ICES Journal of Marine Science, 2023, **80**, 2087–2098
DOI: 10.1093/icesjms/fsad143
Advance access publication date: 21 September 2023
Quo Vadimus

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

Why we need weather forecast analogues for marine ecosystems

J. S. Link[1,*], S. Thur[2,3], G. Matlock[3], and M. Grasso[4]

[1]National Oceanic and Atmospheric Administration, National Marine Fisheries Service, 166 Water St., Woods Hole, MA 02563, USA
[2]National Oceanic and Atmospheric Administration, National Ocean Service, National Centers for Coastal Ocean Science, 1305 East-West Highway, Silver Spring, MD 20910, USA
[3]National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research, 1315 East-West Highway, Silver Spring, MD 20910, USA
[4]National Oceanic and Atmospheric Administration, Office of Chief Financial Officer, Performance, Risk and Social Science Office, 1401 Constitution Avenue NW, Washington, DC 20230, USA

[*] *Corresponding author. tel: +1 508-495-2340;* e-mail: Jason.Link@noaa.gov.

Marine ecosystems face many consequential pressures. Yet, we lack an integrative and predictive capacity to understand how marine ecosystems will respond to the cumulative impacts of these pressures, including climate change. It is not enough to detect responses after the fact; it has become imperative to know in advance where major biological resources or hazards will occur, when they will peak, and how that will impact economic performance. Although forecasts exist for some components of marine ecosystems, these are disparate and suffer from a lack of coordination. There is a need for coordinated, cross-ecosystem scale, integrated, marine ecosystem predictions and synthesis products. The value proposition relative to the blue economy is quite high, positively influencing billions if not trillions of marine sector dollars.

Keywords: biomass production, black swan, distribution, economic outlook, ecosystem modelling, forecasts, model coupling, oceanographic modelling, projection, system of systems.

Marine ecosystems need prediction products

Marine ecosystems are changing in response to climate-induced oceanic changes and other cumulative impacts. But our ability to predict these changes is hampered by the lack of a large ocean regional-level, integrated set of synthesis and prediction products for marine ecosystems. The questions that arise are: (1) how are ecosystems changing, (2) how do those changes affect us, and (3) how can we predict and respond to them? It has become imperative to know in advance where major biological resources or hazards will occur, when they will peak, and how that will impact economic performance. To make this vision a reality, the United States, Europe, Canada, or any large oceanic regional jurisdiction, needs cross-ecosystem scale, integrated, marine ecosystem predictions. Our ability to assess marine ecosystems for past and current conditions is pretty fair to good; our ability to predict, project, and forecast them is not as good (DeYoung *et al.*, 2004; Payne *et al.*, 2016; Shi *et al.*, 2022). Our current ability to address these considerations concurrently and as an integrated system is mostly non-existent and systematically limited. We do not yet have a large ocean regional, integrated set of synthesis and prediction products, but we can and need to produce them.

The need for prediction products has become increasingly clear as climate change impacts are increasingly escalating in the ocean (IPCC, 2014; Bindoff *et al.*, 2019; Canadell *et al.*, 2021), impacting its component biota and associated ecosystem goods and services (Stock *et al.*, 2011; Doney *et al.*, 2012; IPCC, 2014; Bindoff *et al.*, 2019), and ultimately marine-derived human benefits and uses (Figure 1). The ability for society to increase resiliency to future impacts of climate-induced changes depends on our ability to forecast these events as early and accurately as possible, both temporally and geographically (Brandt *et al.*, 2006; Tommasi *et al.*, 2017; Jacox *et al.*, 2020). As climate change continues to impact the oceans, assumptions of equilibrium and status quo as the basis for projections will be increasingly inappropriate and assumptions about non-stationarity in marine ecosystems will be increasingly challenged by unprecedented and unobserved conditions and system states (Hoegh-Guldberg and Bruno, 2010). But most saliently, we have already shifted from "climate is going to change and impact the ocean and its component biota, and we need to prepare", to "it is already changing and we need to respond, now" (USGCRP, 2017). Yet our capability to predict such dynamics, and necessary responses, is currently limited. A novel system of marine ecosystem predictions is warranted to address these continued challenges of marine ecosystem dynamics.

Marine ecosystems are subjected to a plethora of cumulative pressures. Phenomena like harmful algal blooms (HABs), sea-level rise, overfishing, habitat loss, offshore energy development, changes in shipping patterns, competition among endangered species and other endangered or targeted species, hypoxic waters, beach closures, coral reef bleaching, hazard spills, hurricanes, and floods (Diaz and Rosenberg, 2008; Doney *et al.*, 2012; O'Neil *et al.*, 2012; IPCC, 2014; Wells *et al.*, 2015; Bindoff *et al.*, 2019, van Aalst 2006; Jackson *et al.*, 2001; Figure 1) impact marine ecosystems and their associated marine-based economies (aka, the blue economy; OECD, 2016; Spalding, 2016; BEA, 2023). Furthermore, there are changes occurring that extend beyond anything

Received: 30 May 2023; **Revised:** 18 August 2023; **Accepted:** 31 August 2023

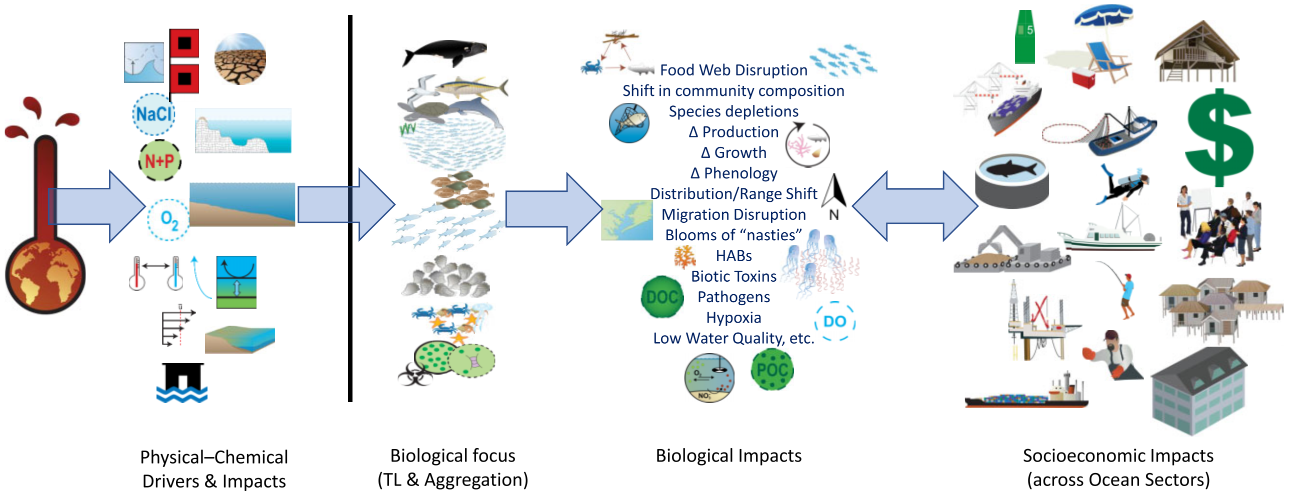

Figure 1. The elements of marine ecosystem predictions, which aim to couple models across a range of pressures, modelling emphases, and interdisciplinary systems. The outcome would be prediction products of biological, economic, and social importance, as driven by climate and physical models. Biological impacts or changes can lead to social and economic impacts across a range of ocean-use sectors supporting the blue economy. TL = trophic level. Icons from: Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/).

that we have detected in our observations to-date (USGCRP, 2017; Bindoff *et al.*, 2019; Brett *et al.*, 2020). These changes are affecting marine ecosystems at the global, large ocean region, and local scales in myriad ways (Hoegh-Guldberg and Bruno, 2010; Doney *et al.*, 2012; Bindoff *et al.*, 2019).

What would we have known and potentially done differently if a system of large ocean region, integrated set of synthesis and prediction products already existed? Even just the past year or two provides poignant examples. The disappearance of crabs in Alaska in response to shifting sea-ice was completely missed by modelling, resulting in a closure of that fishery (Alaska Beacon, 2022). Current sea surface temperatures around Florida for example, at what are historically and unprecedented high levels, were not predicted (Copernicus, 2023) and, by extension, the massive coral bleaching we are now seeing was also not fully expected (NOAA, 2023). Those sea temperatures are influencing weather phenomena leading to extreme heat and precipitation, leading to higher-than-average flooding well-beyond coastal regions (Wing *et al.*, 2022). Looking back just a few years, the Pacific blob (Brodeur *et al.*, 2019; NMFS, 2019), blooms of gelatinous zooplankton (Brodeur *et al.*, 2019), emaciation of pinnipeds (NMFS, 2019), dispersion of coral disease (Burke *et al.*, 2023), and the increasing number of fishery disaster declaration requests (NMFS, 2023) are other events for which a more effective prediction system could have helped. These are just some of the examples of why we need better marine ecosystem predictions, and we anticipate that this need will only continue to grow.

Filling in what existing predictions miss

Admittedly, there are several extant and excellent elements of marine ecosystem predictions (Brandt et al., 2006; Tommasi *et al.*, 2017; Dietze *et al.*, 2018; Coll *et al.*, 2020; Drenkard *et al.*, 2021). These cover a wide range of thematic and economic sectors (Brandt et al., 2006; Tommasi *et al.*, 2017; Dietze *et al.*, 2018; Coll *et al.*, 2020). They are geographically dispersed and regionally focused (Brandt et al., 2006; Stock *et al.*, 2011; Coll *et al.*, 2020; Drenkard *et al.*, 2021, Tommasi *et al.* 2017). They also cover multiple components of marine ecosystems (Stock *et al.*, 2011; Tommasi *et al.*, 2017; Coll *et al.*, 2020; Tittensor *et al.*, 2021; Figure 2). But these predictions are generally disparate, and are not integrated, coordinated, or made at the large ocean region-level as a cohesive system. Thus, the predictions suffer from being dispersed and highly diffuse across geographies, thematic areas, ocean-use sectors, and even across disciplinary and organizational aspects of ocean management agencies and their partner communities (Figures 1 and 2). There is certainly value in those more focused (i.e. single use, single sector, single taxa, narrower geography, and so on) predictions. However, the lack of ecosystem-level integration has resulted in many undesirable outcomes, like loss of resource value, unintended degradation of ecosystem components' condition, inadequate optimization of the blue economy, inability to reconcile competing societal objectives, and increased inefficiencies in modelling, forecasting, and communication efforts (Fulton, 2010; Turschwell *et al.*, 2022). Systematic marine ecosystem predictions have not had the degree of focus, emphasis, and integration that the atmospheric prediction system aspects have had. There is a clear need for coordination, integration, and consistency in these efforts, and the lack thereof has hindered some needed marine ecosystem predictions (Dietze *et al.*, 2018; Coll *et al.*, 2020; Drenkard *et al.*, 2021). There is little cross-ecosystem emphasis of marine ecosystem predictions, nor is there a consistent, focusing mechanism to shepherd these much-needed marine ecosystem predictions and their associated products into cohesive products and outlooks. Limitations of the geographies at which we typically conduct our limited, single sector forecasts suggest the need for a larger scale (i.e. broader than local or LME jurisdictions (Figure 2c). We highlight herein a potential approach for many other jurisdictions.

As noted in the introduction, the question becomes what have we missed—and what are the consequences—because we have not done these integrated predictions for marine ecosystems? The cost of climate change just on US fisheries

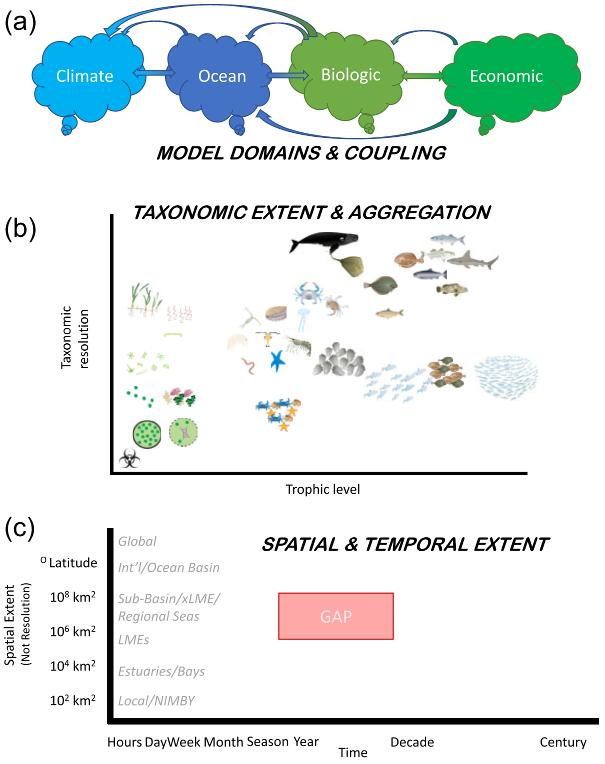

Figure 2. The dimensions of predictions and model coupling proposed for this marine ecosystem modelling and prediction system. (a) The degree of model coupling spans multiple focal areas. (b) The taxonomic resolution varies, but tends to miss the more aggregated considerations, unless at lower trophic levels. (c) The spatial and temporal extent of what is modelled varies across model domains. What is typically modelled is short-term (days to week) or long term (decadal to century) scales, and either global or regional downscale spatial models. Areas of predictions that tend to be overlooked are the large ocean region spatial scales at the Continental scope, and seasonal to two years to a decade on the temporal scope (the gap noted). NIMBY = not in my back yard. xLME = cross Large Marine Ecosystem. Icons in (b) from: Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/imagelibrary/).

alone are an estimated 3–5 billion $US over the past 25 years (Bellquist *et al.*, 2021). The economic risks to obtain the potential value extracted from the top 15 US fisheries (i.e. not including all species harvested) in an LME-scale are higher than they should be by tens of millions of dollars per region (Figure 5d). We posit that there has been foregone value (Lam *et al.*, 2016; Moore *et al.*, 2020), inefficient economics (Weatherdon *et al.*, 2016; Cochrane, 2020; Bakkensen and Barrage, 2021), increased social stress (Otto *et al.*, 2017; Cochrane, 2020; Degroot *et al.*, 2021), loss of (coastal) community resilience (Colburn *et al.*, 2016; Yanda *et al.*, 2019; Berman *et al.*, 2020), ecosystem degradation (Jackson *et al.*, 2001; IPCC, 2014), and loss of human health or even lives (Landrigan *et al.*, 2020; Meierrieks, 2021). For instance, the impacts from the deepwater horizon oil spill have run in the hundreds of billions of dollars (Sumaila *et al.*, 2012; Court *et al.*, 2020), with broader social impacts to Gulf of Mexico coastal communities (Gill *et al.*, 2011; Cope and Slack, 2017; Harrison, 2019). The cost and consequences of such perturbations are only going to intensify over time (IPCC, 2014; Spalding, 2016). Seeking to avert these consequences, it is helpful to focus on the benefits of such prediction products. The marine ecosystem prediction systems we propose will help understand and communicate these costs and benefits to assist in appropriate planning, management, and responses. The products include: more frequent, more operationally routine, more comprehensive, more integrated, better coordinated, and better marine ecosystem forecasting, projection, and prediction products. Such prediction products will enable improved assessments of the status of our living marine resources (LMR), the human communities that depend on them, and their associated economies. By developing and providing a suite of probabilities of major LMR features, risk estimates of major events, and operational predictions (Methot, 2009; Craig and Link, 2023; c.f. Graham et al. 2011), all of which are consistent across multiple ecosystems, expanded in thematic coverage (Figure 2b and c), and distributed regionally, we will be able to provide the routine and regular reporting of marine ecosystem predictions that are sorely needed.

A brief note on scale and terminology

Before proceeding further, as noted by reviewers on previous versions of this work there are many ways that the general population and even scientists can use many of the terms noted herein. Thus, it seems prudent to define a few scales and terms. Here, by prediction we mean stating in advance that an event or phenomena will occur, almost as a statement of expectation from a hypothesis. By projection we mean the calculations, using a relatively straightforward mathematical treatment, to obtain a numerical value of that future event or phenomena. This is an estimate of future conditions based on analytical solutions that seek to simply provide a relatively accurate answer with less concern about elements of precision or delivery. By forecast we mean a probabilistic treatment of the projection (i.e. with uncertainty) that extends prior observations or data, predicting the future state of the phenomena or event (*sensu*; Saaty and Vargas, 1991). This is essentially an estimate of future situations based on current trends which assimilates data and accounts for the many types of uncertainty (certainly statistical, but also others; Peterman, 2004). In our experience, forecasts also include some degree of intentional communication that messages and packages a predictive output into an easily accessible form so that a forecast can be readily used to inform decision-making. All of these are done for a particular time and place. For instance, using a weather analogy we might predict that it will rain tomorrow in our village, we project it will rain around 1 cm during mid-day in our village, and we forecast that it will rain 1 cm +/− 0.25 cm between 11 a.m. and 3 p.m. and in over half of the area covered by our village with a 60–70% probability of occurring. Herein, we use the more general term "prediction" to encompass the increasingly detailed suite of prediction products (predictions, projections, and forecasts) to capture both the hierarchical nature of these treatments of future states (Saaty and Vargas, 1991) and to convey the general need to provide statements about future conditions of marine ecosystems. Though these are technical distinctions, fundamentally all refer to providing some determination about the future state of an ecosystem and have been used interchangeably in the literature across different disciplines.

To do predictions, projections, and forecasts, we note that models are crucial tools to provide such outputs (DeYoung *et al.*, 2004; Fulton, 2010; Link *et al.*, 2017a; Coll *et al.*, 2020). There are many excellent modelling tools and applications thereof, but this work aims not to review any models or model suites, endorse any particular modelling approach, nor make the case for certain types of modelling efforts over others. Rather, we want our forecasting system to be model agnostic, so that it can incorporate the outputs of any appropriate model into the predictions needed. We also note that there are many facets of research and use in studying and managing the ocean. Using the definition of Craig and Link (2023), when they referred to fisheries management (which can be extended to any ocean-use sector management or decision-making process), as "operational" meaning models and resultant predictions that are "used to support and inform resource management, as characterized by (1) use of established methodological approaches and best practices during model development, (2) regular use of the model to provide information in support of a resource management process, (3) use of the most recently available data that has been quality-controlled, archived, and is easily accessible, (4) model outputs that can inform actionable choices from a defined set of alternatives, and (5) ideally, evaluation of trade-offs among ecological, socio-economic, and policy objectives. Operational models are also regularly updated using established procedures and their outputs are familiar to decision-makers". The point is that there are many research models and even published predictions, but for a model to formally provide operational prediction products, as used in a forecasting context, the prediction products need to be routinely and regularly incorporated in a decision-making venue.

We also note that the scale and scope of these predictions are critical to delineate. Whenever such prediction capabilities arise, disparate temporal and especially spatial scales are implied, but need to be expressly stated to avoid confusion. It is intriguing that for large countries like Australia, Russia, Canada, and the United States for example, the term "regional" is sub-national, but for countries in the EU or Africa or parts of Asia, the term "regional" is multi-national, which further complicates the matter. Thus, stating that something is regional can mean very different spatial scales given differing contexts. There are global, international (in smaller countries, regional; 10^9 km^2 to multiple degrees of latitude and longitude), national (10^6–10^9 km^2), sub-national (in larger countries, regional; 10^4–10^8 km^2), and local scales (1–10^3 km^2), which generally (and decreasingly) correspond to the entire world ocean, major ocean basins, sub-basins or regional seas, large marine ecosystems (LME), distinct (enclosed) seas, major coastal features and oceanographic processes (e.g. named currents), estuaries, bays, and harbours. Herein, we largely focus on the cross-LME (i.e. multiple LME) or sub-basin scales, as we view that as the primary gap where improved integration and coordination can provide benefits (Figure 2c). We recognize that some earth system and oceanographic features as well as LMR and economic dynamics (Coll *et al.*, 2020) occur at even larger scales, which also might need to be considered, but global scales tend to be modelled more commonly than sub-basin scales. We use the terms "cross-ecosystem" or "large ocean region" throughout to clarify the spatial scales we emphasize, largely implying either national (for larger countries) or multi-national (for small countries) jurisdictions. We also provide examples primarily from the United States given our affiliation, but recognize the broader, international applicability of what we propose. Regarding temporal scale, it can vary depending upon what is being forecast, but mostly here we are referring to seasonal up to at least multi-annual to sub-decadal scales (Figure 2c), as the shorter and longer time frames tend to have more predictive emphasis, but often miss key elements of what the prediction products we note would convey.

Marine ecosystem prediction products: a system-of-systems

Some form of an integrated, large ocean regional capacity for marine ecosystem prediction is warranted. This would be part of a system-of-systems, spanning the full range of issues that can produce and inform such predictions (Figure 3). There would need to be a suite of linked modelling systems (Wilkin *et al.*, 2017; Link *et al.*, 2017a; Tittensor *et al.*, 2018). An expansion of ocean observing systems (Wilkin *et al.*, 2017; Snowden *et al.*, 2019; Brett *et al.*, 2020) is needed to increase the data and parameter inputs needed for verification, validation, and uncertainty quantification of any models used for forecasting (Link *et al.*, 2017a, b; Brett *et al.*, 2020). This has been raised previously (Wilkin *et al.*, 2017, Brett *et al.*, 2020; Levin *et al.*, 2019), and we support it here as well. The disciplinary scope would cover the range from atmospheric to oceanic physics and chemistry to biological and ecological systems to particularly human dimensions, all with germane model coupling and appropriate feedbacks (Figure 2a). Ongoing and proposed efforts on a range of modelling and forecasting initiatives (Brandt *et al.*, 2006; Rosenzweig *et al.*, 2017; Link *et al.*, 2017a, b; Dietze *et al.*, 2018; Tittensor *et al.*, 2018; Coll *et al.*, 2020; Kawamiya *et al.*, 2020; Steffen *et al.*, 2020) speak to this need, and we collectively support those efforts, but even more so their coupling together to produce integrated marine ecosystem forecasts. And implied in all of this is the research to better improve the predictions and their dissemination. Embedded amongst this system-of-systems would be a large ocean regional coordinated prediction system emphasized here. The focus of these predictions would not be on physics, largely because climatological and oceanic forecasts are already extant and routinely disseminated, but would rather ensure that any climatological, atmospheric, oceanographic, or related physical features would be linked to a biological, ecological, or otherwise LMR response, which would be forecast and presented, along with the socio-economic responses to these changed biological conditions (Figures 1 and 2a). There would also need to be reporting systems, systems for disseminating prediction products, and a system for routine production of outlooks (Figure 3). Finally, there might need to be possible updating or revision of governance systems to include explicit on-ramps for these predictions in management and decision support contexts (Link *et al.*, 2020, 2021), but we also propose that like weather forecasts, marine ecosystem predictions would have broad public appeal apart from any particular governance venue.

This system-of-systems approach would necessarily require the full gamut of observations, modelling, projections, communication, and stakeholder feedback (Figure 3; Link *et al.*, 2017a, b; Capotondi *et al.*, 2019; Link and Marshak, 2019; Snowden *et al.*, 2019). As such, it would necessarily need to be assisted by a wide array of oceanographic-, marine ecosystem-, and marine socio-economic-oriented partners. These predictions would primarily be public goods. Thus, such a large-scale marine ecosystem effort would likely be well-housed in a focused governmental loci. A broad array

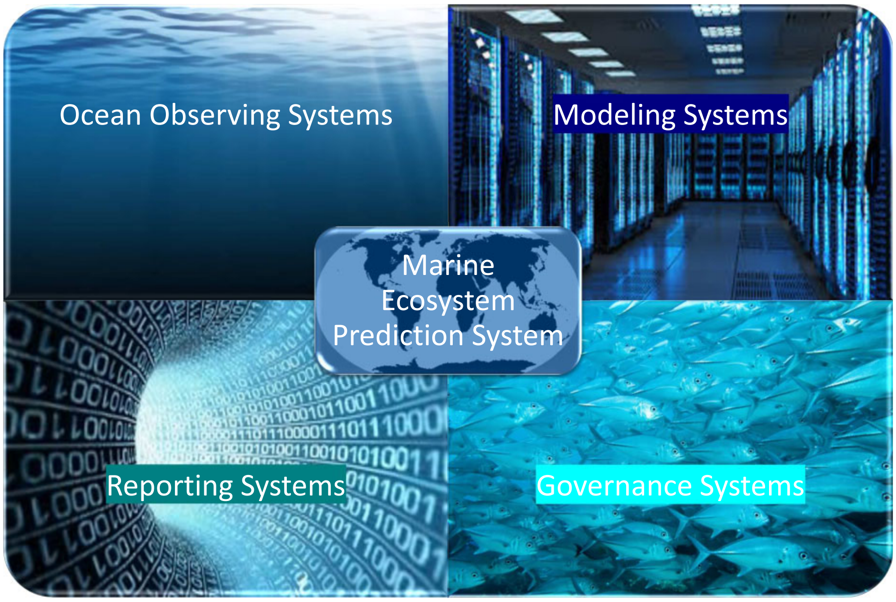

Figure 3. The system of systems approach to developing marine ecosystem predictions. Most associated initiatives focus on one sub-system or various aspects thereof, or they conflate modelling with prediction; here we note the need for a full suite of systems to develop and disseminate marine ecosystem predictions.

of federal, state, academic, private industry, NGO, and foundation partners would be absolutely essential to ensure the full suite of predictions are scientifically rigorous, scientifically advancing, and most beneficial to the widest range of the public.

Elements of marine ecosystem predictions

What would any such prediction capability provide by way of prediction products for these marine ecosystems? We offer four elements that would be useful and necessary prediction products (Figure 4). The first would be locational predictions. That is, under changing ocean conditions, specifically where and when will select LMR populations, entire biological communities, emergent ecosystem properties, human activities, and human responses be; and at what levels of abundance, density, or activity will these occur (Stock *et al.*, 2011; Tommasi *et al.*, 2017; Drenkard *et al.*, 2021; Heneghan *et al.*, 2021; Tittensor *et al.*, 2021)? The applications of these predictions have impact, now, for turtles, whales, highly migratory species, beach closures, HAB avoidance zones, fishery and protected species recovery plans, biodiversity, and restoration plans (e.g. Hawkes *et al.*, 2009; Wells *et al.*, 2015; Weatherdon *et al.*, 2016; Tommasi *et al.*, 2017; NMFS, 2022). Specific examples might also include projections and forecasts of biodiversity hotspots, HAB timing and location, shifts in the location of primary productivity and lower trophic level dynamics, changes in distribution and range of commercially, ecologically, and socially important targeted taxa, shifts in fishing fleet dynamics in response to the prior elements, shifts in cross-regional market dynamics due to differential availability of LMR products, recommendations for siting of offshore structures to minimize impact on novel migration or movement routes, or even recommendations for other spatial management measures. Future projections for multiple mission applications will continue to arise as distribution and range shifts of LMRs escalate under climate change, and these shifts occur across major geographic regions. We already know that major taxa groups are generally moving poleward at a rate six times faster than on land (Lenoir *et al.*, 2020), with the shift in the centroid of all major surveyed species moving at non-trivial rates (Figure 5c). There are exceptions to these general poleward movements. For example, in the US Gulf of Mexico, where geography does not foster a linear, poleward shift, taxa are moving into deeper waters, which is what tends to occur when taxa cannot move parallel to a coast (NMFS, 2022; Lenoir *et al.*, 2020). Being able to better anticipate these projected movements will assist in the collective ability to adapt to them.

The second set of predictions would address production (Figure 4). This refers to estimates of primary production, secondary production, aggregate production, LMR production, fisheries production, and overall ecosystem productivity (Stock *et al.*, 2011; Friedland *et al.*, 2012; Tommasi *et al.*, 2017), all leading to facets of seafood production, fisheries productivity, biodiversity increases, ecosystem resilience, and economic return (Marshak and Link, 2021). Often these estimates are done on a population level, and we anticipate that those will continue in their extant, local or LME-regional contexts. But what is not routinely and regularly provided are overall ecosystem levels of production, and what can be expected for a composite set of LMR taxa or ecosystem goods and services (Link and Marshak, 2019; Marshak and Link, 2021). Augmenting the list above, specific examples include: predictions, projections and forecasts of total ecosystem primary productivity, total (i.e. in aggregate) LMR landings, ecosystem production potential, total fishery yields, HAB intensity, expected LMR-associated economics, or food web and ecosystem-level efficiency, redundancy, recovery, and cybernetic metrics. Projections to delineate future production conditions, what is available to transfer (and how it is transferred) through food webs (Friedland *et al.*, 2012; Marshak and Link, 2021), and what can be reasonably expected for LMRs

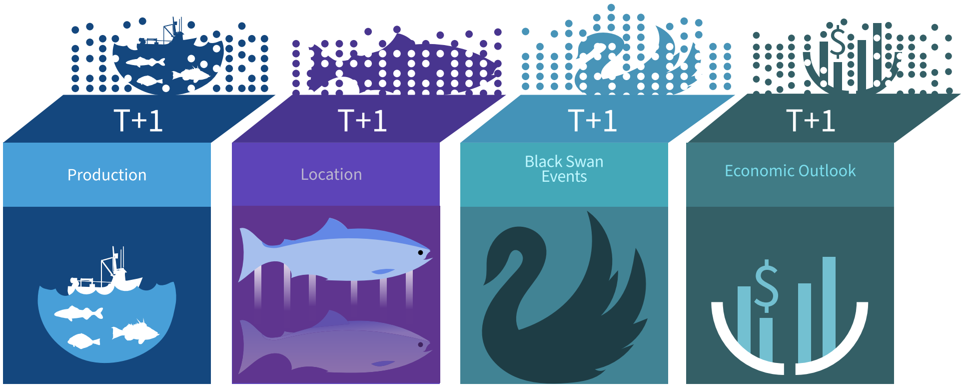

Figure 4. The four main elements of a suite of predictions for marine ecosystems. T + 1 refers to the next time step, with various, possible future conditions.

and utilization thereof would be highly beneficial to provide. Future projections for multiple mission applications will continue to arise as production of LMRs will notably change under climate change. We have known for some time that primary production ultimately limits the amount of production of economically and ecologically important taxa, but now we know that it can have direct implications on regional, LMR-based economies (Figure 5a; Marshak and Link, 2021). The relationships among primary productivity and LMRs has been shown to limit the number of coastal-oriented jobs in a region (Figure 5b; Marshak and Link, 2021). Being able to better predict this will have major utility for local economies around any jurisdiction's use of its EEZ. Furthermore, we have not managed these sectors systematically, and estimates from portfolio analysis (Sanchirico *et al*., 2008; Jin *et al*., 2016) show that the gap between what risk is optimal (or minimized) and what is actually experienced, for any given level of harvest, is actually much higher than it needs to be (Figure 5d). The difference between the portfolio efficiency frontier (Sanchirico *et al*., 2008; Jin *et al*., 2016) and what is actually landed in a US fisheries example demonstrates that in any given region we are 20–50 million US dollars riskier than we need to be to obtain the value of current landings (Figure 5d). That is not sustainable given future, anticipated changes. This is true for other ocean-use sectors as well. Being able to monitor, and lower, the risk gap percentage is wise and needed.

The third element addresses the need to predict "Black Swan" events (i.e. difficult to predict phenomena with potentially major consequences), or at least the probability that they could occur and at what approximate magnitude, or even bracket the range of such possible occurrences (Bray and Wang, 2020; Figure 4). It is known that technically we cannot predict Black Swan events, but there are things we can do to make better decisions today under such deep uncertainty (Wainger *et al*., 2021) to mitigate these events. Further, we need to be able to assess the consequences of these events on ecosystems and human communities. Examples in marine ecosystems usually tend to focus on the physical conditions that can affect LMRs, such as El Nino events, marine heat waves, shifts in major ocean currents, etc. (Federov *et al*., 2003; Smale *et al*., 2019; Drenkard *et al*., 2021). But Black Swan events also include potential oil spills, undesirable biotic outbreaks (i.e. not only HABs, but gelatinous zooplankton blooms, fouling coverage, fishery disasters, invasive species establishments, and so on; Mills, 2001; Molnar *et al*., 2008; Sorte *et al*., 2010; Bellquist *et al*., 2021) and related ecological bio-disturbances. Other examples include: probabilistic forecasts of coral bleaching, unusual mortality events of marine mammals or other charismatic megafauna, unanticipated or unplanned emergency fisheries closures, shellfish toxin poisoning, disease outbreaks (for marine life or humans), or even human conflict over resource access and use. The ability to predict these events, or at least their probability of occurring, is by definition limited, but is sorely needed—even if initially crudely projected—given climate change feedback loops. Yet, this ability is limited when working at scales relevant to these outbreaks (Figure 5h). The number of billion-dollar disasters has increased (Figure 5e; NOAA, 2021, 2022), and is only expected to continue to do so. Being able to at least provide broader warnings about these highly dynamic and disruptive features of marine ecosystems is critically needed.

The fourth set of products is ocean and LMR-oriented economic outlooks (Figure 4). These are bio-economic in nature, and combine outputs from portions of the previously mentioned predictions, albeit translating them into fiscal units (OECD, 2016; Kubiszewski *et al*., 2017). The aim of these predictions is to project likely future conditions of marine ecosystems, LMRs, and ecosystem goods and services as these support myriad social and economic measures. Specific examples include: projections and forecasts of blue economy new business starts, number and value of coastal jobs and markets, national and international asset (e.g. LMR) market dynamics, valuation of marine ecosystem goods and services (especially functional and provisioning), or the combined risk forecast to multiple ocean-use sectors. This blue economic prediction would have multiple facets, multiple uses, and we suspect will have almost immediate generation of high interest, but apart from the sectoral-specific and retrospective reports, none currently do so that integrate across the ocean-use sectors for an entire large ocean region. As noted above (Figure 5a, b, and d), the economic aspects of these predictions can better demonstrate the impacts, and value of mitigating said impacts, on many of the elements for which we are calling for predictions.

An ancillary, secondary level of prediction products, and the true value of a cross-ecosystem, integrated approach, would be to synthesize and communicate the four main predictions noted above (Figure 4) into standard reports that have a mild to moderate degree of interpretation. Chief of these would

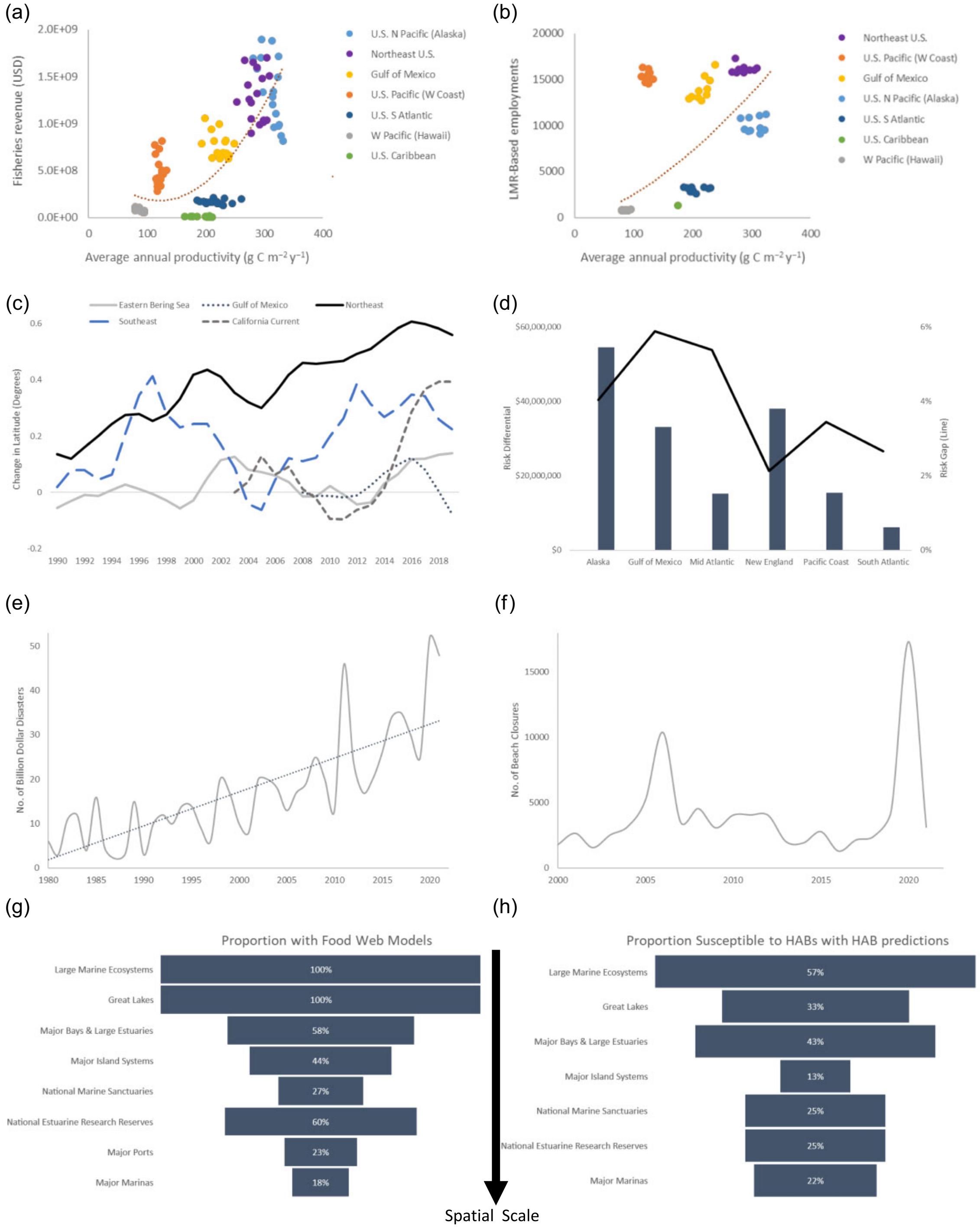

Figure 5. (a) The relationship between primary productivity and fisheries revenue in major regions of the United States. Adapted from Marshak and Link (2021). (b) The relationship between primary productivity and LMR employments in major regions of the United States. Adapted from Marshak and Link (2021). (c) The change in latitude as the average shift in the centroid of species caught in surveys conducted in each region. These species represent a wide range of habitats and species types. As species distributions respond to many environmental and biological factors, combining data from multiple diverse species allows for a more complete picture of the general trends in marine species distribution. Adapted from NOAA Fisheries (2022) and NOAA (2021). (d) The risk differential (bars) and risk gap (line) of fisheries for major regions of the United States in 2020 (Townsend, unpublished data). The risk differential is the amount of actual versus optimized risk of the portfolio frontier, and the gap is the percentage difference (Sanchirico *et al.*, 2008; Jin *et al.*, 2016). These are for all the taxa representing the top (approximately) 50th percentile of value of all fishery landings for the given revenue in any given year. Incurring risk beyond the portfolio frontier is, although never feasible to be at 0, (economically) riskier than values that are closer to said frontier and that have smaller portfolio gaps (relative to the value of what was landed). (e) The number of billion dollar disasters over time. Adapted from NOAA (2021, 2022). (f) The number of beach closures over time. Adapted from NOAA (2021) and EPA (2022). (g) The proportion of each US ecosystem noted that has a food web model. (h) The proportion of each US ecosystem noted that is susceptible to HABs that have HAB forecasts. For both (g) and (h), the spatial scale decreases. The number of ecosystems for both is: Large Marine Ecosystems = 10; Great Lakes = 5; Major Bays and Large Estuaries = 24; Major Island Systems = 9; National Marine Sanctuaries = 15; National Estuarine Research Reserves = 30; Major Ports = 158; and Major Marinas = 202.

be simplified syntheses of the predictions into digestible risk analysis and probabilistic estimates of events. There is high demand for such products in multiple sectors, as analogues to weather reports. We do comparable reporting across the various aspects of the ocean-use framework (e.g. status of LMRs, ecosystem status reports, risk tables, and so on; Slater *et al.*, 2017; Dorn and Zador, 2020) and some forecasts (e.g. weather, hurricanes, and so on; Uccellini and Ten Hoeve, 2019), but those are typically retrospective and dated reports or focused primarily on physical phenomena. For example, that beach closures over the past 20 years show no discernable trends apart from two peaks (one undoubtedly related to COVID-19; Figure 5f), which were not anticipated but could have better informed a range of coastal tourism-related industries. The ability to routinely, systematically, and succinctly report on marine ecosystem predictions with an LMR emphasis does not exist beyond the usual species-by-species or issue-by-issue assessments. Currently, there is no larger scale synthesis of marine ecosystem predictions or their associated products, though there are nascent reports emerging (e.g. in the United States the National Marine Ecosystem Status report and ICES Regional Seas Ecosystem Overviews have been developed; NOAA, 2021; ICES, 2023) that track past trends.

Why marine ecosystem predictions?

The marine ecosystem prediction capability we propose would also help facilitate the escalation of modelling development. As noted above, there are many initiatives proposed to do so (Brandt *et al.*, 2006; Rosenzweig *et al.*, 2017; Link *et al.*, 2017a, b; Dietze *et al.*, 2018; Tittensor *et al.*, 2018; Coll *et al.*, 2020; Kawamiya *et al.*, 2020; Steffen *et al.*, 2020) and there are many extant and excellent models to this, but none are unified into a common modelling system (Link *et al.*, 2017a, b; Figure 3). This model development would also require the escalation of fundamental understanding and research focused in the cross-ecosystem elements for marine systems. There are obvious gaps in what is currently modelled and predicted (DeYoung *et al.*, 2004; Tommasi *et al.*, 2017; Baustert *et al.*, 2018; Steffen *et al.*, 2020). For example, food web models are understood to be the basis for many of the capabilities to address the complex dynamics of marine ecosystems noted above, and as one increases spatial resolution to more local jurisdictions, the capacity for said models decreases (Figure 5g). The same holds for an example of a major coastal stressor, HABs (Figure 5h); whereby at smaller spatial scales our ability to predict HABs decreases when the instance of HABs actually both increases and has higher impact at those scales. In this instance, filling in the spatial resolution but especially the spatial extent would help improve HAB predictions. This proposed prediction system would seek to fill in such gaps at taxonomic, spatial, temporal, and governance scales that are often missed due to a lack of a systematic approach (Link *et al.*, 2017a; Fulton *et al.*, 2019; Link and Marshak, 2019; Holsman *et al.*, 2020; Figure 2b). At this point, most readers are likely saying to themselves, “yes, but which models?”. We want this system of systems to be model agnostic and able to incorporate outputs as input into the forecasting process. This approach is already used in the atmospheric forecasting arena (i.e. weather and climate forecasts that use model ensembles; e.g. Semenov and Stratonovitch 2010; O’Neill *et al.*, 2016). Hence, again there would necessarily need to be a range of partners involved with any prediction effort at the scales noted.

The question then begs: Why now? What has changed to make us think we can now execute such an aspirational vision when many similar efforts have been called for in the past (Brandt *et al.*, 2006; Rosenzweig *et al.*, 2017; Link *et al.*, 2017a, b; Dietze *et al.*, 2018; Tittensor *et al.*, 2018; Coll *et al.*, 2020; Kawamiya *et al.*, 2020; Steffen *et al.*, 2020)? We assert that there are three reasons. First, there is broad, bipartisan support for this concept, with clear economic and other societal benefits (noted below; e.g. in the United States; EOP, 2021; US Congress, 2021). Second, there are more data and observation systems (Snowden *et al.*, 2019), better computing power (Megrey and Moksness, 2009), growing capability to integrate and synthesize massive amounts of information (Harvey *et al.*, 2021), notable advances in modelling techniques and proven case studies of applications (Fulton, 2010; Stock *et al.*, 2011; Evans *et al.*, 2012; Tommasi *et al.*, 2017; Francis *et al.*, 2018; Drenkard *et al.*, 2021, Park *et al.*, 2019; Tittensor *et al.*, 2021). Even the recent widespread advances in artificial intelligence may have application in this context (Agrawal *et al.*, 2019). In short, the technical challenges are rapidly being overcome. Third and very simply, there is growing demand for these predictions, and given the urgency and exigency of the situation we face, we do not have a choice (Stock *et al.*, 2011; Tommasi *et al.*, 2017; Bindoff *et al.*, 2019; Canadell *et al.*, 2021; Drenkard *et al.*, 2021). Thus, in many respects we need to find solutions to make such a suite of prediction products executable.

Another question begs: why do we not yet have these prediction products? What barriers remain that impede the execution and production of such marine ecosystem prediction products? We do not think these primarily include technical barriers, for reasons noted in the previous paragraph. These also likely do not include limits to our scientific knowledge. Granted there is always need to better resolve, refine, and estimate more and newer details of major marine ecosystem processes and mechanisms, and we are not arrogant enough to presume we know everything about marine ecosystems. Yet given what we do know now, and particularly the utility of scaling, aggregation, emergent features, and hierarchy theory (Wu, 2013), we likely do not need to know every detail about every process to start to make these predictions. Rather, barriers that likely do hinder the execution of these prediction products include the usual tropes of relatively limited resourcing (discussed below), structural impediments across ocean science and management organizations, and competing interests among the different ocean-use sectors and their associated institutions. The latter two may require revisiting how institutions are organized and more so how information is provided and used across multiple ocean-use considerations. This element of competing objectives remains a key feature requiring enhanced coordination as noted in calls to better enable ecosystem-based management (Dickey-Collas *et al.*, 2022). Even a synthesis team, which had a modicum of some cross-jurisdictional influence would be highly beneficial to better facilitate these prediction products.

Regarding the value proposition of these predictions, there are two aspects to consider. One is the difference in having them versus not, which of course is difficult to ascertain since we do not fully have them. Yet the potential costs of not having them, as noted above regarding what we may have missed, gives a rough scale that this value would likely be on the order of at least 10s–100s of billions of dollars if such negative impacts were to be even partially mitigated. The second aspect of the value proposition is to evaluate the investment to obtain these predictions relative to the value of what is being predicted. For instance, in the case of the United States it seems logical that there would need to be investment comparable to what we see in, for example, the Federal Communications Commission, Department of Transportation, or National Weather Service relative to a significant fractional portion of the value of the economic sectors that those organizations support. When compared to the predictions, governance, and infrastructure to provide oversight and publicly available projections of future conditions to support comparably sized facets of the economy (i.e. the marine economy accounted for more than 430 billion $US GDP in 2021; BEA, 2023)—for instance telecommunications, federal highways and transportation, or even terrestrial ecosystem goods and services via agriculture or silviculture—the investment in prediction for marine ecosystem goods and services is notably lower. Any such cross-LME marine ecosystem prediction capability needs to be established and proportionately resourced to obtain the benefits of an integrated and coordinated suite of prediction products that influence, in composite for the United States, a value that is annually nearing half a trillion $US now, which comprises nearly 2% of the total US GDP (1.9%; BEA, 2023).

Who would benefit from such regular, routine, marine ecosystem predictions? That question really could be posed as, who would not? Beyond the usual parties typically identified, we particularly note: the business, financial, insurance, and reinsurance and planning sector, as well as other marine sector investors beyond those solely utilizing direct ocean assets and commodities, coastal communities, LMR users and regulators, multiple marine industry sector stakeholders and partners, National Security partners, and other, novel and probably as yet undefined blue economy information users. The international applications are also obvious, given both the highly interconnected nature of global economic sectors as well as key partners in ocean science and modelling [e.g. United Nations Decade of Ocean Science for Sustainable Development (2021–2030); UN, 2018]. The interest by such an array of benefitting parties should make the potential business case for these predictions stronger, resulting in a demand for such prediction products as a routine matter of course. The critical point of these prediction products is that they will assist us in making decisions about the future state of the ocean, and its marine ecosystems, by projecting what may or may not happen under a range of scenarios (both climate change and others) that we can nominally influence.

Hence, the development and formal establishment of a large ocean region marine ecosystem prediction capability, to deal with climate change and cumulative impacts on marine ecosystems, is timely and germane. Such an effort aligns with the need for more effective use of science products, the calls to emplace systems to provide suggestions and forecasts for mitigation and adaptation (IPCC, 2014; Shi *et al.*, 2022), as well as the widely held priorities of US national (EOP, 2021; US Congress, 2021) and international (UN, 2018) leadership. Furthermore, establishing such a marine ecosystem prediction capability builds on a range of extant efforts, ensuring that the return-on-investment from those existing efforts is multiplied. We assert that establishing this predictive capacity would galvanize and focus some much-needed efforts to address what are critical problems facing marine ecosystems, but also place us in a position to take advantage of such opportunities.

Acknowledgements

We thank several of our colleagues at NOAA, the NOAA Science Council, and the NOAA Science Advisory Board, but especially Craig McLean, Cisco Werner, and JoEllen Russell for stimulating discussions as we developed the concepts herein. We thank Howard Townsend, Doug Lipton, and Jon Hare for constructive comments on earlier versions of this draft. We thank Howard Townsend for providing context and data for the portfolio information. We thank Jennifer Dusto and Kelly Cribari for their assistance with the references.

Authors’ contributions

All authors contributed to the editing of this work and to the refinement of the concepts and broader disciplinary contexts. JL conceptualized the initial ideas, analysed the data, wrote the first drafts of the manuscript, developed the graphics, collated feedback, and updated drafts. GM provided writing of selected text sections. ST, GM, and MG reviewed various versions of the manuscript. All authors provided their own caffeine.

Conflict of interest statement

The authors declare no conflict of interest.

Data availability

The data underlying this article are available from duly referenced materials herein or will be shared on reasonable request to the corresponding author.

References

Agrawal, A., Gans, J. S., and Gladfarb, A. 2019. Exploring the impact of artificial intelligence: prediction versus judgment. Information Economics and Policy, 47: 1–6.

Alaska Beacon. 2022. https://alaskapublic.org/2022/12/19/alaska-crab-fishery-collapse-seen-as-warning-about-bering-sea-transformation/ (last accessed 25 July 2023).

Bakkensen, L. A., and Barrage, L. 2021. Going underwater? Flood risk belief heterogeneity and coastal home price dynamics. The Review of Financial Studies, 35: 3666–3709.

Baustert, P., Othoniel, B., Rugani, B., and Leopold, U. 2018. Uncertainty analysis in integrated environmental models for ecosystem service assessments: frameworks, challenges and gaps. Ecosystem Services, 33(B): 110–123.

BEA (U.S. Bureau of Economic Analysis). 2023. Marine economy satellite account, 2021: new statistics for 2021; 2014-2020 updated. BEA 23-24, (U.S. Department of Commerce). https://www.bea.gov/news/2023/marine-economy-satellite-account-2021 (last accessed 8 June 2023).

Bellquist, L., Saccomanno, V., Semmens, B. X., Gleason, M., and Wilson, J. 2021. The rise in climate change-induced federal fishery disasters in the United States. PeerJ, 9: e11186.

Berman, M., Baztan, J., Kofinas, G., Vanderlinden, J.-P., Chouinard, O., Huctin, J.-M., Kane, A. *et al.* 2020. Adaptation to climate change in coastal communities: findings from seven sites on four continents. Climatic Change, 158: 1–16.

Bindoff, N. L., Cheug, W. W. L., Kairo, J. G., Arístegui, J., Guinder, V. A., Hallberg, R., Hilmi, N. *et al.* 2019. Changing ocean, marine ecosystems, and dependent communities. *In* IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, pp. 447–587. Ed. by H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegri´a, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N. M. Weyer, Cambridge University Press, Cambridge, New York, NY. https://doi.org/10.1017/9781009157964.007.

Brandt, S., Hendee, J., Levin, P., Phinney, J., Scheurer, D., and Schwing, F. 2006. Ecological forecasting. *In* Ecosystem Science Capabilities Required To Support NOAA's Mission in the Year 2020. pp. 52–63. Ed. by S. A. Murawski, and G. C. Matlock, U.S. Department of Commerce, Washington, DC. NOAA Technical Memorandum NMFS-F/SPO-74. https://www.pmel.noaa.gov/foci/publications/2006/osgoN619.pdf.

Bray, S. R., and Wang, B. 2020. Forecasting unprecedented ecological fluctuations. PloS Computational Biology, 16: e100802.

Brett, A., Leape, J., and Abbott, M. 2020. Ocean data need a sea change to help navigate the warming world. Nature, 582: 181–183.

Brodeur, R. D., Auth, T. D., and Phillips, A. J. 2019. Major shifts in pelagic micronekton and macrozooplankton community structure in an upwelling ecosystem related to an unprecedented marine heatwave. Frontiers in Marine Science, 6: 212.

Burke, S., Pottier, P., Lagisz, M., Macartney, E. L., Ainsworth, T., Drobniak, S. M., and Nakagawa, S. 2023. The impact of rising temperatures on the prevalence of coral diseases and its predictability: a global meta-analysis. Ecology Letters, 26: 1466–1481.

Canadell, J. G., Monterio, P. M. S., Costa, M. H., Cotrim de Cunha, L., Cox, P. M., Eliseev, A. V., Henson, S. *et al.* 2021. Global carbon and other biogeochemical cycles and feedbacks. *In* Proceedings of the Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. pp. 673–816. Ed. by V. Masson-Delmotte, P. Zhai, A. Pirani, S. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I Gomis, M. Huang, K Leitzell, E. Lonnoy, J. B. R. Matthews, T. K.W. Maycock, T. O. Yelekçi, R. Yu, and B. Zhou, Cambridge University Press, Cambridge, New York, NY. https://doi.org/10.1017/9781009157896.007.

Capotondi, A., Jacox, M., Bowler, C., Kavanaugh, M., Lehodey, P., Barrie, D., Brodie, S. *et al.* 2019. Observational needs supporting marine ecosystems modeling and forecasting: from the global ocean to regional and coastal systems. Frontiers in Marine Science, 6: 623.

Cochrane, K. L. 2020. Reconciling sustainability, economic efficiency and equity in marine fisheries: has there been progress in the last 20 years?. Fish and Fisheries, 22: 298–323.

Colburn, L. L., Jepson, M., Weng, C., Seara, T., Weiss, J., and Hare, J. A. 2016. Indicators of climate change and social vulnerability in fishing dependent communities along the Eastern and Gulf Coasts of the United States. Marine Policy, 74: 323–333.

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: 567877.

Cope, M. R., and Slack, T. 2017. Emplaced social vulnerability to technological disasters: southeast Louisiana and the BP Deepwater Horizon oil spill. Population and Environment, 38: 217–241.

Copernicus. 2023. https://climate.copernicus.eu/record-breaking-north-atlantic-ocean-temperatures-contribute-extreme-marine-heatwaves (last accessed 25 July 2023).

Court, C., Hodges, A. W., Coffey, K., Ainsworth, C. H., and Yoskowitz, D. 2020. Effects of the deepwater horizon oil spill on human communities: catch and economic impacts. *In* Deep Oil Spills: Facts, Fate, and Effects. pp. 569–580. Ed. by S.A. Murawski, C.H. Ainsworth, S. Gilbert, D.J. Hollander, C.B. Paris, M. Schlüter, and D.L. Wetzel, Springer International Publishing, Cham. https://doi.org/10.1007/978-3-030-11605-7_33.

Craig, J. K., and Link, J. S. 2023. It is past time to use ecosystem models tactically to support ecosystem-based fisheries management: case studies using Ecopath with Ecosim in an operational management context. Fish and Fisheries, 24: 381–406.

Degroot, D., Anchukaitis, K., Bauch, M., Burnham, J., Carnegy, F., Cui, J., de Luna, K. *et al.* 2021. Towards a rigorous understanding of societal responses to climate change. Nature, 591: 539–550.

DeYoung, B., Heath, M., Werner, F., Chai, F., Megrey, B., and Monfray, P. 2004. Challenges of modeling ocean basin ecosystems. Science, 304: 1463–1466.

Diaz, R. J., and Rosenberg, R. 2008. Spreading dead zones and consequences for marine ecosystems. Science, 321: 926–929.

Dickey-Collas, M., Link, J. S., Snelgrove, P., Roberts, J. M., Anderson, M. R., Kenchington, E., Bundy, A. *et al.* 2022. Exploring ecosystem-based management in the North Atlantic. Journal of Fish Biology, 101: 342–350.

Dietze, M. C., Fox, A., Beck-Johnson, L. M., Betancourt, J. L., Hooten, M. B., Jarnevich, C. S., Keitt, T. H. *et al.* 2018. Iterative near-term ecological forecasting: needs, opportunities, and challenges. Proceedings of the National Academy of Sciences of the United States of America, 115: 1424–1432.

Doney, S. C., Ruckelshaus, M., Duffy, J. E., Barry, J. P., Chan, F., English, C. A., Galindo, H. M. *et al.* 2012. Climate change impacts on marine ecosystems. Annual Review of Marine Science, 4: 11–37.

Dorn, M. W., and Zador, S. G. 2020. A risk table to address concerns external to stock assessments when developing fisheries harvest recommendations. Ecosystem Health and Sustainability, 6: 1813634.

Drenkard, E. J., Stock, C., Ross, A. C., Dixon, K. W., Adcroft, A., Alexander, M., Balaji, V. *et al.* 2021. Next-generation regional ocean projections for living marine resource management in a changing climate. ICES Journal of Marine Science, 78: 1969–1987.

EOP (Executive Office of the President). 2021. Memorandum for the Heads of Executive Departments and Agencies. Executive Office of the President, Washington, DC. https://www.whitehouse.gov/wp-content/uploads/2021/07/M-21-32-Multi-Agency-Research-and-Development-Prioirties-for-FY-2023-Budget-.pdf (last accessed 30 May 2023).

EPA (Environmental Protection Agency). 2022. EPA BEACON 2.0 website. https://watersgeo.epa.gov/beacon2/ (last accessed 30 May 2023).

Evans, M. R., Norris, K. J., and Benton, T. G. 2012. Predictive ecology: systems approaches. Philosophical Transactions of the Royal Society of London B Bioliogical Sciences, 367: 163–169.

Fedorov, A. V., Harper, S. L., Philander, S. G., Winter, B., and Wittenberg, A. 2003. How predictable is El Niño?. Bulletin of the American Meteorological Society, 84: 911–920.

Francis, T. B., Levin, P. S., Punt, A. E., Kaplan, I. C., Varney, A., and Norman, K. 2018. Linking knowledge to action in ocean ecosystem management: the Ocean Modeling Forum. Elementa: Science of the Anthropocene, 6: 83.

Friedland, K. D., Stock, C., Drinkwater, K. F., Link, J. S., Leaf, R. T., Shank, B. V., Rose, J. M. *et al.* 2012. Pathways between primary production and fisheries yields of large marine ecosystems. PLoS ONE, 7: e28945.

Fulton, E. A. 2010. Approaches to end-to-end ecosystem models. Journal of Marine Systems, 81: 171–183.

Fulton, E. A., Punt, A. E., Dichmont, C. M., Harvey, C. J., and Gorton, R. 2019. Ecosystems say good management pays off. Fish and Fisheries, 20: 66–96.

Gill, D. A., Picou, J. S., and Ritchie, L. A. 2011. The Exxon Valdez and BP oil spills: a comparison of initial social and psychological impacts. American Behavioral Scientist, 56: 3–23.

Graham, R. J., Yun, W.-T., Kim, J., Kumar, A., Jones, D., Bettio, L., Gagnon, N. *et al.* 2011. Long-range forecasting and the Global Framework for Climate Services. Climate Research, 47: 47–55.

Harrison, J. A. 2019. Down here we rely on fishing and oil: work identity and fishers'. Responses to the BP oil spill disaster. Sociological Perspectives, 63: 333–350.

Harvey, C. J., Fluharty, D. L., Fogarty, M. J., Levin, P. S., Murawski, S. A., Schwing, F. B., Shuford, R. L. *et al.* 2021. The origin of NOAA's Integrated Ecosystem Assessment Program: a retrospective and prospective. Coastal Management, 49: 9–25.

Hawkes, L., Broderick, A., Godfrey, M., and Godley, B. 2009. Climate change and marine turtles. Endangered Species Research, 7: 137–154.

Heneghan, R. F., Galbraith, E., Blanchard, J. L., Harrison, C., Barrier, N., Bulman, C., Cheung, W. *et al.* 2021. Disentangling diverse responses to climate change among global marine ecosystem models. Progress in Oceanography, 198: 102659.

Hoegh-Guldberg, O., and Bruno, J. F. 2010. The impact of climate change on the world's marine ecosystems. Science, 328: 1523–1528.

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.

ICES. 2023. ICES ecosystem overviews technical guidelines. Version 4. ICES Guidelines and Policies - Advice Technical Guidelines. ICES Advice. 24pp. https://doi.org/10.17895/ices.pub.22059803.

IPCC. 2014. Climate change 2014: mitigation of climate change. *In* Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Ed. by O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J. C. Minx, Cambridge University Press, Cambridge, New York, NY. https://doi.org/10.1017/CBO9781107415416.

Jackson, J. B. C., Kirby, M. X., Berger, W. H., Bjorndal, K. A., Botsford, L. W., Bourque, B. J., Bradbury, R. H. *et al.* 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science, 293: 629–638.

Jacox, M. G., Alexander, M. A., Siedlecki, S., Chen, K., Kwon, Y.-O., Brodie, S., Ortiz, I. *et al.* 2020. Seasonal-to-interannual prediction of North American coastal marine ecosystems: forecast methods, mechanisms of predictability, and priority developments. Progress in Oceanography, 183: 102307.

Jin, D., DePiper, G., and Hoagland, P. 2016. Applying portfolio management to implement ecosystem-based fishery management (EBFM). North American Journal of Fisheries Management, 36: 652–669.

Kawamiya, M., Hajima, T., Tachiiri, K., Watanabe, S., and Yokohata, T. 2020. Two decades of Earth system modeling with an emphasis on Model for Interdisciplinary Research on Climate (MIROC). Progress in Earth and Planetary Science, 7: 64.

Kubiszewski, I., Costanza, R., Anderson, S., and Sutton, P. 2017. The future value of ecosystem services: global scenarios and national implications. Ecosystem Services, 26(A): 289–301.

Lam, V. W. Y., Cheung, W. W. L., Reygondeau, G., and Sumaila, U. R. 2016. Projected change in global fisheries revenues under climate change. Scientific Reports, 6: 32607.

Landrigan, P. J., Stegeman, J. J., Fleming, L. E., Allemand, D., Anderson, D. M., Backer, L. C., Brucker-Davis, F. *et al.* 2020. Human health and ocean pollution. Annals of Global Health, 86: 151.

Lenoir, J., Bertrand, R., Comte, L., Bourgeaud, L., Hattab, T., Murienne, J., and Grenouillet, G. 2020. Species better track climate warming in the oceans than on land. Nature Ecology and Evolution, 4: 1044–1059.

Levin, L. A., Bett, B. J., Gates, A. R., Heimbach, P., Howe, B. M., Janssen, F., McCurdy, A. *et al.* 2019. Global observing needs in the deep ocean. Frontiers in Marine Science, 6: 241.

Link, J. S., Huse, G., Gaichas, S., and Marshak, A. 2020. Changing how we approach fisheries: a first attempt at an operational framework for ecosystem approaches to fisheries management. Fish and Fisheries, 21: 393–434.

Link, J. S., Karp, M. A., Lynch, P., Morrison, W. E., and Peterson, J. 2021. Proposed business rules to incorporate climate-induced changes in fisheries management. ICES Journal of Marine Science, 78: 3562–3580.

Link, J. S., Tolman, H. L., and Robinson, K. 2017b. NOAA's strategy for unified modelling. Nature, 549: 458.

Link, J., and Marshak, A. R. 2019. Characterizing and comparing marine fisheries ecosystems in the United States: determinants of success in moving toward ecosystem-based fisheries management. Reviews in Fish Biology and Fisheries, 29: 23–70.

Link, J., Tolman, H., Bayler, E., Brown, C., Burke, P., Carman, J., Cross, S. *et al.* 2017a. High-level NOAA unified modeling overview. NOAA Unified Modeling Task Force, National Oceanic and Atmospheric Administration. Washington, DC. pp. 20. 14156. http://doi.org/10.7289/V5GB2248.

Marshak, A. R., and Link, J. S. 2021. Primary production ultimately limits fisheries economic performance. Scientific Reports, 11: 12154.

Megrey, B. A., and Moksness, E. 2009. Computers in Fisheries Research, 2nd edn, Springer Science, Dordrecht. pp. 422. https://doi.org/10.1007/978-1-4020-8636-6.

Meierrieks, D. 2021. Weather shocks, climate change and human health. World Development, 138: 105228.

Methot, R. D. 2009. Stock assessment: operational models in support of fisheries management. *In* The Future of Fisheries Science in North America. Fish & Fisheries Series, 31, pp. 137–165. Ed. by R.J. Beamish, and B.J. Rothschild. Springer, Dordrecht.

Mills, C. E. 2001. Jellyfish blooms: are populations increasing globally in response to changing ocean conditions?. Hydrobiologia, 451: 55–68.

Molnar, J. L., Gamboa, R. L., Revenga, C., and Spalding, M. D. 2008. Assessing the global threat of invasive species to marine biodiversity. Frontiers in Ecology and the Environment, 6: 485–492.

Moore, C., Morley, J. W., Morrison, B., Kolian, M., Horsch, E., FrÖlicher, T., Pinsky, M. L. *et al.* 2020. Estimating the economic impacts of climate change on 16 major US fisheries. Climate Change Economics, 12: 2150002.

NMFS (NOAA Fisheries). 2019. Looking Back at the Blob. https://www.fisheries.noaa.gov/feature-story/looking-back-blob-record-warming-drives-unprecedented-ocean-change (last accessed 30 May 2023).

NMFS (NOAA Fisheries). 2022. DisMAP data records. https://www.fisheries.noaa.gov/dismap/DisMAP.html (last accessed 30 May 2023).

NMFS (NOAA Fisheries). 2023. Fishery disaster determinations. https://www.fisheries.noaa.gov/national/funding-and-financial-services/fishery-disaster-determinations (last accessed 25 July 2023).

NOAA. 2021. National Marine Ecosystem Status. https://ecowatch.noaa.gov (last accessed 30 May 2023).

NOAA. 2022. National Centers for Environmental Information (NCEI) U.S. Billion-dollar weather and climate disasters. https://www.ncei.noaa.gov/access/billions/ (last accessed 30 May 2023).

NOAA. 2023. Coral Reef Watch. https://coralreefwatch.noaa.gov/ (last accessed 25 July 2023).

O'Neil, J. M., Davis, T. W., Burford, M. A., and Gobler, C. J. 2012. The rise of harmful cyanobacteria blooms: the potential roles of eutrophication and climate change. Harmful Algae, 14: 313–334.

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., *et al.* 2016. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. Geoscientific Model Development, 9: 3461–3482.

OECD. 2016. The Ocean Economy in 2030. OECD Publishing, Berlin. https://doi.org/10.1787/9789264251724-en.

Otto, I. M., Reckien, D., Reyer, C. P. O., Marcus, R. E. G., Masson, V. L., Jones, L., Norton, A. L. *et al.* 2017. Social vulnerability to climate change: a review of concepts and evidence. Regional Environmental Change, 17: 1651–1662.

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

Payne, M. R., Barange, M., Cheung, W. L., MacKenzie, B. R., Batchelder, H. P., Cormon, X., Eddy, T. D. *et al.* 2016. Uncertainties in projecting climate-change impacts in marine ecosystems. ICES Journal of Marine Science, 73: 1272–1282.

Peterman, R. M. 2004. Possible solutions to some challenges facing fisheries scientists and managers. ICES Journal of Marine Science, 61: 1331–1343.

Rosenzweig, C., Arnell, N. W., Ebi, K. L., Lotze-Campen, H., Raes, F., Rapley, C., Smith, M. S. *et al.* 2017. Assessing inter-sectoral climate change risks: the role of ISIMIP. Environmental Research Letters, 12: 1–16.

Saaty, T. L., and Vargas, L. G. 1991. Prediction, Projection and Forecasting: Applications of the Analytic Hierarchy Process in Economics, Finance, Politics, Games and Sports. Springer Science and Business Media, New York, NY.

Sanchirico, J. N., Smith, M. D., and Lipton, D. W. 2008. An empirical approach to ecosystem-based fishery management. Ecological Economics, 64: 586–596.

Semenov, M. A., and Stratonovitch, P. 2010. Use of multi-model ensembles from global climate models for assessment of climate change impacts. Climate Research, 41: 1–14.

Shi, H., Jin, F.-F., Wills, R. C. J., Jacox, M. G., Amaya, D. J., Black, B. A., Rykaczewski, R. R. *et al.* 2022. Global decline in ocean memory over the 21st century. Science Advances, 8: eabm3468.

Slater, W. L., DePiper, G., Gove, J. M., Harvey, C. J., Hazen, E. L., Lucey, S. M., Karnauskas, M. *et al.* 2017. Challenges, opportunities and future directions to advance NOAA Fisheries Ecosystem Status Reports (ESRs): report of the National ESR Workshop. NOAA Technical Memorandum NMFS-F/SPO-174. National Oceanic and Atmospheric Administration, Washington. DC, 66. pp. https://spo.nmfs.noaa.gov/sites/default/files/TMSPO174_0.pdf (last accessed 30 May 2023).

Smale, D. A., Wernberg, T., Oliver, E. C. J., Thomsen, M., Harvey, B. P., Straub, S. C., Burrows, M. T. *et al.* 2019. Marine heatwaves threaten global biodiversity and the provision of ecosystem services. Nature Climate Change, 9: 306–312.

Snowden, J., Hernandez, D., Quintrell, J., Harper, A., Morrison, R., Morell, J., and Leonard, L. 2019. The U.S. Integrated Ocean Observing System: governance milestones and lessons from two decades of growth. Frontiers in Marine Science, 6: 242.

Sorte, C. J. B., Williams, S. L., and Zerebecki, R. A. 2010. Ocean warming increases threat of invasive species in a marine fouling community. Ecology, 91: 2198–2204.

Spalding, M. 2016. The new blue economy: the future of sustainability. Journal of Ocean and Coastal Economics, 2: 8.

Steffen, W., Richardson, K., Rockström, J., Schellnhuber, H., Dube, O. P., Dutreuil, S., Lenton, T. *et al.* 2020. The emergence and evolution of Earth System science. Nature Reviews Earth and Environment, 1: 54–63.

Stock, C. A., Alexander, M. A., Bond, N. A., Brander, K. M., Cheung, W. W. L., Curchitser, E. N., Delworth, T. L. *et al.* 2011. On the use of IPCC-class models to assess the impact of climate on living marine resources. Progress in Oceanography, 88: 1–27.

Sumaila, U. R., Cisneros-Montemayor, A. M., Dyck, A., Huang, L., Cheung, W., Jacquet, J., Kleisner, K. *et al.* 2012. Impact of the Deepwater Horizon well blowout on the economics of US Gulf fisheries. Canadian Journal of Fisheries and Aquatic Sciences, 69: 499–510.

Tittensor, D. P., Eddy, T. D., Lotze, H. K., Galbraith, E. D., Cheung, W., Barange, M., Blanchard, J. L. *et al.* 2018. A protocol for the intercomparison of marine fishery and ecosystem models: fish-MIP v1.0. Geoscientific Model Development, 11: 1421–1442.

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

Turschwell, M. P., Hayes, M. A., Lacharité, M., Abundo, M., Adams, J., Blanchard, J., Brain, E. *et al.* 2022. A review of support tools to assess multi-sector interactions in the emerging offshore Blue Economy. Environmental Science and Policy, 133: 203–214.

Uccellini, L. W., and Ten Hoeve, J. E. 2019. Evolving the National Weather Service to build a weather-ready nation: connecting observations, forecasts, and warnings to decision-makers through impact-based decision support services. Bulletin of the American Meteorological Society, 100: 1923–1942.

UN. 2018. General Assembly Resolution 72/73, Oceans and the law of the sea, A/RES/72/73. 46. pp. https://undocs.org/en/a/res/72/73 (last accessed 30 May 2023).

US Congress. 2021. 117th Congress (2021-2022): Infrastructure Investment and Jobs Act (Library of Congress). H.R. 3684. https://www.congress.gov/bill/117th-congress/house-bill/3684 (date last accessed 15 November 2021).

USGCRP. 2017. Climate Science Special Report: Fourth National Climate Assessment, I, pp. 470. Ed. by D.J. Wuebbles, D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, U.S. Global Change Research Program, Washington, DC.

van Aalst, M. K. 2006. The impacts of climate change on the risk of natural disasters. Disasters, 30: 5–18.

Wainger, L. A., Rose, K. A., Castellini, M. A., McCammon, M., and Newton, J. 2021. Decision making under deep uncertainty: what is it and how might NOAA use it?. pp. 19. NOAA Science Advisory Board, Ecosystem Sciences and Management Working Group. NOAA, Silver Spring, MD. https://sab.noaa.gov/wp-content/uploads/2021/08/FINAL_ESMWG_DMDU-Report_03-30_Final.pdf (last accessed 30 May 2023).

Weatherdon, L. V., Magnan, A. K., Rogers, A. D., Sumaila, U. R., and Cheung, W. W. L. 2016. Observed and projected impacts of climate change on marine fisheries, aquaculture, coastal tourism, and Human health: an update. Frontiers in Marine Science, 3: 48.

Wells, M. L., Trainer, V. L., Smayda, T. J., Karlson, B. S. O., Trick, C. G., Kudela, R. M., Ishikawa, A. *et al.* 2015. Harmful algal blooms and climate change: learning from the past and present to forecast the future. Harmful Algae, 49: 68–93.

Wilkin, J., Rosenfeld, L., Allen, A., Baltes, R., Baptista, A., He, R. Y., Hogan, P. *et al.* 2017. Advancing coastal ocean modelling, analysis, and prediction for the US Integrated Ocean Observing System. Journal of Operational Oceanography, 10: 115–126.

Wing, O. E. J., Lehman, W., Bates, P. D., Sampson, C. C., Quinn, N., Smith, A. M., Neal, J. C. *et al.* 2022. Inequitable patterns of US flood risk in the Anthropocene. Nature Climate Change, 12: 156–162.

Wu, J. G. 2013. Hierarchy theory: an overview. *In* Linking Ecology and Ethics for a Changing World: Values, Philosophy, and Action. Ed. by R. Rozzi, S.T.A. Pickett, C. Palmer, J.J. Armesto, and J.B. Callicott. Springer, New York, NY. pp. 281–301.

Yanda, P. Z., Mabhuye, E., Johnson, N., and Mwajombe, A. 2019. Nexus between coastal resources and community livelihoods in a changing climate. Journal of Coastal Conservation, 23: 173–183.

Handling editor: Valerio Bartolino

Received: 30 May 2023; **Revised:** 18 August 2023; **Accepted:** 31 August 2023