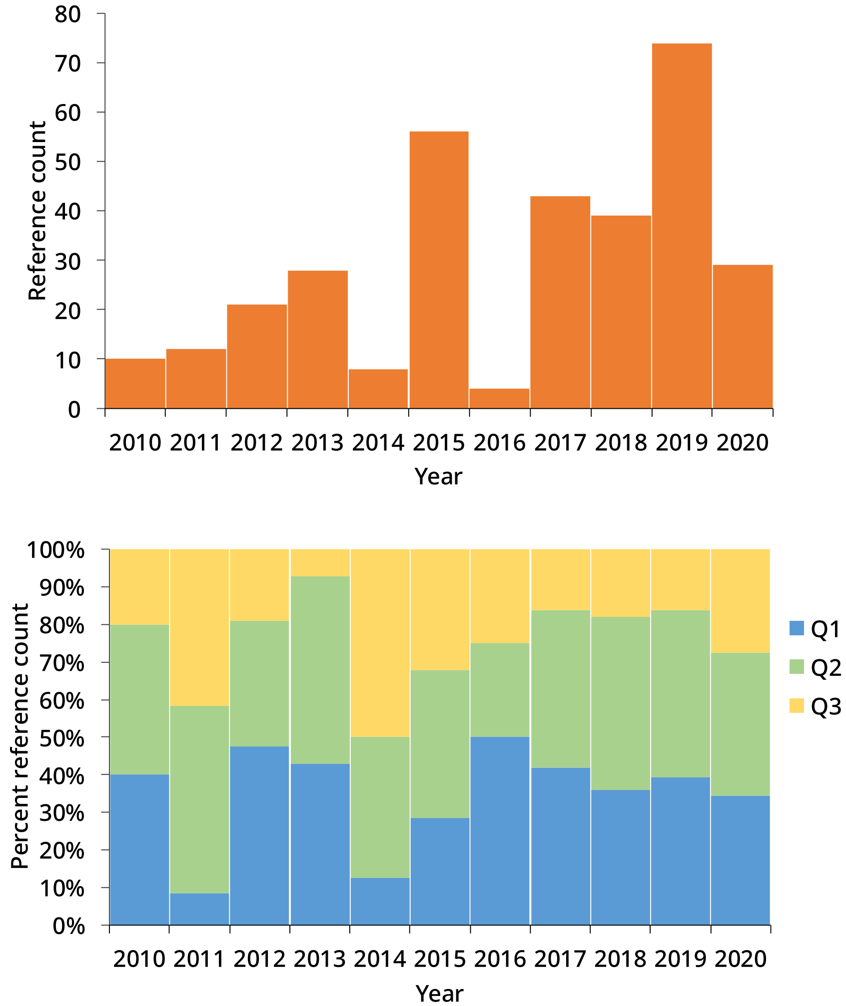

Figure 4. Total count (top panel) and % (bottom panel) of references linked to FUTURE's three main science questions, 2010–2020. The questions are: Question 1 (Q1)—What determines an ecosystem's intrinsic resilience and vulnerability to natural and anthropogenic forcing?; Question 2 (Q2): How do ecosystems respond to natural and anthropogenic forcing, and how might they change in the future?; and Question 3 (Q3): How do human activities affect coastal ecosystems and how are societies affected by changes in these ecosystems?

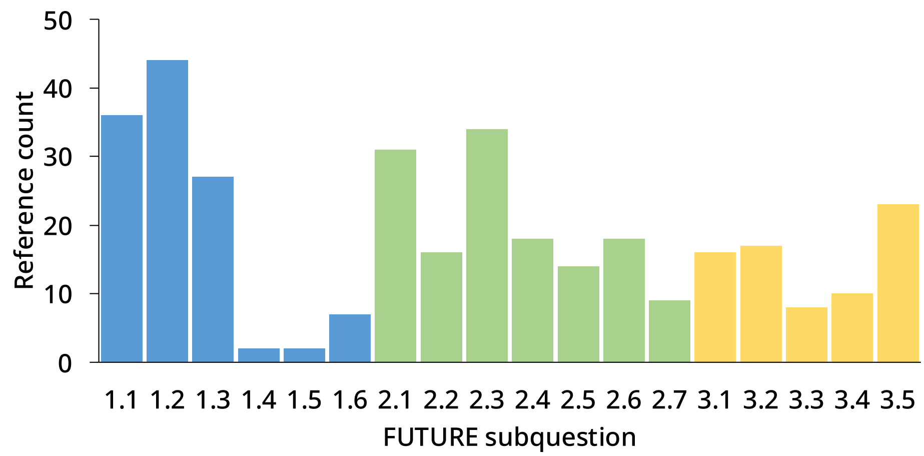

Figure 5. Count of references with information to address PICES FUTURE 18 sub-questions for 2010–2020 combined.

discuss and share ideas on common ground. It has allowed specialized researchers in each discipline to conceptualize the interconnectedness of their knowledge about North Pacific marine ecosystems and how changes have impacted coastal communities reliant on these ecosystems for their sustained livelihoods.

Finally, the FUTURE Scientific Steering Committee (SSC), established in 2014, provided science integration to address the FUTURE science questions. It organized interdisciplinary sessions and workshops at Annual Meetings and spent considerable effort on developing liaisons and communication protocols throughout the evolution of PICES. Discussions in the SSC were guided by the SEES framework, and the SSC evaluated its activities from this interdisciplinary, PICES-wide perspective. This framework linked the various disciplines through a lens of societal and real-world problems (Bograd et al. 2019), resulting in an increase of interdisciplinary activities within PICES as reflected in the text and Product Matrix analyses.

Although the FUTURE Program made great strides towards better integration of natural and social science spheres by employing the SEES approach, it is recognized that the perspectives of the majority of PICES researchers from the six member countries represent similar academic backgrounds and training. Thus, the next iteration of a PICES flagship Science Program should incorporate, from the beginning, the diverse perspectives that exist around the North Pacific in order to move towards a truly transdisciplinary program. In such a scenario, PICES could serve as the knowledge broker and provide the space in which diverse perspectives and knowledge systems could be brought together to improve our understanding of marine ecosystems and maximize our collective ability to manage and preserve them for future generations. By being more inclusive and considering input from different knowledge systems, it will ensure that rights holders are embedded in the process and that the outputs are fit-for-purpose.

Knowledge gaps and areas for future work

The PICES FUTURE Program was highly ambitious, and our analyses showed there were key FUTURE science questions that were not well addressed over the course of the program. PICES has made the most progress on FUTURE Question 1, but there are differences in the extent to which different sub-questions were addressed. For example, within Question 1, most progress has been made on characterizing and understanding marine ecosystem responses to various stressors. However, less has been achieved around ecosystem resilience (sub-questions 1.4 and 1.5), especially regarding the ability to identify thresholds and tipping points, given its inherent complexity. This is perhaps not a surprise, given that various research programs conducted within PICES member countries are focused on the more fundamental components of ecosystem change. Dealing with resilience is fraught with challenges and will require additional tools and expertise to advance this component.

There were fewer FUTURE products that addressed prediction, a key element of Questions 2 and 3. However, quantitative text analysis showed that over time there was an increase in the use of related terms, such as "state," "prediction," "forecast," "consequence," and "future" (see Supplementary Fig. S1). Forecasting is one of the main goals of FUTURE, and continued model improvements (Babanin 2023) inform best practices (DCC-OCC 2023) for accurate prediction of ocean and climate globally, including the North Pacific. This may present an opportunity for FUTURE to develop high-quality operational products.

Similarly, as evidenced by the case studies in Bograd et al. (2019), PICES has gained increased knowledge about how human activities are affecting coastal ecosystems and how, in turn, coastal communities are themselves affected by these changes. There are significant differences in coastal ecosystems and their communities around the North Pacific (e.g. population density, dependance on marine resources, etc.) but our analyses showed that despite some context dependencies, there are some common responses to the same anthropogenic stressors (e.g. invasive species, harmful algal blooms) that continue to affect the coastal zone. In general, there were fewer references addressing Question 3, on how human activities affect coastal ecosystems and how societies are affected by changes in these ecosystems, compared to Questions 1 and 2. In particular, sub-questions 3.3 and 3.4 had fewer references; these two sub-questions require an understanding of cumulative impacts and consequences, predictability, and uncertainty of forecasted changes. As our analyses reveal, more research is needed regarding the human dimensions and their integration to natural scientific knowledge (see "How has FUTURE accomplished its scientific objectives").

Limitations and prospects of large research program evaluation

Text analysis allowed us to understand the chronological changes in research topics in PICES. However, the results of the text analysis are trends derived from the PICES Annual Meetings, and it is not clear whether these trends are unique to PICES or due to global international research trends in marine science. For example, the results of this study identified "sardine" as a representative research keyword for PICES in the early 1990s. The period of increased research presentations at the PICES Annual Meeting is consistent with reports indicating that sardine catches increased rapidly between 1980 and 1990 on both the east and west coasts of the North Pacific and that stock status was favorable (Takasuka et al. 2008). Focusing on the global trend of research on sardine, the number of publications on sardine increased rapidly from the late 1980s to the 1990s, suggesting that sardines were a popular research topic in the field of marine science at that time (Supplementary Fig. S2). Since the 1990s, the number of research papers on sardines has been increasing worldwide, while the probability of "sardines" occurring in the PICES abstract book has been decreasing. The period of decreasing research presentations on sardines at the PICES Annual Meetings is also consistent with a report (Takasuka et al. 2008) that the status of sardine stocks differed significantly between the eastern and western sides of the North Pacific between 1990 and 2000. These results suggest that the trend of fewer studies on sardines in recent years compared to the 1990s is unique to PICES. On the other hand, the research trend on "Ecosystem Based Fisheries Management; EBFM" increased rapidly after 1990 both within PICES and globally. Therefore, in order to understand PICES-specific research trends in more detail, future studies employing comparative analyses using control data (repositories of international organizations such as International Council for the Exploration of the Sea: ICES, World Fisheries Congress: WFC, World Congress of Ocean: WCO, etc.) will be necessary.

The Product Matrix allowed us to evaluate the extent to which the FUTURE Program was or was not able to address its key science questions. It should be noted, however, that some PICES FUTURE sub-questions were particularly ambitious and difficult to answer within the life cycle of a typical research program without dedicated funding or a global research umbrella. For example, studies of the resilience and stability of marine ecosystems require long-term observations to understand their response to disturbances. To address this limitation, PICES scientists are applying two alternative approaches to long-term observations: comparative ecosystem studies (Perry and McKinnell 2004, McKinnell and Dagg 2010, Chandler and Yoo 2021) and the development of ecosystem models of varying complexity (e.g. Minobe et al. 2022), although these are also ambitious tasks. In recent years some studies have begun to assess ecosystem resilience in the North Pacific by comparing ecosystem characteristics and fishery impacts to modeling studies (e.g. Kiyota et al. 2020) or developing a social-ecological vulnerability assessment (e.g. Li et al. 2024). Such studies can be extended in the SEES framework to cascade ecosystem responses through the different natural and social science spheres to explore possible future scenarios/states.

Lessons learned: best practices for planning large-scale integrated science programs

First, there are still considerable gaps in scientific knowledge about marine ecosystems, such as resilience and impacts of cumulative pressures; filling these gaps is essential to addressing all of FUTURE's scientific questions (and to improve decision making). Also, there is a need to link this knowledge to societal benefits and impacts, and to social science knowledge and expertise. New data collection tools, such as autonomous samplers, and advances in computational power and artificial intelligence hold tremendous promise for tackling some of the challenges identified by FUTURE. Data sharing is also urgently required. In that sense, strengthening collaboration with other marine science organizations such as International Council for the Exploration of the Sea (ICES) is essential. Similarly, communicating scientific findings beyond peers to managers and stakeholders is not trivial. As part of the Implementation Plan for FUTURE, it was envisioned that developing more effective ways to convey knowledge and predictions was essential, as the vision statement indicated, "to broadly communicate this scientific information to members, governments, resource managers, stakeholders and the public." (https://meetings.pices.int/Members/Scientific-Programs/Materials/FUTURE/FUTURE-PhaseIII-Implementation-Plan.pdf)
PICES periodically produces a large-scale status report on the North Pacific but the rate at which marine ecosystems are changing means other forms of communicating status and forecasts are necessary to complement summary reports.

In addition, the Barcelona Statement, a report document of the 2024 UNDOS Conference held in Barcelona in April 2024, identified several priorities to be addressed in the future: adaptive governance, management systems, and decision support tools to assess vulnerabilities and risks to coastal and marine industries (UNESCO-IOC 2024). Related research on the above topics has been conducted in the U.S., the Nature Conservancy, NOAA, and in Australia, CSIRO developed "FishPATH," a tool for climate change adaptation and sustainable fisheries management in a data-limited situation (Dowling et al. 2023). Meanwhile, in Japan, the Japan Fisheries Research and Education Agency developed a self-assessment tool, "Fishery Management Toolbox (Hama no Dougubako)," to support fishers to improve the management of Japanese coastal fisheries, which have historically relied co-management and self-assessment (Makino and Tajima 2018, Takemura et al. 2020). Thus, in response to the rapid changes in marine ecosystems in the North Pacific Ocean, PICES member countries are developing decision support tools to promote to adaptation to climate change and/or improve fisheries management. And PICES scientists have been accumulating social science knowledge and expertise in collaboration with stakeholders. However, in order to link PICES's science knowledge with society, PICES also needs to provide new initiatives for integration with social scientists around the world (e.g. MSEAS symposium audiences and participants).

From our experiences in PICES, we put forward several recommendations for developing a Science Plan for a large-scale intergovernmental program: (a) balance aspirational goals with more tractable and tactical goals; (b) adjust expectations, and identify metrics of success, that account for making progress or identifying new, emerging issues rather than just addressing initial objectives; and (c) use the SEES approach or similar to facilitate interdisciplinary communication and collaboration, provide regular assessment of the science, and allow evolution of the organization/program to address emerging issues and key gaps that can be tackled.

FUTURE Phase III began in 2021, and our integrated research activities have been progressing further. This is reflected in the development of new interdisciplinary expert groups such as WG49 (Climate Extremes and Coastal Impacts in the Pacific) and WG51 (Exploring Human Networks to Power Sustainability). At the same time, UNDOS started in 2021, and its ICES-PICES jointly sponsored program SmartNet is establishing a global knowledge network for ocean science by strengthening and expanding the collaboration of ICES, PICES, and their partner organizations. Within SmartNet, there is also a focus on including indigenous communities, under-represented groups, industrial sectors, and local communities to build a more inclusive knowledge network (Bograd et al. 2021, 2024, Trainer et al. 2021) where PICES serves as the knowledge broker. For the above-mentioned scientific communication with a wide range of stakeholders, the Advisory Panel on Science Communications has been created, and discussions have started. Additionally, the environmental impacts of PICES scientific activities themselves are also being considered by the Study Group on Generating Recommendations to Encourage Environmentally Responsible Networking (SG-GREEN). Of particular importance is that activities of Early Career Ocean Professionals (ECOP) within PICES have been very actively promoted and facilitated by the Advisory Panel on ECOP. In 2022, an ECOP was inaugurated as a co-Chair of the FUTURE SSC, promoting the intergenerational transfer of integrated and innovative ocean research leadership. The ocean connects countries and cultures, and the Pacific Ocean is the largest ocean on Earth. PICES, through interdisciplinary research programs, will continue to promote integrated ocean research, and to support an informed and sustainable use of the North Pacific Ocean to the benefit of all.

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Author contributions

S.T., H.N., J.B., S.B., M.M.: original draft and writing. S.T., M.M., K.H.: quantitative text analysis presented in Figs 2 and 3. J.B., S.B., S.K., S.K., T.T.: systematic review (FUTURE Product Matrix) presented in Figs 4 and 5. All authors: conceptualization, planning, writing, and editing.

Supplementary data

Supplementary data is available at *ICES Journal of Marine Science* online.

Conflict of interest: The authors have no conflict of interest to declare.

Data availability

The R code used for a quantitative text analysis in this study will be publicly available on GitLab at the following repository: https://gitlab.com/shiontakemura/pices-abstract-books-text-analysis. The repository includes all scripts necessary to reproduce the results presented in this paper. Also, the data underlying a systematic review (FUTURE Product Matrix) in this article is available in "Supplementary-Material-(Takemura-etal-20250731-ices-jms)-final-version-clear.docx."

Appendix 1. PICES FUTURE three main science questions and 18 sub-questions.

1. What determines an ecosystem's intrinsic resilience and vulnerability to natural and anthropogenic forcing?
   a. What are the important physical, chemical and biological processes that underlie the structure and function of ecosystems?
   b. How might changing physical, chemical and biological processes cause alterations to ecosystem structure and function?
   c. How do changes in ecosystem structure affect the relationships between ecosystem components?
   d. How might changes in ecosystem structure and function affect an ecosystem's resilience or vulnerability to natural and anthropogenic forcing?
   e. What thresholds, buffers and amplifiers are associated with maintaining ecosystem resilience?
   f. 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?
   a. 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?
   b. What factors might be mediating changes in the physical, chemical and biological processes?
   c. How does physical forcing, including climate variability and climate change, affect the processes underlying ecosystem structure and function?
   d. How do human uses of marine resources affect the processes underlying ecosystem structure and function?
   e. How are human uses of marine resources affected by changes in ecosystem structure and function?
   f. How can understanding of these ecosystem processes and relationships, as addressed in the preceding sub-questions, be used to forecast ecosystem response?
   g. 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?
   a. What are the dominant anthropogenic pressures in coastal marine ecosystems and how are they changing?
   b. 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?
   c. How do multiple anthropogenic stressors interact to alter the structure and function of the systems, and what are the cumulative effects?
   d. What will be the consequences of projected coastal ecosystem changes and what is the predictability and uncertainty of forecasted changes?
   e. 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 2. References examined for the FUTURE product matrix.

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