Integrating human dimensions in decadal-scale prediction for marine social–ecological systems: lighting the grey zone

Jess Melbourne-Thomas, Desiree Tommasi, Marion Gehlen, Eugene Murphy, Jennifer Beckensteiner, Francisco Bravo, Tyler Eddy, Mibu Fischer, Elizabeth Fulton, Mayya Gogina, et al.

ICES Journal of Marine Science, 2023, **80**, 16–30
DOI: 10.1093/icesjms/fsac228
Advance access publication date: 24 December 2022
Review Article

ICES CIEM International Council for the Exploration of the Sea Conseil International pour l'Exploration de la Mer

Integrating human dimensions in decadal-scale prediction for marine social–ecological systems: lighting the grey zone

Jess Melbourne-Thomas [1,2,*], Desiree Tommasi[3,4], Marion Gehlen [5], Eugene J. Murphy [6], Jennifer Beckensteiner [7], Francisco Bravo[8], Tyler D. Eddy [9], Mibu Fischer [2,10], Elizabeth Fulton [1,2], Mayya Gogina [11], Eileen Hofmann[12], Maysa Ito [13,14], Sara Mynott [2,15], Kelly Ortega-Cisneros [16], Anna N. Osiecka [17], Mark R. Payne [18], Romeo Saldívar-Lucio [19] and Kim J. N. Scherrer [20]

[1]CSIRO Environment, Castray Esplanade, Battery Point, Tasmania 7004, Australia
[2]Centre for Marine Socioecology, University of Tasmania, Australia
[3]NOAA Southwest Fisheries Science Center, 8901 La Jolla Shores Drive, La Jolla, CA 92037, United States
[4]Institute of Marine Sciences, University of California Santa Cruz, Santa Cruz, CA, United States
[5]CEA Saclay, Bat 714, Site de l'Orme des Merisiers, Chemin de Saint Aubin - RD 128, F-91191 Gif sur Yvette Cedex, France
[6]British Antarctic Survey, High Cross, Madingley Road, Cambridge, UK
[7]European Institute for Marine studies (IUEM), Rue Dumont d'Urville, 29280 Plouzané, France
[8]Fundación CSIRO Chile Research, Apoquindo 4700, Las Condes, Santiago, Chile
[9]Centre for Fisheries Ecosystems Research, Fisheries and Marine Institute, Memorial University of Newfoundland, 155 Ridge Road, St. John's, NL, A1C 5R3, Canada
[10]CSIRO Environment, 306 Carmody Road, St Lucia, Queensland 4067, Australia
[11]Leibniz Institute for Baltic Sea Research, Seestraße 15, 18119 Rostock, Germany
[12]Center for Coastal Physical Oceanography, Old Dominion University, Norfolk, VA 23508, United States
[13]IFREMER, Unite halieutique Manche-Mer du Nord Ifremer, HMMN, 150 Quai Gambetta, 62200 Boulogne Sur Mer, France
[14]Marine Evolutionary Ecology, GEOMAR Helmholtz Center for Ocean Research Kiel, Düsternbrooker Weg 20, 24105 Kiel, Germany
[15]School of Environmental Studies, University of Victoria, 3800 Finnerty Road, Victoria BC V8P 5C2, Canada
[16]Department of Biological Sciences, University of Cape Town, HW Pearson Building, University Ave N, Rondebosch, Cape Town, 7701, South Africa
[17]Department of Vertebrate Ecology and Zoology, Faculty of Biology, University of Gdańsk, ul. Wita Stwosza 59, 80-308 Gdańsk, Poland
[18]Danish Meterological Institute, Lyngbyvej 100, Copenhagen 2100, Denmark
[19]CONACYT - Centro de Investigación Científica y Educación Superior de Ensenada (CICESE Unidad La Paz), Miraflores 334, C.P. 23050, La Paz, B.C.S., México
[20]Department of Biological Sciences, University of Bergen, Thormøhlens gate 53 A/B, 5006 Bergen, Norway
[*]*Corresponding author: tel: +61362325212*; e-mail: Jess.Melbourne-Thomas@csiro.au.

The dynamics of marine systems at decadal scales are notoriously hard to predict—hence references to this timescale as the "grey zone" for ocean prediction. Nevertheless, decadal-scale prediction is a rapidly developing field with an increasing number of applications to help guide ocean stewardship and sustainable use of marine environments. Such predictions can provide industry and managers with information more suited to support planning and management over strategic timeframes, as compared to seasonal forecasts or long-term (century-scale) predictions. The most significant advances in capability for decadal-scale prediction over recent years have been for ocean physics and biogeochemistry, with some notable advances in ecological prediction skill. In this paper, we argue that the process of "lighting the grey zone" by providing improved predictions at decadal scales should also focus on including human dimensions in prediction systems to better meet the needs and priorities of end users. Our paper reviews information needs for decision-making at decadal scales and assesses current capabilities for meeting these needs. We identify key gaps in current capabilities, including the particular challenge of integrating human elements into decadal prediction systems. We then suggest approaches for overcoming these challenges and gaps, highlighting the important role of co-production of tools and scenarios, to build trust and ensure uptake with end users of decadal prediction systems. We also highlight opportunities for combining narratives and quantitative predictions to better incorporate the human dimension in future efforts to light the grey zone of decadal-scale prediction.

Keywords: decadal prediction, decision support tools, grey zone, human dimensions, Indigenous science, marine social–ecological systems.

Introduction

The ocean and its associated resources support human communities and societies across the world. A vast range of marine activities such as fisheries, aquaculture, tourism, transport, and energy generation provide food security, resources, economic returns, and employment as part of what has been termed the "blue economy". However, at the heart of the blue economy concept is sustainability and equity (Silver *et*

Received: July 27, 2022. **Revised:** November 27, 2022. **Accepted:** November 29, 2022

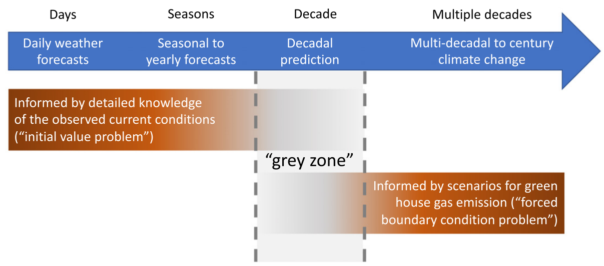
al., 2015). This must not be forgotten, as the world-wide development of marine industries will likely result in an ever more intense penetration of human activities into the marine realm and competing ocean uses (Jouffray *et al.*, 2020). This blue acceleration (Jouffray *et al.*, 2020) will intensify stressors on marine ecosystems already impacted by pollution, resource extraction, and climate change (Halpern *et al.*, 2019; Williams *et al.*, 2021). Consequently, careful management is required to meet the "blue economy" vision of thriving and sustainable use of the oceans. Adaptive management of any impacts requires the timely understanding of when ecosystem and socioeconomic development thresholds are likely to be crossed, exceeding them may be undesirable, irreversible, and in some cases, may limit future options for management actions (Couce *et al.*, 2020; Murphy *et al.*, 2021).

Annual to decadal timescales are particularly important to management decisions associated with the adjustment of practices and infrastructure to ensure long-term sustainability. These timescales are targeted by decadal predictions (the so-called "grey zone" for ocean prediction; Box 1), a rapidly developing field with an increasing number of applications to help govern marine resources (Salinger *et al.*, 2016). Such predictions can provide industry and managers with direct information more suitable for planning activities and management of resources than global-scale, long-term predictions (e.g. of climate; Lotze *et al.*, 2019). The relevance of these predictions depends on their ability to provide insight into different factors across a range of scales, including (i) general trends (e.g. population and economic growth), (ii) long-term variability at annual-to-decadal and regional scales, (iii) short-term variability of marine climate, weather, and extreme events (e.g. marine heat waves and cold spells—noting that these are also influenced by larger-scale climate cycles), (iv) abrupt regime shifts (e.g. due to catastrophic events), (v) sudden migration or disappearance of fishing resources, or (vi) changes in water quality.

These decadal- and regional-scale processes align with investment and planning scales often associated with major infrastructure or capital investments, but they have been notoriously hard to predict with significant degrees of confidence. This is frustrating and disappointing for both modelers and potential end users because this information is needed across the myriad of marine industries. While the demand may be obvious for new industries (e.g. renewable energy; Munroe *et al.*, 2022; Scheld *et al.*, 2022) making large-scale decisions pertaining to their commercial foundation, even the most established ocean industries such as fishing require new predictions with skill on decadal scales. With the disappearance of traditionally fished species, the arrival of new species (e.g. due to climate-driven range shifts) and the formation of novel ecosystems, fishing opportunities are changing particularly rapidly in some locations (e.g. Pecl *et al.*, 2017; Melbourne-Thomas *et al.*, 2022). This means that local fishery-dependent communities are forced to adjust their techniques, infrastructure, markets, and even culinary tastes (Payne *et al.*, 2022), and also generates significant consequences for management regimes.

Box 1. What is decadal-scale prediction?

In climate science, decadal predictions are defined as forecasts of conditions [e.g. monthly sea surface temperature (SST)] 1–30 years into the future, generated from the output of a climate model that has been initialized with observations and run with multiple ensemble members (Meehl *et al.*, 2014). This scale is challenging to predict because multiscale processes generate decadal variability and while the influence of immediate observed conditions wanes at these decadal scales, the long-term climate patterns (driven by greenhouse gas emission scenarios) have not yet come to be the major/sole determinant of the dynamics. This is why performance is not as good as for weather or seasonal forecasts, where knowing what the present, observed climate conditions are (e.g. the presence of an El Niño) helps prediction systems to correctly forecast conditions, typically on the orders of weeks or months (e.g. Gehlen *et al.*, 2015; Fennel *et al.*, 2019). It is also why prediction uncertainty at decadal timescales, unlike for long-term climate projections, is dominated by internal variability rather than external forcings (greenhouse gas emission scenarios). At decadal scales, we deal with a mix of processes both from shorter (weather defining) scales and long-term (climate-determining) scales; all of these processes should be considered in decadal-scale prediction systems (Meehl *et al.*, 2014).



Visualization of the "grey zone" of decadal prediction, modified from Meehl *et al.* (2009).

This cross-scale challenge at decadal scales extends beyond the physical realm into biogeochemical, ecological, and social–ecological dimensions (Fulton *et al.*, 2019). The time and space scales involved require consideration of entire life histories, variable reproductive success, large-scale movements (including range shifts or invasive species establishment), whole-of-ecosystem processes, and eco-evolutionary responses, especially as climate change puts ever stronger selective pressure on marine life (Pecl *et al.*, 2017). Within the human realm, decadal scales not only match up with investment and planning scales, but are sufficiently long for significant shifts in policy, attitudes, and behaviours to occur.

While example applications of seasonal climate forecasts for fisheries exist (Payne *et al.*, 2017; Tommasi *et al.*, 2017a), and many studies have linked climate projections to ecological models to assess climate change impacts on marine resources (Bellard *et al.*, 2012; Lotze *et al.*, 2019; Coll *et al.*, 2020; Tittensor *et al.*, 2021), the low availability of decadal predictions has limited development of decadal ecological forecasts. Nevertheless, improved methods to link environmental variability to ecological change and rapidly developing capacity to draw on Big Data has helped ecologists and managers better understand mechanisms of ecological predictability (Séférian *et al.*, 2014) and develop initial pioneering applications (e.g. Franklin *et al.*, 2017; Koul *et al.*, 2021; Payne *et al.*, 2022).

The transition towards sustainable management of marine social–ecological systems should, however, not only rely on the development of coupled physical–ecological prediction systems, but should ideally integrate humanity explicitly into numerical models. Indeed, while human processes

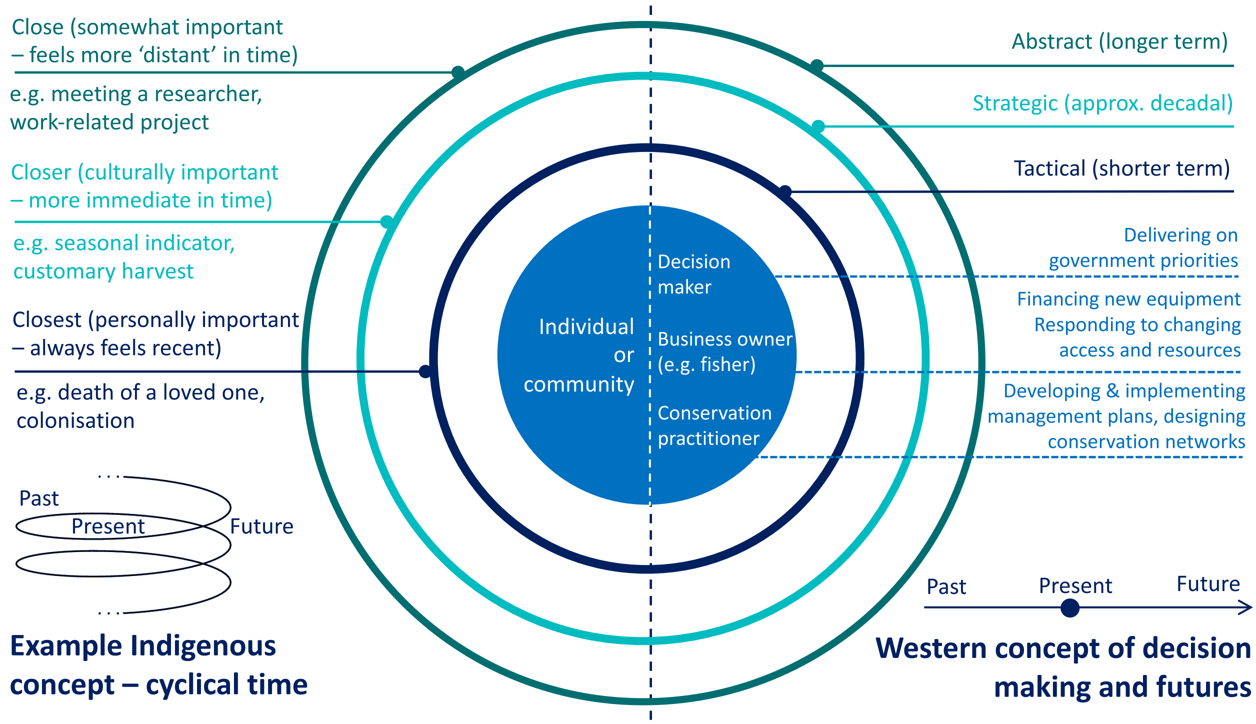


Figure 1. Decision-making timescales for marine social–ecological systems. The right side of the figure shows the Western concept of decision-making and future time horizons, with example decadal-scale decision types for different stakeholders. The left side of the figure contrasts an example Indigenous concept of cyclical time, where events such as the death of a loved one or colonization are experienced as being more immediate and recent than events that are more peripheral (such as meeting a researcher) (Janca and Bullen, 2003). Janca and Bullen (2003) highlight that many Indigenous (and non-Indigenous) cultures do not perceive time as linear and describe it as having "circular" or "cyclic" form.

are major drivers of climate and environmental changes, they are still absent from most model systems (e.g. Tittensor *et al.*, 2021). With modelling increasingly evolving into decision support tools, next-generation decadal prediction systems should incorporate the human dimension. To achieve sustainable management of marine resources and ecosystems while ensuring lasting ocean-based benefits to society, there is thus an urgent need to put in place science-based approaches that explicitly account for feedbacks between marine ecosystem dynamics and the anthroposphere (Bruno Soares and Dessai, 2016; Rickels *et al.*, 2019; Blythe *et al.*, 2021). This includes approaches that can facilitate decision-making on annual to decadal timescales that align with those on which marine management decisions are planned and implemented, and on which major ocean environmental changes are expected.

Approach

In this review, we consider information needs for decision-making at decadal scales, and assess current capabilities for meeting these needs through decadal-scale prediction for physical, biogeochemical, and ecological systems. We identify key gaps in current capabilities, including the challenge of integrating human elements into decadal prediction systems. We then suggest approaches for overcoming these challenges and gaps, in particular highlighting the important role of co-production of tools and scenarios, to build trust and ensure uptake with end users of decadal prediction systems. We also discuss opportunities for combining narratives and quantitative predictions to better incorporate the human dimension in future efforts to light the grey zone of decadal-scale prediction.

This review is an outcome from a 5-day online expert workshop as part of the "IMBIZO 6 Marine Biosphere Research: Buoyant Solutions for Ocean Sustainability" event held in October 2021. Ideas underpinning the synthesis provided in this paper were formulated and developed during workshop discussions. The workshop-to-paper process then comprised sub-teams of authors undertaking targeted literature reviews and developing syntheses as text. The final form of the review was generated through an iterative process of linking, revising, and re-ordering the text developed by sub-teams.

To identify published material on decadal-scale prediction and decision-making, we first compiled references from the authors' own multidisciplinary expertise, as well as from presentations given during the IMBIZO workshop. We then performed additional searches on key themes identified through the workshop, using Google Scholar and Web of Science. Further material was identified based on citations of and by key papers and previous reviews. Literature searches were conducted between December 2021 and May 2022.

Information needs for decision-making at decadal scales

What are the information needs in marine systems on a decadal scale? Different users have differing information needs, capacity to use information, and objectives (Figure 1). Thus, the answer is clearly dependent on the decision context and the decision-maker (Dickey-Collas *et al.*, 2014). Industry, social groups, governments, conservationists, or natural resource managers, all require different sorts of information, covering a broad spectrum of social and ecological inputs. Furthermore, we all act on partial knowledge, but we do so in different ways—as exemplified by the stark contrast between typical patterns of "Western" decision-making and that of Indigenous cultures around the world (see Figure 1, which contrasts Western decision-making with an example Indigenous concept of cyclical time).

While Western decisions are often focused on more tactical (year-to-year) time frames [although there are exceptions to this, such as the Wellbeing for Future Generations Act in Wales (https://www.futuregenerations.wales/about-us/future-generations-act/), which ensures that policy enacted by the Welsh Assembly Government must take into account the social and economic impacts on future generations], decision-making in Indigenous cultures can require contemplation of needs and implications 1000s of generations into the past and the future (Fischer *et al.*, 2022). This is an important challenge in terms of enhancing opportunities for Local Communities and Indigenous Peoples to engage with and lead decision-making processes for marine environments. Understanding the variations in how different communities and people view time will assist in their involvement in decision-making processes and increase our understanding of human connections with our world (Wright *et al.*, 2020). Sensitivities exist around how to incorporate Indigenous deep-time understandings of our climate into climate research and decadal-scale prediction, with care needed to avoid continued racial hierarchies and repressive authentication processes, amongst other things (Rademaker, 2021). This is an emerging and active area of research in-and-of itself, with many uncertainties and complexities—full exploration of the topic is beyond the scope of our paper (but we endeavour to consider the nature and value of Indigenous perspectives on decadal-scale prediction in later sections of the paper).

Intuitively, we may think that decadal predictions will inform only long-term strategic decisions ("big picture", direction-setting, and contextual, typically 5–10 + years, and large territorial scales, e.g. regional, national), but decadal processes in the ocean imply that a determined condition will persist/vanish or will be more/less frequent than usual, thus also altering the tactical timespan (focused on management actions on short timescales, typically yearly, but often underpinned by decadal-scale model projections). A system may be affected by significant short-term variability (e.g. of marine temperature), which guides tactical decisions, but at the same time short-term variability may change significantly on decadal scales and should, therefore, be considered in strategic decisions as well. Similarly, while abrupt changes (such as habitat loss due to marine heatwaves) are likely to influence short-term decisions and/or responses, some abrupt change may be anticipated, and therefore, considered in strategic long-term planning and decisions. Thus, decadal predictions are relevant for both tactical and strategic decisions.

A set of representative examples of available end-user tools and initiatives to support tactical and strategic decision-making for marine systems at multi-year to decadal scales is shown in Table 1. These tools are based on the separate or combined use of quantitative, semi-quantitative, and qualitative models and methods (but are not modelling frameworks themselves) and are presented as examples of ways in which model outputs can be made accessible for decadal-scale decision-making contexts. The list in Table 1 was identified based on the authors' knowledge of available tools (hence, this list is representative but not comprehensive).

In fisheries management, a range of time horizons are considered when making decisions, including tactical and longer-term strategic decisions to inform management and sustainability—both of fish stocks and fishing fleets (Benson and Stephenson, 2018; Munroe *et al.*, 2022; Scheld *et al.*, 2022). Tactical decisions, such as setting catch limits or developing rebuilding plans, which often project trends in a fish stock 10 years into the future, can benefit from forecasts of ocean conditions months to a few years into the future (Tommasi *et al.*, 2017a). Decadal information may also help fisheries managers to adjust management to achieve a better balance between economic, societal, and ecological objectives. For instance, strategic assessments of management performance, such as optimal allocation of marine resources or licensing decisions informed by decadal predictions, can improve climate readiness and long-term resilience of fisheries in a dynamic environment (Tommasi *et al.*, 2017a). Operational and capital investment planning by aquaculture and fishing industries (such as procurement of new vessels or infrastructure that is robust to future conditions) may also benefit from decadal predictions (Tommasi *et al.*, 2017a).

Furthermore, decadal predictions may improve users' ability to foresee potential conflicts and undesirable circumstances, and to act to de-escalate before they become entrenched. For instance, such predictions could have helped foresee and avoid the recent conflicts over Atlantic mackerel fishing rights (between European Union countries and Norway on one hand and Iceland and Greenland on the other) (Payne *et al.*, 2022). In short, recent reduction of stocks of blue whiting due to overfishing left the pelagic trawler fleets of the Faroe Islands and Iceland looking for a new target species. Consequently, when an environmentally driven shift in Atlantic mackerel resulted in increased availability in Icelandic and Greenlandic waters, they sought increased quotas of Atlantic mackerel (Spijkers and Boonstra, 2017). The transboundary stock of that species was overfished, and its Marine Stewardship Council (MSC) certification of sustainable status was lost. The dispute was partly resolved when the International Council for the Exploration of the Seas revised their assessment and announced higher mackerel stocks, meaning all the involved countries could safely fish the stock. However, although plans to increase catches were made, major arguments about shares and quotas continue at this time (Gray, 2021).

Spijkers *et al.* (2019) analysed patterns of international fisheries conflicts since the 1970s and uncovered an increase in their frequency. The occurrence of conflicts shifted geographically from North America and Europe to Asia, with more severe confrontations in territorial disputes, and higher involvement of illegal, unreported, or unregulated fisheries over time. This highlights the need to foresee distributional changes for commercial species to help avoid conflicts around transboundary stocks and to adapt marine fisheries to climate variations (Pinsky *et al.*, 2018; Payne *et al.*, 2022).

Decadal predictions have the potential to bridge the more immediate (year-to-year/tactical) concerns in management and more abstract multi-decadal drivers of change, facilitating good strategic management on the decadal scale (Figure 1, right side). However, the relatively slow progress of human processes such as technology can be difficult to ac-

Table 1. Examples of end-user tools and initiatives aimed to support decision-making and management of marine and coastal ecosystems and resources that draw on decadal-scale predictions. Some tools are applied in tactical (operational) decision-making, typically at yearly timescales, but are informed by decadal predictions. Other tools are used to support strategic decision-making at decadal and multi-decadal timescales.

Class	Platform	Description	Application	
			Tactical/operational	Strategic
Coastal management	MSPGLOBAL2030	Maritime/Marine Spatial Planning (MSP) is a public process of analysing and allocating the spatial and temporal distribution of human activities in marine areas (https://www.mspglobal2030.org/).		X
Coastal zoning	MSP Challenge Simulation Platform	Maritime Spatial Planning (MSP) challenge has been designed to help decision-makers, stakeholders, and students understand and manage the maritime (blue) economy and marine environment (Steenbeek *et al.*, 2020) (https://www.mspchallenge.info/).	X	
Coastal management	SeaView	A portal for accessing libraries of runs from Atlantis and InVitro "whole of system" modelling projects from around Australia. Applications include Atlantis-SE (management arrangements for the Australian Southern Eastern Scalefish and Shark Fishery), Atlantis SEAP (implications of climate change for marine ecosystems in the southeast of Australia), InVitro-Ningaloo (improve understanding of the reef and the natural processes that support it), and the Gladstone Harbour Model (flow-on effects of ecological or economic changes can be modelled and summarize) (https://seaview.csiro.au/index.html).		X
Ocean futures	Radical Ocean Futures	A Science Fiction Prototyping approach to imagining our future oceans (Merrie *et al.*, 2018) (https://radicaloceanfutures.earth/).		X
Climate Futures	SFI (Norway)	Climate Futures is a centre for research-based innovation developing climate prediction for handling climate risk interannual and decadal variability and predictability of climate (https://www.climatefutures.no/en/home-en/).	X	X
Climate change and extreme weather events	IPCC WGI Interactive Atlas	A novel tool for flexible spatial and temporal analyses of much of the observed and projected climate change information underpinning the Working Group I contribution to the Sixth Assessment Report, including regional synthesis for Climatic Impact-Drivers (CIDs) (https://interactive-atlas.ipcc.ch/).		X
Climate change and extreme weather events	Climate Risk Atlas for Chile (ARClim)	The Climate Risk Atlas for Chile (ARClim) is a set of maps that show impact chains associated with 12 socio-ecological and productive areas. For each, maps of climate threat (A), exposure (E), and sensitivity (S) of the affected system (such as corn production) are displayed (https://arclim.mma.gob.cl/).		X
Integrated valuation of ecosystem services and trade-offs	InVEST Natural Capital Project	InVEST enables decision-makers to assess quantified trade-offs associated with alternative management choices and to identify areas where investment in natural capital can enhance human development and conservation. On the marine and coastal realm it includes tools for evaluation of Habitat Risk Assessment, Coastal Blue Carbon, Offshore Wind Energy, Scenic Quality, Wave Energy, Coastal Vulnerability, Habitat Quality, and Recreation (https://naturalcapitalproject.stanford.edu/software/invest).		X

count for year-to-year management, despite having major impacts on social–ecological marine systems over multi-decadal time (Scherrer and Galbraith, 2020). In particular, integrating human processes and trends such as catchability creep (Whitmarsh, 1990; Engelhard, 2008), employment reductions (Hannesson, 2007), and increasing demand due to human population growth and shifts in consumer preferences (FAO, 2020) into decadal predictions can contribute greatly to improved strategic and proactive management.

Current capabilities for decadal-scale prediction

Decadal prediction systems for ocean physics and biogeochemistry

The science and methodologies for decadal-scale prediction of physical and biogeochemical variables are relatively new and rapidly evolving (Table 2) (Meehl *et al.*, 2021). Initializing climate prediction systems, testing performance over recent decades, and understanding the present state of the cli-

Table 2. Recent advances and key challenges for decadal-scale prediction across physical, biogeochemical, ecological, and human dimensions. Further details are provided in the main text.

Component	Recent advances	Challenges/needs
Physical	Use of large multi-model ensembles to increase predictive skill for key variables Improved data assimilation for model initialization	Influence of both short-term (weather) and long-term (climate) processes Decadal predictions not yet operational
Biogeochemical	Integration of Earth system models into decadal prediction systems has resulted in skilful predictions of net primary production, chlorophyll, surface ocean pCO_2, and pH	Need for best practice guidelines for initialization and construction of ensembles
Ecological	Advances in dynamical statistical prediction systems (e.g. niche, species distribution, and gradient forest models) Improved capability for decadal prediction for multi-species systems and ecosystems	Shortness of the observational records relative to the timescale of interest Remaining knowledge gaps around fundamental ecological processes and their cross-scale interactions
Human	Implicit representation as shared socio-economic pathways Improved capability in approaches such as agent-based modelling, stochastic models, cellular automata, qualitative network models, classical economic models, and their integration into whole-of-system models Co-production of scenarios	Dynamic feedbacks not captured Opportunity/need to use narrative approaches to incorporate human dimensions and traditional knowledge in a manner that better meets decision-making needs Lack of detailed information on some processes (such as institutional evolution and more informal governance processes)

mate are all necessary for skilful predictions over decadal scales. Decadal prediction systems rely on the same global climate models used to generate climate projections (nested as required to increase resolution), but they also employ a global data assimilation system that integrates observations of the current ocean or atmospheric state to initialize the model to present conditions before running the forecast into the future (Tommasi *et al.*, 2017a). Unlike for climate projections, the prediction skill of data-initialized decadal predictions can be verified using retrospective forecasts (or hindcasts, i.e. forecasts generated for the historical period that can be verified by comparison with observations or reanalyses). Such studies have demonstrated that decadal predictions have high prediction skill for SST (Meehl *et al.*, 2021), including at the regional coastal scales most relevant for decision-making (Tommasi *et al.*, 2017b).

Sources of predictive skill at the decadal scale are associated with slowly evolving decadal modes of climate variability such as the Atlantic Multi-decadal Variability, the Interdecadal Pacific Oscillation, the Meridional Modes, and the North Pacific Gyre Oscillation (Meehl *et al.*, 2021). Recent advances in the use of large multi-model ensembles have also led to predictive skill at the decadal scale for sea level pressure and precipitation (Smith *et al.*, 2019). Finally, recent integration of Earth system models [i.e. climate models including simplified representations of terrestrial and marine ecosystems, as well as key biogeochemical cycles (e.g. carbon cycle)] into decadal prediction systems has enabled forecasts of biogeochemical variables in addition to physical ones. These have shown that skilful predictions of net primary production, chlorophyll, surface ocean pCO_2, and pH are possible (Séférian *et al.*, 2014; Li *et al.*, 2019; Lovenduski *et al.*, 2019; Park *et al.*, 2019; Brady *et al.*, 2020).

Decadal ecological predictions

Ecological niche modelling (ENM, also known as habitat or species distribution modelling) is a particularly promising potential tool for marine–ecological predictions, as habitats are a key determinant of ecosystem function and can provide information useful for adaptive management practices. Indeed, ENMs based on classification and regression approaches (e.g. generalized linear mixed models, generalized additive mixed models, and boosted regression trees) or machine learning methods (e.g. random forest) have been successfully used to generate near-real time (Hazen *et al.*, 2018) and seasonal (Malick *et al.*, 2020) habitat forecasts, or to project climate-driven changes in distributions (e.g. Gogina *et al.*, 2020; Frémont *et al.*, 2022). Interannual environmental variability has been shown to be an important source of predictability for ENMs, suggesting potential predictive skill also at multi-annual scales (Brodie *et al.*, 2021).

Such modelling is increasingly using multi-model averaging and ensembles to help quantify uncertainty, increase reliability and predictive power, and to improve utility for scientific and applied purposes. For example, a combination of marine climate predictions with an ecological niche model (ENM) and an ensemble approach were employed to generate skilful decadal-scale forecasts for the habitat and distribution of three marine fish (bluefin tuna, blue whiting, and mackerel) in the northern North Atlantic (Payne *et al.*, 2022), one of the most predictable regions on the decadal scale (Frölicher *et al.*, 2020). Reported forecast skills were significantly better than climatological reference forecasts for the lead times of 3–10 years, highlighting the suitability of similar tools for planning and climate adaptation in the ocean dependent regions, such as small island developing states (SIDS) and the global south, if environmental habitat drivers have adequate prediction skill.

At the scale of a continental shelf ecosystem, Couce *et al.* (2020) suggested gradient forest models as a suitable method for identifying threshold effects and to generate new insights on the multi-organism responses to anthropogenic and environmental pressures over multi-decadal time periods. Kiaer *et al.* (2021) generated an ensemble of retrospective sandeel recruitment forecasts using generalized additive models with integrated temperature anomalies based on time series data, and demonstrated that environmentally informed recruitment forecasts are skilful and valuable a year in advance. Koul *et al.* (2021) published skilful forecasts for cod stocks biomass in the North and Barents Seas for the coming decade. They used a unified dynamical–statistical prediction system, wherein statistical models linked future stock biomass to dynamical predictions of sea surface temperature, while also considering different fishing mortalities.

In coastal areas fishing, shipping, and other maritime human activities can easily interact and/or compete for space. To assist decision-makers, stakeholders, and researchers in understanding and managing the maritime (blue) economy and marine environment, multiple programs and science-based end-user tools have been developed in the last few years, including the Maritime Spatial Planning (MSP) Challenge, msp-global2030, and seaview.csiro.au. To varying degrees, these models and tools integrate the complex human–environment interactions and dependencies to provide predictions as inputs for tactical to strategic management of coastal areas. To foster stakeholder engagement, planning through co-design, learning, and education, these tools make use of multiple approaches such as board games, simulation platforms, and virtual and augmented reality (Fulton *et al.*, 2011, 2017; Abspoel *et al.*, 2021; UNESCO-IOC, 2021).

Key gaps in current capabilities

Despite showing promising prediction skill, decadal predictions—unlike seasonal ones—are not yet operational, limiting their availability to users (although noting that the World Meteorological Organization recently endorsed the establishment of operational decadal predictions; Smith *et al.*, 2019). Particular challenges to establishing operational decadal predictions include the need for an adequate number of model ensemble members, the lack of subsurface observations for model initialization and skill assessment, and the limited effective sample size with which decadal prediction skills can be evaluated, given that most retrospective forecasts are 40 years long at most (Tommasi *et al.*, 2017a; Bojovic *et al.*, 2019; Meehl *et al.*, 2021). Improvements in climate model development, data assimilation for model initialization, construction of ensembles as well as assessment of a wider set of predicted variables are also active areas of research in this field (Meehl *et al.*, 2021). To move forward with decadal prediction from being primarily a research activity to a widely used operational climate service, requires use of coordinated multi-model approaches to better understand predictability and forecast quality, systematic sensitivity studies to address knowledge gaps, and ideally the provision of a set of best practice guidelines for the initialization of decadal predictions (Bojovic *et al.*, 2019).

The timely availability of data sets for model initialization is a key requirement for the operational implementation of decadal predictions. Inconsistencies among observational datasets and heterogeneous data quality through time can compromise the final forecasts, for example by introducing nonstationary features into the initial conditions, which then propagate through the modelling processes. Moreover, not all mechanisms and processes driving decadal variability are equally predictable; those involving ocean dynamics are expected to be more predictable than ecological or human elements (e.g. behavioural responses, or shifts in norms and attitudes). Isolating which processes are predictable within a model intercomparison framework helps to evaluate the limits of predictability associated with those mechanisms and their impacts. Also, making data publicly accessible can foster research and development of products, allow a critical mass of researchers and users, and thereby build increased usability of decadal predictions in decision-making (Bojovic *et al.*, 2019).

Progress towards operational ecological predictions at decadal scales remains limited by the shortness of the observational records relative to the timescale of interest as well as knowledge gaps around fundamental ecological processes (e.g. Fulton *et al.*, 2019; Ehrnsten *et al.*, 2020; Mejjad and Rovere, 2021). In many regions, the lack of long-term, concurrent multi-stressor, and biological observational datasets with which to evaluate prediction skill and develop test cases for management can limit the development of relevant ecological forecasts. Data availability is also an issue for human elements, as quantitative data are often not collected for some aspects (e.g. around institutional change) or is protected under privacy laws. While some data are universally protected in this way, other data streams vary country to country, for example vessel monitoring system (VMS) data and fishing effort are considered as sensitive and are tracked by regulators in some jurisdictions but not in others.

Human behaviour is among the most poorly understood (and often the most neglected) of modelled processes. It can be said that emission scenarios used for climate projections (shared socio-economic pathways; SSPs), and hence decadal predictions implicitly contain human dimensions, as they are built on (qualitative) narrative storylines and then quantitative descriptions of how concentrations of anthropogenic greenhouse gases in the atmosphere will change in the future, integrating population growth, energy use, technological, and economical changes (i.e. gross domestic product; GDP—see also "Linking and combining narratives and quantitative predictions"). While the SSPs were not developed to be prescriptive (but instead as exploratory scenarios), the climate system forcing by these scenarios is one-way in nature, with few attempts for inclusion of dynamic feedback. This means that there is also a high likelihood of ecological surprises (Filbee-Dexter *et al.*, 2017), as human activities in coastal regions and offshore can mask and accelerate impacts and even override the biological changes predicted based on climate change scenarios (e.g. Schewe *et al.*, 2019).

Meeting the needs for decision-making

On one hand, advances in global dynamic climate prediction now allow skilful predictions of the ocean state and the drivers of shifts in distribution of marine species for a decade ahead (Tommasi *et al.*, 2017a; Payne *et al.*, 2022). On the other hand, the usability of these predictions for the benefit of stakeholders and ocean-dependent communities and businesses has yet to be improved (Payne *et al.*, 2022). This is in part because the forecasts are not operational and in an immediately useful form, but also because of inexperience and unfamiliarity by potential users who do not yet have a good feeling for the reliability of the predictions or how they can best be used. In the following sections, we consider three complementary approaches that can assist in meeting decision-making needs and improving uptake of predictions and decision support tools: (i) co-production of tools and scenarios to build trust and enhance uptake; (ii) improved definition and integration of the human dimension; and (iii) linking and combining narratives and quantitative predictions.

Co-production of tools and scenarios to build trust and enhance uptake

Knowledge co-production between researchers, stakeholders, and/or rightsholders is key to addressing complex sustainability problems such as increasing resilience and fostering adaptation to climate variability and change. Trust and relationship building are key to successful co-production and underpin the achievement of shared goals in marine conservation, and environmental science and policy (Cvitanovic *et al.*, 2021; van Putten *et al.*, 2022). Approaches adopted in the past for conservation of species and ecosystems did not consider the engagement of all sectors of society, which in some cases resulted in feelings of exclusion, lack of endorsement of management plans by local communities, and resulting collapse of resources (Aburto *et al.*, 2014). In contrast, raising awareness in communities can promote participation in conservation and management. Frameworks co-developed based on a shared vision of an ideal environmental state enable a "social ecological transformation" towards sustainability of conservation programs (Olsson *et al.*, 2004). The engagement between diverse sectors enhances adaptive capacities and resilience (Chapin *et al.*, 2010).

The way in which local climate dynamics and social–ecological aspects are represented in prediction systems and decision support tools can affect or benefit a trust-building process. There are well-documented difficulties with respect to the effective communication of climate threats (and opportunities), partially because narratives are focused on globally catastrophic consequences, implying inadequate representations of local climate dynamics and the corresponding local consequences (O'Neill and Nicholson-Cole, 2009; Shaw *et al.*, 2009). In addition, the global problem/priority may not apply at a particular site, or proposed solutions may not be suitable for every locality. For example, some communities may not be willing to adopt particular management approaches because of environmental, cultural, or socio-psychological reasons (Stoll-Kleemann *et al.*, 2001; Viglione *et al.*, 2014). Developing trust and response capacities demands understanding how local climate relates to everyday human perceptions, activities, and priorities. Locally relevant narratives must be part of climate scenarios and communication strategies in order to trigger the three basic psychosocial factors that stimulate empathy and participation: (1) collective memory, (2) reduced psychological distance, and (3) social engagement (Saldívar-Lucio *et al.*, 2021) (see also "Linking and combining narratives and quantitative predictions").

Integrating human dimensions

The human dimension is often defined as the social (including cultural), economic, and governance aspects of a social–ecological system (Stephenson *et al.*, 2017). The scope of the human dimension and its position with regard to the larger system is very broad (Box 2) and will change with the worldview from which it is considered. For example, while Western societies tend to see social and ecological dimensions separately, these are inherently one in many Indigenous societies (Rose, 2005; Stoeckl *et al.*, 2021) (see also Box 3). As a result, there is not necessarily one definition that fits all purposes—instead, human dimensions need to be considered from different perspectives, decision contexts, and scales. Their aspects can both shape future environmental changes as well as be shaped by environmental variability. Anticipating events is fundamental in making choices for the future, but the considered aspects of future human dimensions shape our predictions (Berns *et al.*, 2007). Thus, identifying and incorporating the main drivers of change in human dimensions in relevant models is crucial for making accurate decadal-scale predictions.

Box 2. Understanding and defining human dimensions in the context of decadal prediction for marine systems

The following dimensions are neither exhaustive, nor separated from each other. Instead, they demonstrate a very basic level of the immense complexity of the many, often contradictory, factors that need to be considered and balanced when contemplating human dependencies and impact on marine ecosystems.

Population numbers and movement

Around 40% of the human population live within 100 km from the sea (United Nations, Factsheet: People and Oceans. The Ocean Conference, New York, 5–9 June 2017) (with this figure projected to double by 2050; IPCC, 2019), which includes areas most threatened by displacement due to the rising sea level and coastal erosion. There is a need to consider how people and cultures will move due to the changing climate and its effects on habitability of lands. The negative effects on human rights and well-being are disproportionately bigger in populations that are already at an economic disadvantage (Österblom *et al.*, 2020), and appropriate public assistance needs to be planned accordingly (Dasgupta *et al.*, 2022).

Access and use of natural resources

From deep sea mining to artisanal fisheries, exploitation of natural resources at various scales needs to be considered in ecosystem modelling and, likewise, efforts need to be made to provide fair access, or appropriate sharing of benefits and royalties.

Response to natural disasters

Small islands and coastal areas are strongly affected by extreme weather events and natural disasters, and nearly two-thirds of cities over 5 million inhabitants are located in high risk areas for sea level rise (United Nations, Factsheet: People and Oceans. The Ocean Conference, New York, 5–9 June 2017). Long-term forecasting of future threats and planning conservation, response, and rescue is crucial for safety and well-being of these populations.

Adaptation to climate change

Long-term predictions are necessary for design and implementation of locally adequate housing, food and energy sources, and other solutions for a resilient future (IPCC, 2022).

Employment and education

Understanding of local economic needs and trends over the next decades allows for provision of adequate employment and education opportunities (e.g. van Putten *et al.*, 2016), including training of future generations of marine scientists and conservationists (Alexander *et al.*, 2022). This is particularly important to shift the current geographical, gender, and social imbalances of economic power. Long-term planning and predictions are needed to ensure a smoother transition and adaptation period.

Well-being, cultural, and personal freedom

Social indicators tend to be limited to economic wealth, or an index for well-being/happiness. Incorporation of culture, heritage, and values into long-term planning is challenging even at a scale of a country, yet crucial to limit future conflicts and improve universal well-being (Cummins, 2019), and most importantly, to provide scenarios that are locally relevant and acceptable.

When thinking of global solutions, there might be a risk of oversimplification for the needs of models, or study design, and therefore, considering cultures or countries as monolithic blocks of values, opinions, or needs. It is necessary to include the finer-scale diversity, so that future actions are not only beneficial for the local majorities. Particularly difficult may be planning and predictions in and for war-torn populations, as well as the political dimension of predicting future conflicts and their impact on social–ecological systems (Spijkers *et al.*, 2021). Finally, any long-term planning or predictions should take into account not only a culture's right to preserve, but also to change and redefine itself.

Word cloud generated during the IMBIZO workshop based on the question "what elements constitute the 'human dimension' in terms of decadal-scale prediction and decision-making"?

Human dimensions can be integrated in decadal-scale prediction systems via direct modelling and/or through stakeholder engagement (in varying combinations). Dynamic representation of socio-ecological systems have been developed (e.g. Kluger *et al.*, 2019; see also Tables 1 and 2), although there are particular challenges in representing human behaviour and culture directly in models (as noted in "Key gaps in current capabilities"). Alternatively (or in addition), stakeholders can be integrated as part of the process of developing decision support tools consisting of ecological forecasts tailored to stakeholders (see "Co-production of tools and scenarios to build trust and enhance uptake").

Propelled by the revolution in computing hardware and software in the 1980s, the development of predictive computational models of human systems have expanded significantly (e.g. Engelen *et al.*, 1997; White and Engelen, 2000). These include agent-based models, cellular automata, empirical observation-based models, and stochastic differential equation-based models, among others. The integration of these individual models into ensemble models has helped address applied problems such as urban, land use, watershed, coastal and marine planning, and management. For coastal and marine realms, models include explicit representations of major industries such as aquaculture, fishing, tourism, and secondary service industries, as well as the spatiotemporal evolution of population including ethnic group formation. Examples include the WadBOS policy support system developed for and applied to the Dutch Wadden Sea (Engelen, 2013), and the Atlantis modelling framework (Fulton *et al.*, 2011), among others. These models represent industry and human processes via integrated socio-economic and industry sub-models with linkages and data flows between model representations of local industry and shipping, direct extraction of biological resources by fisheries, and shell mining, as well as recreation, defence, and energy generation.

Since marine social–ecological systems are diverse and vary greatly in their spatial scales and socio-economic contexts (Ostrom, 2007), approaches to integrate human dimensions into decadal predictions need to be equally diverse (and tailored to specific contexts and needs). It is also key to consider differences in the objectives of marine resource users, management, and other stakeholders (Pascoe *et al.*, 2017). Explicitly representing a human dimension in a model system requires both data and an understanding of the relationships between the human dimension and other variables. For example, van Putten *et al.* (2018) provide a framework with attributes that underpin sense of place in the marine environment, together with a series of measurable indicators (e.g. diversity, iconic species, habitat damage, and water quality) that can be represented in models. Causal relationships can vary greatly among systems and across scales—for example, Daw *et al.* (2012) showed that the readiness to exit a declining fishery was highly site specific, and difficult to predict from a universal set of socio-economic variables such as economic development. The experience of the fishing occupation is also extremely diverse, ranging from an enjoyable occupation that increases subjective well-being (Miñarro *et al.*, 2021) to forced labour under abusive forms (ILO, 2013).

Modellers "should not wait to integrate" social and ecological model components (Kasperski *et al.*, 2021). Kasperski *et al.* (2021) note that the timing of coupling the natural and social systems is crucial, as it influences the capacity of the model to address management questions and trade-offs among users. If such coupling/integration occurs from the project design and scoping phase, there is greater capacity for models to fully consider the social–ecological system. Management strategy evaluation based on single species, multi-species, or ecosystem models incorporating environmentally influenced population processes (Fulton *et al.*, 2014; Holsman *et al.*, 2020) is commonly used to assess performance of alternative fishery management strategies in meeting conservation, social, and economic objectives given climate variability and change. Given this approach often already integrates management or economic modules, requires stakeholder involvement and, in some instances, social and ecological scientists working together on model design (e.g. Holsman *et al.*, 2020), it may serve as a potential avenue to explore integration of the human dimension in decadal prediction.

However, the most effective approach for integrating human dimensions in decadal-scale prediction is highly dependent on the spatial scale and the particular decision-making context (e.g. Figure 1; Melbourne-Thomas *et al.*, 2017). The nature of decadal-sale predictions for human dimensions, particularly in a climate-change context, but also for other domains such as management strategy evaluation, may also be unique in that forecasts of global-scale consequences or opportunities only become evident when longer timescales are considered.

Linking and combining narratives and quantitative predictions

Narratives (also referred to as "storylines" in the context of physical climate change; Shepherd *et al.*, 2018) have an important role in the context of modelling, decision support tools, and decadal predictions (Figure 2). They can help us question

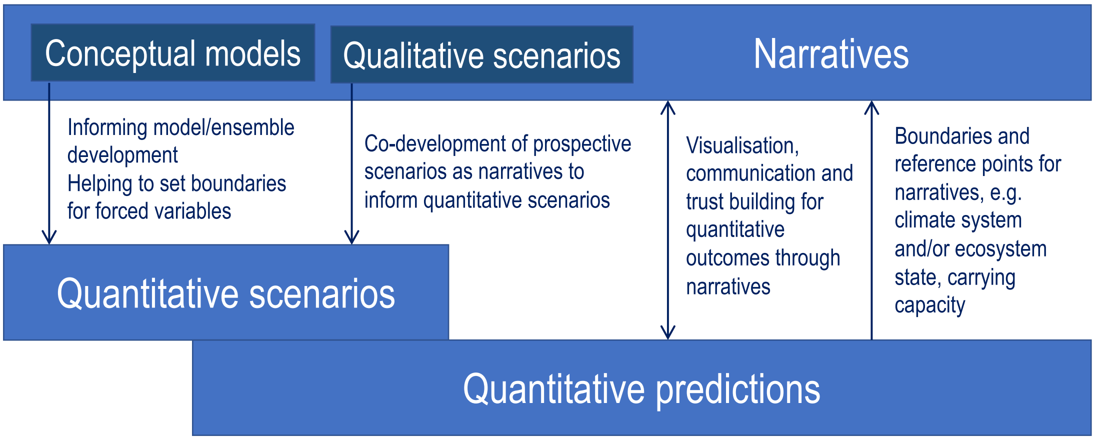


Figure 2. Visual representation of the relationship between narratives, quantitative scenarios, and quantitative predictions, in the context of decadal-scale prediction. Conceptual models and qualitative scenarios are included as a subset (particular cases) of narratives.

assumptions in quantitative models, leading to potential improvements in model design. They can be used in the context of evaluating current management practices, helping to construct processes that challenge the status quo and yield solutions that may not have been considered previously (e.g. Merrie *et al.*, 2018; Nash *et al.*, 2022). This process also allows existing power dynamics to be challenged, which can further innovation. Blythe *et al.* (2021) argue that it is essential to consider power dynamics in the context of human dimensions, as these dynamics define whose agendas and narratives can drive transformational change. Spijkers *et al.* (2021) suggest that combining imaginative approaches with participatory elements can boost the utility and relatability of narratives and future scenarios and provide a platform for the engagement of a diversity of actors.

Narratives can act as tools for interacting with different types of stakeholders and to communicate the complexity of quantitative models in a more accessible way (see "Co-production of tools and scenarios to build trust and enhance uptake"). Narratives are arguably most useful when there are large uncertainties around political context and human behaviour, and in areas where there may be very limited data to support a quantitative approach. In such cases, narratives can draw on the perspectives and experiential knowledge of diverse stake- and rights-holders and can also include associated qualitative approaches such as process tracing and mechanism-based reasoning (Waldner, 2012).

Due to real world complexity and stochasticity, the timing, intensity and full suite of consequences of "shocks"—such as the world financial crisis or recent pandemic—cannot be readily foreseen (at least in a numerical sense) and forecasted on a decadal scale. However, they can be considered in the context of "what if" exploration ("exploratory scenarios") using multi-year models to consider potential consequences and provide information into response planning, risk assessment, and future planning (e.g. Steinmann *et al.*, 2020). Another useful means of exploring such events is to use foresighting and the narrative creation of realistic scenarios, which can be played out, learning from the past (Kelly *et al.*, 2022). Where quantitative integration of human dimensions is limited, qualitative analysis methods from the social science arsenal can assist with progress. For example, process-tracing based on interviews of experts (politicians, civil servants, scientists, and industry stakeholders), was used by Spijkers and Boonstra (2017) to study causal mechanisms linking the distributional shift of the northeast mackerel and the resulting international fisheries conflict—between the EU, Norway, the Faroe Islands, and Iceland—mentioned in "Information needs for decision-making at decadal scales". These authors examined three social factors that influenced the pathway from environmental change to social response: institutions, power, and knowledge. This approach of contrasting generated narratives is especially suited to situations where causality is complex and it is impossible to control for intervening variables. Qualitative network modelling informed by narratives and expert opinion can also be used across diverse contexts, such as to "map" stakeholder perceptions, assess governance structures, and model ecosystem dynamics (Metcalf *et al.*, 2014; Dambacher *et al.*, 2015).

Narratives, scenarios, and quantitative predictions can be combined as a means to help consider and integrate human dimensions in decadal prediction (Figure 2). In particular, conceptual models (which can be considered as a subset, or particular type of narratives) can inform model development and help to set boundaries for forced variables in quantitative scenarios (e.g. Boschetti *et al.*, 2020). Co-development of future scenarios as narratives can also inform the development of quantitative scenarios to evaluate using models (e.g. Fulton *et al.*, 2015; Maury *et al.*, 2017). Quantitative predictions can be combined with narrative approaches to help visualize and communicate model predictions in a way that builds trust, and quantitative predictions can also directly underpin narrative scenarios by providing reference points (e.g. in relation to the climate system or ecosystem state; Nash *et al.*, 2022). Quantitative models can also be used to test for internal inconsistencies that might arise in mental models (and that relate to the way people conceptualize and understand the past, present, and future, e.g. see Richert *et al.*, 2017). Importantly, the significance and nature of narratives can vary amongst stakeholders and cultures, and it is important for researchers and modellers to understand and respect these differences (Box 3).

Box 3. Indigenous Knowledge and narratives

The recognition of Indigenous Knowledge and Traditional Ecological Knowledge as a science is increasing amongst natural resource scientists, researchers, managers, practitioners, and some policy partners (Whyte *et al.*, 2016; Whyte, 2018; Atalay, 2020; Suarmika *et al.*, 2020). As rights-holders, the rights, perspectives, and worldviews of Indigenous peoples are essential for informing future scenarios, narratives, and predictions, and their use to support decision-making (Figure 1).

Indigenous Knowledge frameworks provide a means to empower and weave Indigenous rights and knowledge with scenarios, models, and predictions. Internationally the "Two-eyed Seeing" or Etuaptmumk (in Mi'kmaw) framework—as envisaged by Mi'kmaw Elder Albert Marshall—is an example of an Indigenous framework that has been used in research (Reid *et al.*, 2021). The framework uses the idea of seeing through one eye with strengths and ways of knowing from the Indigenous lens and the other eye with the strengths of western ways of knowing. Using both eyes together can help find benefits for all. In Australia the eight-ways pedagogy framework—that involves narrative-driven learning, visualized learning processes, hands-on/reflective techniques, use of symbols/metaphors, land-based learning, indirect/synergistic logic, modelled/scaffolded genre mastery, and connectedness to community—has been used by some scholars (https://www.8ways.online/).

Narratives themselves can be a useful tool to help integrate multiple world views and when engaging with Indigenous Peoples, for whom story and narrative is at the heart of culture. Importantly, Indigenous stories may be associated with particular permissions and require suitable authority to share; appropriate protocols and knowledge governance arrangement are needed if and when such stories are being shared (Woodward *et al.*, 2020). In the context of understanding decadal-scale futures, including through narrative and modelling approaches, Indigenous values and needs might include guardianship/stewardship of the environment, understanding impacts on cultural keystone species, and the need to weave together multiple knowledge systems (Fischer *et al.*, 2022).

Conclusions

The role of humans in driving change in the world's oceans, the potential consequences for the oceans' continued ability to provide services to people, and the ability of humans to react to or prevent negative outcomes, are key aspects of the sustainability challenge (Jouffray *et al.*, 2020; IPCC, 2022). Simultaneously, decadal predictions are becoming increasingly important tools for decision-making in marine systems. Moreover, local communities and Indigenous peoples are increasingly being involved in climate decision-making processes, and as such there is a need for their knowledge and timescales to be reflected. To encourage the development of truly social–ecological decadal predictions, we have here reviewed the current state and use of decadal prediction, the information needs for future development (see Table 2), and how to transform decadal predictions to decision support tools.

Our key findings are that there have been significant recent advances in decadal-scale prediction across physical, biogeochemical, ecological, and human systems, but that remaining challenges for modelling human dimensions relate to capturing dynamic feedbacks with the environment and the lack of detailed information on processes such as institutional evolution and more informal governance processes. To support decision-making needs and improve uptake of predictions and decision support tools we recommend co-production of tools and scenarios to build trust and enhance uptake together with enhanced efforts to link and combine narratives and quantitative predictions.

Decision-making at decadal scales is challenged by the ambiguity of available evidence (e.g. predictions) and fantasy (e.g. expectations). How effectively can people grasp decadal time frames, especially a few decades ahead (Richert *et al.*, 2017)? How well can models represent the future? What are the most appropriate means for bracketing the range of possible futures across different decision-making contexts? It is hard to anticipate many aspects of future dynamics, especially with regards to the human dimension and at the decadal scale. The only certainty is that, on decadal horizons, things are almost certain to change and that humanity will demand the best available information to support decisions on a timescale relevant to sustainability. With this in mind, it is critical to provide predictions that capture these relatively rapid, decadal-scale changes across physical, ecological, and human dimensions and are relevant to decision-making timelines and contexts.

Acknowledgements

We thank all the invited speakers—Inna Senina, Mark Payne, Alan Haynie, Andrew Merrie, and Mibu Fischer—and all the participants of the virtual 18–22 October 2021 workshop "Lighting the 'grey zone': how can we integrate human dimensions in decadal-scale prediction systems?" at the "IMBIZO 6 Marine Biosphere Research: Buoyant Solutions for Ocean Sustainability" meeting for the many thought-provoking discussions that inspired this manuscript. A special thanks also to the IMBIZO 6 Organizing Committee, the IMBeR International Project Offices, and the workshop volunteers that helped with logistics and audio–visual issues. This publication resulted in part from support from the U.S. National Science Foundation (grant OCE-1840868) to the Scientific Committee on Oceanic Research (SCOR) and the U.S. National Oceanographic and Atmospheric Administration's Climate and Fisheries Adaptation Program (grant NA20OAR430507).

Authors' contributions

JM-T, DT, MG, and EJM conceived the review topic. All authors contributed to writing and revising the manuscript.

Conflict of interest

The authors have no conflicts of interest to declare.

Data availability statement

No new data were generated or analysed in support of this research.

References

Abspoel, L., Mayer, I., Keijser, X., Warmelink, H., Fairgrieve, R., Ripken, M., Abramic, A. *et al.* 2021. Communicating Maritime Spatial Planning: the MSP Challenge approach. Marine Policy, 132: 103486.

Aburto, J. A., Stotz, W. B., and Cundill, G. 2014. Social-ecological collapse: TURF Governance in the context of highly variable resources in Chile. Ecology and Society, 19: 2.

Alexander, K. A., Fleming, A., Bax, N., Garcia, C., Jansen, J., Maxwell, K. H., Melbourne-Thomas, J. *et al.* 2022. Equity of our future oceans: practices and outcomes in marine science research. Reviews in Fish Biology and Fisheries, 32: 297–311.

Atalay, S. 2020. Indigenous science for a world in crisis. Public Archaeology, 19: 1–16.

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., and Courchamp, F. 2012. Impacts of climate change on the future of biodiversity. Ecology Letters, 15: 365–377.

Benson, A. J., and Stephenson, R. L. 2018. Options for integrating ecological, economic, and social objectives in evaluation and management of fisheries. Fish and Fisheries, 19: 40–56.

Berns, G. S., Laibson, D., and Loewenstein, G. 2007. Intertemporal choice – toward an integrative framework. Trends in Cognitive Sciences, 11: 482–488.

Blythe, J. L., Armitage, D., Bennett, N. J., Silver, J. J., and Song, A. M. 2021. The politics of ocean governance transformations. Frontiers in Marine Science, 8: 634718.

Bojovic, D., Bilbao, R., Díaz, L. B., Donat, M., Ortega, P., Ruprich-Robert, Y., Solaraju-Murali, B. *et al.* 2019. The biggest unknowns related to decadal prediction: what 50 experts think are the 5 major knowledge gaps. Bulletin of the American Meteorological Society, 100: ES255–ES259.

Boschetti, F., Bulman, C. M., Hobday, A. J., Fulton, E. A., Contardo, S., Lozano-Montes, H., Robinson, L. M. *et al.* 2020. Sectoral futures are conditional on choices of global and national scenarios – Australian marine examples. Frontiers in Marine Science, 7: 563205.

Brady, R. X., Lovenduski, N. S., Yeager, S. G., Long, M. C., and Lindsay, K. 2020. Skillful multiyear predictions of ocean acidification in the California Current System. Nature Communications, 11: 2166.

Brodie, S., Abrahms, B., Bograd, S. J., Carroll, G., Hazen, E. L., Muhling, B. A., Pozo Buil, M. *et al.* 2021. Exploring timescales of predictability in species distributions. Ecography, 44: 832–844.

Bruno Soares, M., and Dessai, S. 2016. Barriers and enablers to the use of seasonal climate forecasts amongst organisations in Europe. Climatic Change, 137: 89–103.

Chapin, F. S., Carpenter, S. R., Kofinas, G. P., Folke, C., Abel, N., Clark, W. C., Olsson, P. *et al.* 2010. Ecosystem stewardship: sustainability strategies for a rapidly changing planet. Trends in Ecology and Evolution, 25: 241–249.

Coll, M., Steenbeek, J., Pennino, M. G., Buszowski, J., Kaschner, K., Lotze, H. K., Rousseau, Y. *et al.* 2020. Advancing global ecological modeling capabilities to simulate future trajectories of change in marine ecosystems. Frontiers in Marine Science, 7: 1–23.

Couce, E., Engelhard, G. H., and Schratzberger, M. 2020. Capturing threshold responses of marine benthos along gradients of natural and anthropogenic change. Journal of Applied Ecology, 57: 1137–1148.

Cummins, R. A. 2019. Wellbeing Across Cultures: Issues of Measurement and the Interpretation of Data. Pages 516-530 Cross-Cultural Psychology: Contemporary Themes and Perspectives, 2nd edn. Wiley Blackwell, New York, NY.

Cvitanovic, C., Shellock, R. J., Mackay, M., van Putten, E. I., Karcher, D. B., Dickey-Collas, M., and Ballesteros, M. 2021. Strategies for building and managing ‘trust’ to enable knowledge exchange at the interface of environmental science and policy. Environmental Science and Policy, 123: 179–189.

Dambacher, J. M., Rothlisberg, P. C., and Loneragan, N. R. 2015. Qualitative mathematical models to support ecosystem-based management of Australia’s Northern Prawn Fishery. Ecological Applications, 25: 278–298.

Dasgupta, S., Wheeler, D., Bandyopadhyay, S., Ghosh, S., and Roy, U. 2022. Coastal dilemma: climate change, public assistance and population displacement. World Development, 150: 105707.

Daw, T. M., Cinner, J. E., McClanahan, T. R., Brown, K., Stead, S. M., Graham, N. A. J., and Maina, J. 2012. To fish or not to fish: factors at multiple scales affecting artisanal fishers’ readiness to exit a declining fishery. PLoS ONE, 7: e31460.

Dickey-Collas, M., Payne, M. R., Trenkel, V. M., and Nash, R. D. M. 2014. Hazard warning: model misuse ahead. ICES Journal of Marine Science, 71: 2300–2306.

Ehrnsten, E., Sun, X., Humborg, C., Norkko, A., Savchuk, O. P., Slomp, C. P., Timmermann, K. *et al.* 2020. Understanding environmental changes in temperate coastal seas: linking models of benthic fauna to carbon and nutrient fluxes. Frontiers in Marine Science, 7: 450.

Engelen, G. 2013. Models in policy formulation and assessment: the WadBOS decision-support system. In Environmental Modelling. Eds J. Wainwright, and M Mulligan. https://doi.org/10.1002/9781118351475.ch21

Engelen, G., White, R., and Uljee, I. 1997. Integrating constrained cellular automata models, GIS and decision support tools for urban planning and policy-making. *In* Decision Support Systems in Urban Planning, pp. 113–135. Routledge, London.

Engelhard, G. H. 2008. One hundred and twenty years of change in fishing power of English North Sea trawlers. *In* Advances in Fisheries Science, pp. 1–25. Wiley, New York, NY.

FAO. 2020. The State of World Fisheries and Aquaculture 2020. Sustainability in action. Rome.

Fennel, K., Gehlen, M., Brasseur, P., Brown, C. W., Ciavatta, S., Cossarini, G., Crise, A. *et al.* 2019. Advancing marine biogeochemical and ecosystem reanalyses and forecasts as tools for monitoring and managing ecosystem health. Frontiers in Marine Science, 6: 1240.

Filbee-Dexter, K., Pittman, J., Haig, H. A., Alexander, S. M., Symons, C. C., and Burke, M. J. 2017. Ecological surprise: concept, synthesis, and social dimensions. Ecosphere, 8: e02005.

Fischer, M., Maxwell, K., Pedersen, H., Greeno, D., Jingwas, N., Graham Blair, J., Hugu, S. *et al.* 2022. Empowering her guardians to nurture our ocean’s future. Reviews in Fish Biology and Fisheries, 32: 271–296.

Franklin, J., Serra-Diaz, J. M., Syphard, A. D., and Regan, H. M. 2017. Big data for forecasting the impacts of global change on plant communities. Global Ecology and Biogeography, 26: 6–17.

Frémont, P., Gehlen, M., Vrac, M., Leconte, J., Delmont, T. O., Wincker, P., Iudicone, D., *et al.* 2022. Restructuring of plankton genomic biogeography in the surface ocean under climate change. Nature Climate Change, 12: 393–401.

Frölicher, T. L., Ramseyer, L., Raible, C. C., Rodgers, K. B., and Dunne, J. 2020. Potential predictability of marine ecosystem drivers. Biogeosciences, 17: 2061–2083.

Fulton, E. A., Blanchard, J. L., Melbourne-Thomas, J., Plagányi, É. E., and Tulloch, V. J. D. 2019. Where the ecological gaps remain, a modelers’ perspective. Frontiers in Ecology and Evolution, 7: 424.

Fulton, E. A., Boschetti, F., Sporcic, M., Jones, T., Little, L. R., Dambacher, J. M., Gray, R. *et al.* 2015. A multi-model approach to engaging stakeholder and modellers in complex environmental problems. Environmental Science and Policy, 48: 44–56.

Fulton, E. A., Hutton, T., van Putten, E. I., Lozano-Montes, H., and Gorton, R. 2017. Gladstone Atlantis Model – Implementation and Initial Results. Report to the Gladstone Healthy Harbour Partnership. CSIRO, Rockhampton.

Fulton, E. A., Link, J. S., Kaplan, I. C., Savina-Rolland, M., Johnson, P., Ainsworth, C., Horne, P. *et al.* 2011. Lessons in modelling and management of marine ecosystems: the Atlantis experience. Fish and Fisheries, 12: 171–188.

Fulton, E. A., Smith, A. D. M., Smith, D. C., and Johnson, P. 2014. An integrated approach is needed for ecosystem based fisheries management: insights from ecosystem-level management strategy evaluation. PLoS ONE, 9: e84242.

Gehlen, M., Barciela, R., Bertino, L., Brasseur, P., Butenschön, M., Chai, F., Crise, A. *et al.* 2015. Building the capacity for forecasting marine biogeochemistry and ecosystems: recent advances and future developments. Journal of Operational Oceanography, 8: s168–s187.

Gogina, M., Zettler, M. L., Wåhlström, I., Andersson, H., Radtke, H., Kuznetsov, I., and MacKenzie, B. R. 2020. A combination of species distribution and ocean-biogeochemical models suggests that climate change overrides eutrophication as the driver of future distributions of a key benthic crustacean in the estuarine ecosystem of the Baltic Sea. ICES Journal of Marine Science, 77: 2089–2105.

Gray, T. 2021. Normative theory of international relations and the 'mackerel war' in the North East Atlantic. Marine Policy, 131: 104620.

Halpern, B. S., Frazier, M., Afflerbach, J., Lowndes, J. S., Micheli, F., O'Hara, C., Scarborough, C. *et al.* 2019. Recent pace of change in human impact on the world's ocean. Scientific Reports, 9: 11609.

Hannesson, R. 2007. Growth accounting in a fishery. Journal of Environmental Economics and Management, 53: 364–376.

Hazen, E. L., Scales, K. L., Maxwell, S. M., Briscoe, D. K., Welch, H., Bograd, S. J., Bailey, H. *et al.* 2018. A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. Science Advances, 4: eaar3001.

Holsman, K. K., Haynie, A. C., Hollowed, A. B., Reum, J. C. P., Aydin, K., Hermann, A. J., Cheng, W. *et al.* 2020. Ecosystem-based fisheries management forestalls climate-driven collapse. Nature Communications, 11: 4579.

ILO. 2013. Caught at sea: forced labour and trafficking in fisheries. International Labour Office, Special Action Programme to Combat Forced Labour (DECLARATION/SAP-FL). Sectoral Activities Department (SECTOR), Geneva.

IPCC. 2019. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Ed. by H.-O. Po¨rtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N.M Weyer. Cambridge University Press, Cambridge and New York, NY.

IPCC. 2022. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Ed. by H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B Rama. Cambridge University Press, Cambridge.

Janca, A., and Bullen, C. 2003. The Aboriginal concept of time and its mental health implications. Australasian Psychiatry, 11: S40–S44.

Jouffray, J. - B., Blasiak, R., Norström, A. V., Österblom, H., and Nyström, M. 2020. The blue acceleration: the trajectory of human expansion into the ocean. One Earth, 2: 43–54.

Kasperski, S., DePiper, G. S., Haynie, A. C., Blake, S., Colburn, L. L., Freitag, A., Jepson, M. *et al.* 2021. Assessing the state of coupled social-ecological modeling in support of ecosystem based fisheries management in the United States. Frontiers in Marine Science, 8: 631400.

Kelly, R., Foley, P., Stephenson, R. L., Hobday, A. J., Pecl, G. T., Boschetti, F., Cvitanovic, C. *et al.* 2022. Foresighting future oceans: considerations and opportunities. Marine Policy, 140: 105021.

Kiaer, C., Neuenfeldt, S., and Payne, M. R. 2021. A framework for assessing the skill and value of operational recruitment forecasts. ICES Journal of Marine Science, 78: 3581–3591.

Kluger, L. C., Scotti, M., Vivar, I., and Wolff, M. 2019. Specialization of fishers leads to greater impact of external disturbance: evidence from a social-ecological network modelling exercise for Sechura Bay, northern Peru. Ocean and Coastal Management, 179: 104861.

Koul, V., Sguotti, C., Årthun, M., Brune, S., Düsterhus, A., Bogstad, B., Ottersen, G. *et al.* 2021. Skilful prediction of cod stocks in the North and Barents Sea a decade in advance. Communications Earth and Environment, 2: 140.

Li, H., Ilyina, T., Müller, W. A., and Landschützer, P. 2019. Predicting the variable ocean carbon sink. Science Advances, 5: eaav6471.

Lotze, H. K., Tittensor, D. P., Bryndum-Buchholz, A., Eddy, T. D., Cheung, W. W. L., Galbraith, E. D. *et al.* 2019. Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. Proceedings of the National Academy of Sciences, 116: 12907–12912.

Lovenduski, N. S., Yeager, S. G., Lindsay, K., and Long, M. C. 2019. Predicting near-term variability in ocean carbon uptake. Earth System Dynamics, 10: 45–57.

Malick, M. J., Siedlecki, S. A., Norton, E. L., Kaplan, I. C., Haltuch, M. A., Hunsicker, M. E., Parker-Stetter, S. L. *et al.* 2020. Environmentally driven seasonal forecasts of Pacific hake distribution. Frontiers in Marine Science, 7: 578490.

Maury, O., Campling, L., Arrizabalaga, H., Aumont, O., Bopp, L., Merino, G., Squires, D. *et al.* 2017. From shared socio-economic pathways (SSPs) to oceanic system pathways (OSPs): building policy-relevant scenarios for global oceanic ecosystems and fisheries. Global Environmental Change, 45: 203–216.

Meehl, G. A., Goddard, L., Boer, G., Burgman, R., Branstator, G., Cassou, C., Corti, S. *et al.* 2014. Decadal climate prediction: an update from the trenches. Bulletin of the American Meteorological Society, 95: 243–267.

Meehl, G. A., Goddard, L., Murphy, J., Stouffer, R. J., Boer, G., Danabasoglu, G., Dixon, K. *et al.* 2009. Decadal prediction: can it be skillful?. Bulletin of the American Meteorological Society, 90: 1467–1486.

Meehl, G. A., Richter, J. H., Teng, H., Capotondi, A., Cobb, K., Doblas-Reyes, F., Donat, M. G. *et al.* 2021. Initialized Earth System prediction from subseasonal to decadal timescales. Nature Reviews Earth and Environment, 2: 340–357.

Mejjad, N., and Rovere, M. 2021. Understanding the impacts of blue economy growth on deep-sea ecosystem services. Sustainability, 13: 12478,

Melbourne-Thomas, J., Audzijonyte, A., Brasier, M. J., Cresswell, K. A., Fogarty, H. E., Haward, M., Hobday, A. J. *et al.* 2022. Poleward bound: adapting to climate-driven species redistribution. Reviews in Fish Biology and Fisheries, 32: 231–251.

Melbourne-Thomas, J., Constable, A. J., Fulton, E. A., Corney, S. P., Trebilco, R., Hobday, A. J., Blanchard, J. L. *et al.* 2017. Integrated modelling to support decision-making for marine social–ecological systems in Australia. ICES Journal of Marine Science, 74: 2298–2308.

Merrie, A., Keys, P., Metian, M., and Österblom, H. 2018. Radical ocean futures-scenario development using science fiction prototyping. Futures, 95: 22–32.

Metcalf, S. J., Dambacher, J. M., Rogers, P., Loneragan, N., and Gaughan, D. J. 2014. Identifying key dynamics and ideal governance structures for successful ecological management. Environmental Science and Policy, 37: 34–49.

Miñarro, S., Reyes-García, V., Aswani, S., Selim, S., Barrington-Leigh, C. P., and Galbraith, E. D. 2021. Happy without money: minimally monetized societies can exhibit high subjective well-being. PLoS ONE, 16: e0244569.

Munroe, D. M., Powell, E. N., Klinck, J. M., Scheld, A. M., Borsetti, S., Beckensteiner, J., and Hofmann, E. E. 2022. The Atlantic surfclam fishery and offshore wind energy development: 1. Model development and verification. ICES Journal of Marine Science, 79: 1787–1800.

Murphy, E. J., Robinson, C., Hobday, A. J., Newton, A., Glaser, M., Evans, K., Dickey-Collas, M. *et al.* 2021. The global pandemic has shown we need an action plan for the ocean. Frontiers in Marine Science, 8: 760731.

Nash, K. L., Alexander, K., Melbourne-Thomas, J., Novaglio, C., Sbrocchi, C., Villanueva, C., and Pecl, G. T. 2022. Developing achievable alternate futures for key challenges during the UN Decade of Ocean Science for Sustainable Development. Reviews in Fish Biology and Fisheries, 32: 19–36.

O'Neill, S., and Nicholson-Cole, S. 2009. "Fear Won't Do It": promoting positive engagement with climate change through visual and iconic representations. Science Communication, 30: 355–379.

Olsson, P., Folke, C., and Hahn, T. 2004. Social-ecological transformation for ecosystem management: the development of adaptive co-management of a wetland landscape in southern Sweden. Ecology and Society, 9: 2.

Österblom, H., Wabnitz, C. C., Tladi, D., Allison, E., Arnaud-Haond, S., Bebbington, J., Bennett, N. *et al.* 2020. Towards Ocean Equity. Working paper of the High Level Panel for a Sustainable Ocean Economy. World Resources Institute, Washington, DC. https://hdl.handle.net/20.500.12348/4486 (accessed 22 Nov 2022).

Ostrom, E. 2007. A diagnostic approach for going beyond panaceas. Proceedings of the National Academy of Sciences, 104: 15181–15187.

Park, J. - Y., Stock Charles, A., Dunne John, P., Yang, X., and Rosati, A. 2019. Seasonal to multiannual marine ecosystem prediction with a global Earth system model. Science, 365: 284–288.

Pascoe, S. D., Plagányi, É. E., and Dichmont, C. M. 2017. Modelling multiple management objectives in fisheries: Australian experiences. ICES Journal of Marine Science, 74: 464–474.

Payne, M. R., Danabasoglu, G., Keenlyside, N., Matei, D., Miesner, A. K., Yang, S., and Yeager, S. G. 2022. Skilful decadal-scale prediction of fish habitat and distribution shifts. Nature Communications, 13: 2660.

Payne, M. R., Hobday, A. J., MacKenzie, B. R., Tommasi, D., Dempsey, D. P., Fässler, S. M. M., Haynie, A. C. *et al.* 2017. Lessons from the first generation of marine ecological forecast products. Frontiers in Marine Science, 4: 289.

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I. C., Clark, T. D. *et al.* 2017. Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. Science, 355: eaai9214–9211.

Pinsky, M. L., Reygondeau, G., Caddell, R., Palacios-Abrantes, J., Spijkers, J., and Cheung, W. W. L. 2018. Preparing ocean governance for species on the move. Science, 360: 1189–1191.

Rademaker, L. 2021. 60,000 years is not forever: 'time revolutions' and Indigenous pasts'. Postcolonial Studies, 25: 1–19.

Reid, A. J., Eckert, L. E., Lane, J. - F., Young, N., Hinch, S. G., Darimont, C. T., Cooke, S. J. *et al.* 2021. "Two-Eyed Seeing": an indigenous framework to transform fisheries research and management. Fish and Fisheries, 22: 243–261.

Richert, C., Boschetti, F., Walker, I., Price, J., and Grigg, N. 2017. Testing the consistency between goals and policies for sustainable development: mental models of how the world works today are inconsistent with mental models of how the world will work in the future. Sustainability Science, 12: 45–64.

Rickels, W., Weigand, C., Grasse, P., Schmidt, J., and Voss, R. 2019. Does the European Union achieve comprehensive blue growth? Progress of EU coastal states in the Baltic and North Sea, and the Atlantic Ocean against sustainable development goal 14. Marine Policy, 106: 103515.

Rose, D. 2005. An indigenous philosophical ecology: situating the human. The Australian Journal of Anthropology, 16: 294–305.

Saldívar-Lucio, R., Trasviña-Castro, A., Jiddawi, N., Chuenpagdee, R., Lindström, L., Jentoft, S., Fraga, J., *et al.* 2021. Fine-tuning climate resilience in marine socio-ecological systems: the need for accurate space-time representativeness to identify relevant consequences and responses. Frontiers in Marine Science, 7: 600403.

Salinger, J., Hobday, A. J., Matear, R. J., O'Kane, T. J., Risbey, J. S., Dunstan, P., Eveson, J. P. *et al.* 2016. Chapter one - decadal-scale forecasting of climate drivers for marine applications. *In* Advances in Marine Biology, pp. 1–68. Ed. by B. E. Curry. Academic Press, Cambridge, MA.

Scheld, A. M., Beckensteiner, J., Munroe, D. M., Powell, E. N., Borsetti, S., Hofmann, E. E., and Klinck, J. M. 2022. The Atlantic surfclam fishery and offshore wind energy development: 2. Assessing economic impacts. ICES Journal of Marine Science, 79: 1801–1814.

Scherrer, K., and Galbraith, E. 2020. Regulation strength and technology creep play key roles in global long-term projections of wild capture fisheries. ICES Journal of Marine Science, 77: 2518–2528.

Schewe, J., Gosling, S. N., Reyer, C., Zhao, F., Ciais, P., Elliott, J., Francois, L. *et al.* 2019. State-of-the-art global models underestimate impacts from climate extremes. Nature Communications, 10: 1005.

Séférian, R., Bopp, L., Gehlen, M., Swingedouw, D., Mignot, J., Guilyardi, E., and Servonnat, J. 2014. Multiyear predictability of tropical marine productivity. Proceedings of the National Academy of Sciences, 111: 11646–11651.

Shaw, A., Sheppard, S., Burch, S., Flanders, D., Wiek, A., Carmichael, J., Robinson, J. *et al.* 2009. Making local futures tangible—synthesizing, downscaling, and visualizing climate change scenarios for participatory capacity building. Global Environmental Change, 19: 447–463.

Shepherd, T. G., Boyd, E., Calel, R. A., Chapman, S. C., Dessai, S., Dima-West, I. M., Fowler, H. J. *et al.* 2018. Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. Climatic Change, 151: 555–571.

Silver, J. J., Gray, N. J., Campbell, L. M., Fairbanks, L. W., and Gruby, R. L. 2015. Blue economy and competing discourses in International Oceans Governance. The Journal of Environment and Development, 24: 135–160.

Smith, D. M., Eade, R., Scaife, A. A., Caron, L. P., Danabasoglu, G., DelSole, T. M., Delworth, T. *et al.* 2019. Robust skill of decadal climate predictions. npj Climate and Atmospheric Science, 2: 13.

Spijkers, J., and Boonstra, W. J. 2017. Environmental change and social conflict: the northeast Atlantic mackerel dispute. Regional Environmental Change, 17: 1835–1851.

Spijkers, J., Merrie, A., Wabnitz, C. C. C., Osborne, M., Mobjörk, M., Bodin, Ö., Selig, E. R. *et al.* 2021. Exploring the future of fishery conflict through narrative scenarios. One Earth, 4: 386–396.

Spijkers, J., Singh, G., Blasiak, R., Morrison, T. H., Le Billon, P., and Österblom, H. 2019. Global patterns of fisheries conflict: forty years of data. Global Environmental Change, 57: 101921.

Steenbeek, J., Romagnoni, G., Bentley, J. W., Heymans, J. J., Serpetti, N., Gonçalves, M., Santos, C. *et al.* 2020. Combining ecosystem modeling with serious gaming in support of transboundary maritime spatial planning. Ecology and Society, 25: 21.

Steinmann, P., Wang, J. R., van Voorn, G. A. K., and Kwakkel, J. H. 2020. Don't try to predict COVID-19. If you must, use Deep Uncertainty methods. Review of Artificial Societies and Social Simulation. 17 April 2020. https://rofasss.org/2020/04/17/deep-uncertainty/ (accessed 22 Nov 2022).

Stephenson, R. L., Benson, A. J., Brooks, K., Charles, A., Degnbol, P., Dichmont, C. M., Kraan, M. *et al.* 2017. Practical steps toward integrating economic, social and institutional elements in fisheries policy and management. ICES Journal of Marine Science, 74: 1981–1989.

Stoeckl, N., Jarvis, D., Larson, S., Larson, A., Grainger, D., and Ewamian Aboriginal, C. 2021. Australian Indigenous insights into ecosystem services: beyond services towards connectedness – people, place and time. Ecosystem Services, 50: 101341.

Stoll-Kleemann, S., O'Riordan, T., and Jaeger, C. C. 2001. The psychology of denial concerning climate mitigation measures: evidence from Swiss focus groups. Global Environmental Change, 11: 107–117.

Suarmika, P. E., Arnyana, I. B. P., Suarni, N. K., and Marhaeni, A. A. I. N. 2020. Indigenous science: what we can learn? (the exploration of balinese local wisdom for science learning). Journal of Physics: Conference Series, 1567: 042016.

Tittensor, D. P., Novaglio, C., Harrison, C. S., Heneghan, R. F., Barrier, N., Bianchi, D., Bopp, L. *et al.* 2021. Next-generation ensemble projections reveal higher climate risks for marine ecosystems. Nature Climate Change, 11: 973–981.

Tommasi, D., Stock, C. A., Alexander, M. A., Yang, X., Rosati, A., and Vecchi, G. A. 2017a. Multi-annual climate predictions for fisheries: an assessment of skill of sea surface temperature forecasts for large marine ecosystems. Frontiers in Marine Science, 4: 201.

Tommasi, D., Stock, C. A., Hobday, A. J., Methot, R., Kaplan, I. C., Eveson, J. P., Holsman, K. *et al.* 2017b. Managing living marine resources in a dynamic environment: the role of seasonal to decadal climate forecasts. Progress in Oceanography, 152: 15–49.

UNESCO-IOC. 2021. MSPglobal International Guide on Marine/Maritime Spatial Planning. UNESCO (IOC Manuals and Guides no 89). Paris.

van Putten, I., Cvitanovic, C., and Fulton, E. A. 2016. A changing marine sector in Australian coastal communities: an analysis of inter and intra sectoral industry connections and employment. Ocean and Coastal Management, 131: 1–12.

van Putten, I., Ison, S., Cvitanovic, C., Hobday, A. J., and Thomas, L. 2022. Who has influence?: the role of trust and communication in the conservation of flatback turtles in Western Australia. Regional Studies in Marine Science, 49: 102080.

van Putten, I. E., Plagányi, É. E., Booth, K., Cvitanovic, C., Kelly, R., Punt, A. E., and Richards, S. A. 2018. A framework for incorporating sense of place into the management of marine systems. Ecology and Society, 23: 1–24.

Viglione, A., Di Baldassarre, G., Brandimarte, L., Kuil, L., Carr, G., Salinas, J. L., Scolobig, A. *et al.* 2014. Insights from socio-hydrology modelling on dealing with flood risk – roles of collective memory, risk-taking attitude and trust. Journal of Hydrology, 518: 71–82.

Waldner, D. 2012. Process tracing and causal mechanisms. *In* The Oxford Handbook of Philosophy of Social Science. pp. 65–84. Ed. by H. Kincaid. Oxford University Press, Oxford.

White, R., and Engelen, G. 2000. High-resolution integrated modelling of the spatial dynamics of urban and regional systems. Computers, Environment and Urban Systems, 24: 383–400.

Whitmarsh, D. 1990. Technological change and marine fisheries development. Marine Policy, 14: 15–22.

Whyte, K. P. 2018. Indigenous science (fiction) for the Anthropocene: ancestral dystopias and fantasies of climate change crises. Environment and Planning E: Nature and Space, 1: 224–242.

Whyte, K. P., Brewer, J. P., and Johnson, J. T. 2016. Weaving Indigenous science, protocols and sustainability science. Sustainability Science, 11: 25–32.

Williams, B. A., Watson, J. E. M., Beyer, H. L., Klein, C. J., Montgomery, J., Runting, R. K., Roberson, L. A. *et al.* 2021. Global rarity of intact coastal regions. Conservation Biology, 36: e13874.

Woodward, E., Hill, R., Harkness, P., and Archer, R. (Ed.) 2020. Our Knowledge Our Way in caring for Country: indigenous-led approaches to strengthening and sharing our knowledge for land and sea management. *In* Best Practice Guidelines from Australian Experiences. NAILSMA and CSIRO, Cairns.

Wright, S., Suchet-Pearson, S., Lloyd, K., Burarrwanga, L., Ganambarr, R., Ganambarr-Stubbs, M., Ganambarr, B. *et al.* 2020. Gathering of the Clouds: attending to Indigenous understandings of time and climate through songspirals. Geoforum, 108: 295–304.

Handling Editor: Kanae Tokunaga