Forecasting review bibliography

## Ecological Forecasting

* Clarissa R. Anderson, Elisa Berdalet, Raphael M. Kudela, Caroline K. Cusack, Joe Silke, Eleanor O’Rourke, Darcy Dugan, Molly McCammon, Jan A. Newton, Stephanie K. Moore, Kelli Paige, Steve Ruberg, John R. Morrison, Barbara Kirkpatrick, Katherine Hubbard, Julio Morell. 2019. **Scaling Up From Regional Case Studies to a Global Harmful Algal Bloom Observing System**. Frontiers in Marine Science. 6, <https://doi.org/10.3389/fmars.2019.00250>

Harmful algal blooms (HABs) produce local impacts in nearly all freshwater and marine systems. They are a global problem that require integrated and coordinated scientific understanding leading to regional responses and solutions. Given that these natural phenomena will never be completely eliminated, improved scientific understanding of HAB dynamics coupled with monitoring and ocean observations facilitates new prediction and prevention strategies. Regional efforts are underway worldwide to create state-of-the-art HAB monitoring and forecasting tools, vulnerability assessments, and observing networks. In the United States, these include Alaska, Pacific Northwest, California, Gulf of Mexico, Gulf of Maine, Great Lakes, and the U.S. Caribbean islands. This paper examines several regional programs in the United States, European Union, and Asia and concludes that there is no one-size-fits-all approach. At the same time, successful programs require strong coordination with stakeholders and institutional sustainability to maintain and reinforce them with new automating technologies, wherever possible, to ensure integration of modelling efforts with multiple regional to national programs. Recommendations for scaling up to a global observing system for HABs can be summarized as follows: 1) advance and improve cost-effective and sustainable HAB forecast systems that address the HAB-risk warning requirements of key end-users at global and regional levels; 2) design programs that leverage and expand regional HAB observing systems to evaluate emerging technologies for Essential Ocean Variables (EOVs) and Essential Biodiversity Variables (EBVs) in order to support interregional technology comparisons and regional networks of observing capabilities; 3) fill the essential need for sustained, preferably automated, near real-time information from nearshore and offshore sites situated in HAB transport pathways to provide improved, advanced HAB warnings; 4) merge ecological knowledge and models with existing Earth System Modelling Frameworks to enhance end-to-end capabilities in forecasting and scenario-building; 5) provide seasonal to decadal forecasts to allow governments to plan, adapt to a changing marine environment, and ensure coastal industries are supported and sustained in the years ahead; and 6) support implementation of the recent calls for action by the United Nations Decade 2010 Sustainable Development Goals (SDGs) to develop indicators that are relevant to an effective and global HAB early warning system.

* Clarissa R. Anderson, Raphael M. Kudela, Mati Kahru, Yi Chao, Leslie K. Rosenfeld, Frederick L. Bahr, David M. Anderson, Tenaya A. Norris. 2016. **Initial skill assessment of the California Harmful Algae Risk Mapping (C-HARM) system**. Harmful Algae. 59, 1-18, <https://doi.org/10.1016/j.hal.2016.08.006>

Toxic algal events are an annual burden on aquaculture and coastal ecosystems of California. The threat of domoic acid (DA) toxicity to human and wildlife health is the dominant harmful algal bloom (HAB) concern for the region, leading to a strong focus on prediction and mitigation of these blooms and their toxic effects. This paper describes the initial development of the California Harmful Algae Risk Mapping (C-HARM) system that predicts the spatial likelihood of blooms and dangerous levels of DA using a unique blend of numerical models, ecological forecast models of the target group, Pseudo-nitzschia, and satellite ocean color imagery. Data interpolating empirical orthogonal functions (DINEOF) are applied to ocean color imagery to fill in missing data and then used in a multivariate mode with other modeled variables to forecast biogeochemical parameters. Daily predictions (nowcast and forecast maps) are run routinely at the Central and Northern California Ocean Observing System (CeNCOOS) and posted on its public website. Skill assessment of model output for the nowcast data is restricted to nearshore pixels that overlap with routine pier monitoring of HABs in California from 2014 to 2015. Model lead times are best correlated with DA measured with solid phase adsorption toxin tracking (SPATT) and marine mammal strandings from DA toxicosis, suggesting long-term benefits of the HAB predictions to decision-making. Over the next three years, the C-HARM application system will be incorporated into the NOAA operational HAB forecasting system and HAB Bulletin.

* John A. Barth, Susan E. Allen, Edward P. Dever, Richard K. Dewey, Wiley Evans, Richard A. Feely, Jennifer L. Fisher, Jonathan P. Fram, Burke Hales, Debby Ianson, Jennifer Jackson, Kim Juniper, Orest Kawka, Deborah Kelley, Jody M. Klymak, John Konovsky, P. Michael Kosro, Alexander Kurapov, Emilio Mayorga, Parker MacCready, Jan Newton, R. Ian Perry, Craig M. Risien, Marie Robert, Tetjana Ross, R. Kipp Shearman, Joe Schumacker, Samantha Siedlecki, Vera L. Trainer, Stephanie Waterman, Christopher E. Wingard. 2019. **Better regional ocean observing through cross-national cooperation: A case study from the Northeast Pacific**. Frontiers in Marine Science. 6, <https://doi.org/10.3389/fmars.2019.00093>

The ocean knows no political borders. Ocean processes, like summertime wind-driven upwelling, stretch thousands of kilometers along the Northeast Pacific (NEP) coast. This upwelling drives marine ecosystem productivity and is modulated by weather systems and seasonal to interdecadal ocean-atmosphere variability. Major ocean currents in the NEP transport water properties such as heat, fresh water, nutrients, dissolved oxygen, pCO 2 , and pH close to the shore. The eastward North Pacific Current bifurcates offshore in the NEP, delivering open-ocean signals south into the California Current and north into the Gulf of Alaska. There is a large and growing number of NEP ocean observing elements operated by government agencies, Native American Tribes, First Nations groups, not-for-profit organizations, and private entities. Observing elements include moored and mobile platforms, shipboard repeat cruises, as well as land-based and estuarine stations. A wide range of multidisciplinary ocean sensors are deployed to track, for example, upwelling, downwelling, ocean productivity, harmful algal blooms, ocean acidification and hypoxia, seismic activity and tsunami wave propagation. Data delivery to shore and observatory controls are done through satellite and cell phone communication, and via seafloor cables. Remote sensing from satellites and land-based coastal radar provide broader spatial coverage, while numerical circulation and biogeochemical modeling complement ocean observing efforts. Models span from the deep ocean into the inland Salish Sea and estuaries. NEP ocean observing systems are used to understand regional processes and, together with numerical models, provide ocean forecasts. By sharing data, experiences and lessons learned, the regional ocean observatory is better than the sum of its parts.

* Jacob W. Bentley, Mathieu G. Lundy, Daniel Howell, Steven E. Beggs, Alida Bundy, Francisco {de Castro}, Clive J. Fox, Johanna J. Heymans, Christopher P. Lynam, Debbi Pedreschi, Pia Schuchert, Natalia Serpetti, Johnny Woodlock, David G. Reid. 2021. **Refining Fisheries Advice With Stock-Specific Ecosystem Information**. Frontiers in Marine Science. 8, <https://doi.org/10.3389/fmars.2021.602072>

Although frequently suggested as a goal for ecosystem-based fisheries management, incorporating ecosystem information into fisheries stock assessments has proven challenging. The uncertainty of input data, coupled with the structural uncertainty of complex multi-species models, currently makes the use of absolute values from such models contentious for short-term single-species fisheries management advice. Here, we propose a different approach where the standard assessment methodologies can be enhanced using ecosystem model derived information. Using a case study of the Irish Sea, we illustrate how stock-specific ecosystem indicators can be used to set an ecosystem-based fishing mortality reference point (FECO) within the “Pretty Good Yield” ranges for fishing mortality which form the present precautionary approach adopted in Europe by the International Council for the Exploration of the Sea (ICES). We propose that this new target, FECO, can be used to scale fishing mortality down when the ecosystem conditions for the stock are poor and up when conditions are good. This approach provides a streamlined quantitative way of incorporating ecosystem information into catch advice and provides an opportunity to operationalize ecosystem models and empirical indicators, while retaining the integrity of current assessment models and the FMSY-based advice process.

* David Chagaris, Katie Drew, Amy Schueller, Matt Cieri, Joana Brito, Andre Buchheister. 2020. **Ecological Reference Points for Atlantic Menhaden Established Using an Ecosystem Model of Intermediate Complexity**. Frontiers in Marine Science. 7, <https://doi.org/10.3389/fmars.2020.606417>

Atlantic menhaden (Brevoortia tyrannus) are an important forage fish for many predators, and they also support the largest commercial fishery by weight on the U.S. East Coast. Menhaden management has been working toward ecological reference points (ERPs) that account for menhaden’s role in the ecosystem. The goal of this work was to develop menhaden ERPs using ecosystem models. An existing Ecopath with Ecosim model of the Northwest Atlantic Continental Shelf (NWACS) was reduced in complexity from 61 to 17 species/functional groups. The new NWACS model of intermediate complexity for ecosystems (NWACS-MICE) serves to link the dynamics of menhaden with key managed predators. Striped bass (Morone saxatilis) were determined to be most sensitive to menhaden harvest and therefore served as an indicator of ecosystem impacts. ERPs were based on the tradeoff relationship between the equilibrium biomass of striped bass and menhaden fishing mortality (F). The ERPs were defined as the menhaden F rates that maintain striped bass at their biomass target and threshold when striped bass are fished at their Ftarget, and all other modeled species were fished at status quo levels. These correspond to an ERP Ftarget of 0.19 and an ERP Fthreshold of 0.57, which are lower than the single species reference points by 30–40%, but higher than current (2017) menhaden F. The ERPs were then fed back into the age-structured stock assessment model projections to provide information on total allowable catch. The ERPs developed in this study were adopted by the Atlantic menhaden Management Board, marking a shift toward ecosystem-based fishery management for this economically and ecologically important species.

* Michael C. Dietze, Andrew Fox, Lindsay M. Beck-Johnson, Julio L. Betancourt, Mevin B. Hooten, Catherine S. Jarnevich, Timothy H. Keitt, Melissa A. Kenney, Christine M. Laney, Laurel G. Larsen, Henry W. Loescher, Claire K. Lunch, Bryan C. Pijanowski, James T. Randerson, Emily K. Read, Andrew T. Tredennick, Rodrigo Vargas, Kathleen C. Weathers, Ethan P. White. 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, <https://doi.org/10.1073/pnas.1710231115>

Two foundational questions about sustainability are “How are ecosystems and the services they provide going to change in the future?” and “How do human decisions affect these trajectories?” Answering these questions requires an ability to forecast ecological processes. Unfortunately, most ecological forecasts focus on centennial-scale climate responses, therefore neither meeting the needs of near-term (daily to decadal) environmental decision-making nor allowing comparison of specific, quantitative predictions to new observational data, one of the strongest tests of scientific theory. Near-term forecasts provide the opportunity to iteratively cycle between performing analyses and updating predictions in light of new evidence. This iterative process of gaining feedback, building experience, and correcting models and methods is critical for improving forecasts. Iterative, near-term forecasting will accelerate ecological research, make it more relevant to society, and inform sustainable decision-making under high uncertainty and adaptive management. Here, we identify the immediate scientific and societal needs, opportunities, and challenges for iterative near-term ecological forecasting. Over the past decade, data volume, variety, and accessibility have greatly increased, but challenges remain in interoperability, latency, and uncertainty quantification. Similarly, ecologists have made considerable advances in applying computational, informatic, and statistical methods, but opportunities exist for improving forecast-specific theory, methods, and cyberinfrastructure. Effective forecasting will also require changes in scientific training, culture, and institutions. The need to start forecasting is now; the time for making ecology more predictive is here, and learning by doing is the fastest route to drive the science forward.

* Katie Drew, Matthew Cieri, Amy M. Schueller, Andre Buchheister, David Chagaris, Geneviève Nesslage, Jason E. McNamee, James H. Uphoff. 2021. **Balancing Model Complexity, Data Requirements, and Management Objectives in Developing Ecological Reference Points for Atlantic Menhaden**. Frontiers in Marine Science. 8, <https://doi.org/10.3389/fmars.2021.608059>

Atlantic menhaden is an important forage fish and the target of the largest fishery along the US East Coast by volume. Since 1999, managers at the Atlantic States Marine Fisheries Commission, stakeholders, and scientists have been interested in developing ecological reference points (ERPs) that account for menhaden’s role as a forage species. To accomplish this, we developed a suite of modeling approaches that incorporated predation on menhaden and changes in productivity over time and allowed for evaluation of trade-offs between menhaden harvest and ecosystem management objectives. These approaches ranged in complexity, from models with minimal data requirements and few assumptions to approaches with extensive data needs and detailed assumptions. This included a surplus production model with a time-varying intrinsic growth rate, a Steele-Henderson surplus production model, a multispecies statistical catch-at-age model, an Ecopath with Ecosim (EwE) model with a limited predator and prey field, and a full EwE model. We evaluated how each model could address managers’ objectives and compared outputs across the approaches, highlighting their strengths, weaknesses, and management utility. All models produced estimates of age-1 + biomass and exploitation rate that were similar in trend and magnitude to the single-species statistical catch-at-age model, especially in recent years. While the less complex models were relativity easy to implement and update, they lacked key elements needed to manage multiple species simultaneously. More complex models required a wider array of data and were more difficult to update within the current management time-frames, but produced a more useful framework for managers. Ultimately, an EwE model of intermediate complexity coupled with the existing single-species assessment model was recommended for use in management.

* Jose A. Fernandes-Salvador, Keith Davidson, Marc Sourisseau, Marta Revilla, Wiebke Schmidt, Dave Clarke, Peter I. Miller, Paola Arce, Raúl Fernández, Luz Maman, Alexandra Silva, Callum Whyte, Maria Mateo, Patricia Neira, Marcos Mateus, Manuel Ruiz-Villarreal, Luis Ferrer, Joe Silke. 2021. **Current Status of Forecasting Toxic Harmful Algae for the North-East Atlantic Shellfish Aquaculture Industry**. Frontiers in Marine Science. 8, <https://doi.org/10.3389/fmars.2021.666583>

Across the European Atlantic Arc (Scotland, Ireland, England, France, Spain, and Portugal) the shellfish aquaculture industry is dominated by the production of mussels, followed by oysters and clams. A range of spatially and temporally variable harmful algal bloom species (HABs) impact the industry through their production of biotoxins that accumulate and concentrate in shellfish flesh, which negatively impact the health of consumers through consumption. Regulatory monitoring of harmful cells in the water column and toxin concentrations within shellfish flesh are currently the main means of warning of elevated toxin events in bivalves, with harvesting being suspended when toxicity is elevated above EU regulatory limits. However, while such an approach is generally successful in safeguarding human health, it does not provide the early warning that is needed to support business planning and harvesting by the aquaculture industry. To address this issue, a proliferation of web portals have been developed to make monitoring data widely accessible. These systems are now transitioning from “nowcasts” to operational Early Warning Systems (EWS) to better mitigate against HAB-generated harmful effects. To achieve this, EWS are incorporating a range of environmental data parameters and developing varied forecasting approaches. For example, EWS are increasingly utilizing satellite data and the results of oceanographic modeling to identify and predict the behavior of HABs. Modeling demonstrates that some HABs can be advected significant distances before impacting aquaculture sites. Traffic light indices are being developed to provide users with an easily interpreted assessment of HAB and biotoxin risk, and expert interpretation of these multiple data streams is being used to assess risk into the future. Proof-of-concept EWS are being developed to combine model information with in situ data, in some cases using machine learning-based approaches. This article: (1) reviews HAB and biotoxin issues relevant to shellfish aquaculture in the European Atlantic Arc (Scotland, Ireland, England, France, Spain, and Portugal; (2) evaluates the current status of HAB events and EWS in the region; and (3) evaluates the potential of further improving these EWS though multi-disciplinary approaches combining heterogeneous sources of information.

* Isabel Gutierrez-Montes, Maureen Arguedas, Felicia Ramirez-Aguero, Leida Mercado, Jorge Sellare. 2020. **Contributing to the construction of a framework for improved gender integration into climate-smart agriculture projects monitoring and evaluation: MAP-Norway experience**. Climatic Change. 158, 93-106, <https://doi.org/10.1007/s10584-018-2231-1>

The Mesoamerican Agroenvironmental Program (MAP-Norway) is a multi-dimensional rural development program implemented in Central America since 2009, working with smallholder families, producer organizations, governmental organizations, and regional governance platforms. To monitor, assess, and evaluate the effects of the program on its beneficiaries, MAP-Norway uses a series of indicators that allow project managers and donors to adapt and follow-up on the interventions. Because gender is a cross-cutting theme in the program, gender indicators are used at all levels: families, producer organizations, and governmental organizations and governance platforms. In this document, we use the experience of MAP-Norway to critically assess these indicators, considering their potential usability in the monitoring and evaluation of climate-smart agriculture (CSA) initiatives. Furthermore, we propose a series of other indicators that capture various dimensions of gender relations. These indicators can be used to assess the effect of CSA practices, services, and technologies on equity in decision-making, women’s empowerment (including economic empowerment), intra-household food security, and equity in ownership over productive resources, among others, thus providing evidence that can help better design and target CSA interventions.

* M. A. Haltuch, E. N. Brooks, J. Brodziak, J. A. Devine, K. F. Johnson, N. Klibansky, R. D.M. Nash, M. R. Payne, K. W. Shertzer, S. Subbey, B. K. Wells. 2019. **Unraveling the recruitment problem: A review of environmentally-informed forecasting and management strategy evaluation**. Fisheries Research. 217, 198-216, <https://doi.org/10.1016/j.fishres.2018.12.016>

Studies describing and hypothesizing the impact of climate change and environmental processes on vital rates of fish stocks are increasing in frequency, and concomitant with that is interest in incorporating these processes in fish stock assessments and forecasting models. Previous research suggests that including environmental drivers of fish recruitment in forecasting is of limited value, concluding that forecasting improvements are minimal while potential spurious relationships were sufficient to advise against inclusion. This review evaluates progress in implementing environmental factors in stock-recruitment projections and Management Strategy Evaluations (MSEs), from the year 2000 through 2017, by reviewing studies that incorporate environmental processes into recruitment forecasting, full-cycle MSEs, or simulations investigating harvest control rules. The only successes identified were for species with a short pre-recruit survival window (e.g., opportunistic life-history strategy), where the abbreviated life-span made it easier to identify one or a limited set of key drivers that directly impact dynamics. Autoregressive methods appeared to perform as well, if not better, for species with a longer pre-recruit survival window (e.g., seasonal, inter-annual) during which the environment could potentially exert influence. This review suggests that the inclusion of environmental drivers into assessments and forecasting is most likely to be successful for species with short pre-recruit survival windows (e.g., squid, sardine) and for those that have bottlenecks in their life history during which the environment can exert a well-defined pressure (e.g., anadromous fishes, those reliant on nursery areas). The effects of environment may be more complicated and variable for species with a longer pre-recruit survival window, reducing the ability to quantify environment-recruitment relationships. Species with more complex early life histories and longer pre-recruit survival windows would benefit from future research that focuses on relevant species-specific spatio-temporal scales to improve mechanistic understanding of abiotic-biotic interactions.

* Cecilie Hansen, Richard D.M. Nash, Kenneth F. Drinkwater, Solfrid Sætre Hjøllo. 2019. **Management Scenarios Under Climate Change – A Study of the Nordic and Barents Seas**. Frontiers in Marine Science. 6, <https://doi.org/10.3389/fmars.2019.00668>

The effects of increasing fishing pressure in combination with temperature increases in the Nordic and Barents Seas have been evaluated using an end-to-end model for the area forced by a downscaled RCP 4.5 climate scenario. The scenarios that have been applied have used four different fractions of fisheries mortality at maximum sustainable yield (Fmsy); 0.6, 0.8, 1.0 and 1.1 × Fmsy. As it is highly likely that more ecosystem components will be harvested in the future, the four scenarios have been repeated with fishing on a larger number of ecosystem components, including harvesting of lower trophic levels (mesozooplankton and mesopelagic fish). The zooplankton biomass had an increasing trend, regardless of the increase in fishing pressure on their predators. However, when introducing harvest on the lower trophic levels, this increase was no longer evident. When harvesting more components, the negative response in biomass of pelagic and demersal fish to increasing harvest became more prominent, indicating an increasing vulnerability in the ecosystem structure to stressors. Although harvest on lower trophic level led to an immense increase in the total catch, it also resulted in a decrease in the total catches of pelagic and demersal fish, despite more species being harvested in these guilds.

* Alistair J. Hobday, Claire M. Spillman, J. Paige Eveson, Jason R. Hartog. 2016. **Seasonal forecasting for decision support in marine fisheries and aquaculture**. Fisheries Oceanography. 25, 45-56, <https://doi.org/10.1111/fog.12083>

The production of marine protein from fishing and aquaculture is influenced by environmental conditions. Ocean temperature, for example, can change the growth rate of cultured animals, or the distribution of wild stocks. In turn these impacts may require changes in fishing or farming practices. In addition to short-term environmental fluctuations, long-term climate-related trends are also resulting in new conditions, necessitating adjustment in fishing, farming and management approaches. Longer-term climate forecasts, however, are seen as less relevant by many in the seafood sector owing to more immediate concerns. Seasonal forecasts provide insight into upcoming environmental conditions, and thus allow improved decision making. Forecasts based on dynamic ocean models are now possible and offer improved performance relative to statistical forecasts, particularly given baseline shifts in the environment as a result of climate change. Seasonal forecasting is being used in marine farming and fishing operations in Australia, including wild tuna and farmed salmon and prawns, to reduce uncertainty and manage business risks. Forecast variables include water temperature, rainfall and air temperature, and are considered useful up to approximately 4 months into the future, depending on the region and season of interest. Species-specific habitat forecasts can also be made by combining these environment forecasts with biological habitat preference data. Seasonal forecasts are useful when a range of options are available for implementation in response to the forecasts. The use of seasonal forecasts in supporting effective marine management may also represent a useful stepping stone to improved decision making and industry resilience at longer timescales.

* Alistair J. Hobday, Jason R. Hartog, John P. Manderson, Katherine E. Mills, Matthew J. Oliver, Andrew J. Pershing, Samantha Siedlecki, Howard Browman. 2019. **Ethical considerations and unanticipated consequences associated with ecological forecasting for marine resources**. ICES Journal of Marine Science. 76, 1244-1256, <https://doi.org/10.1093/icesjms/fsy210>

Forecasts of marine environmental and ecosystem conditions are now possible at a range of time scales, from nowcasts to forecasts over seasonal and longer time frames. Delivery of these products offers resource managers and users relevant insight into ecosystem patterns and future conditions to support decisions these stakeholders face associated with a range of objectives. The pace of progress in forecast development is so rapid that the scientific community may not be considering fully the impacts on stakeholders and their incentives. Delivery of information, particularly about future conditions and the uncertainties associated with it, involves a range of judgements, or {“}ethical{”} considerations, including treatment of forecast failure, inequity in stakeholder response options, and winners and losers in commercial markets. Here, we explore these often unanticipated considerations via a set of case studies spanning commercial fishing, recreational fishing, aquaculture, and conservation applications. We suggest that consideration of ethical issues by scientists and their research partners is needed to maintain scientific integrity and fairness to end users. Based on these case studies and our experience, we suggest a set of ten principles that might be considered by developers and users of ecological forecasts to avoid these ethical pitfalls. Overall, an interdisciplinary approach, and co-production with end users will provide insurance against many unanticipated consequences.

* Anne Babcock Hollowed, Kirstin Kari Holsman, Alan C. Haynie, Albert J. Hermann, Andre E. Punt, Kerim Aydin, James N. Ianelli, Stephen Kasperski, Wei Cheng, Amanda Faig, Kelly A. Kearney, Jonathan C.P. Reum, Paul Spencer, Ingrid Spies, William Stockhausen, Cody S. Szuwalski, George A. Whitehouse, Thomas K. Wilderbuer. 2020. **Integrated Modeling to Evaluate Climate Change Impacts on Coupled Social-Ecological Systems in Alaska**. Frontiers in Marine Science. 6, <https://doi.org/10.3389/fmars.2019.00775>

The Alaska Climate Integrated Modeling (ACLIM) project represents a comprehensive, multi-year, interdisciplinary effort to characterize and project climate-driven changes to the eastern Bering Sea (EBS) ecosystem, from physics to fishing communities. Results from the ACLIM project are being used to understand how different regional fisheries management approaches can help promote adaptation to climate-driven changes to sustain fish and shellfish populations and to inform managers and fishery dependent communities of the risks associated with different future climate scenarios. The project relies on iterative communications and outreaches with managers and fishery-dependent communities that have informed the selection of fishing scenarios. This iterative approach ensures that the research team focuses on policy relevant scenarios that explore realistic adaptation options for managers and communities. Within each iterative cycle, the interdisciplinary research team continues to improve: methods for downscaling climate models, climate-enhanced biological models, socio-economic modeling, and management strategy evaluation (MSE) within a common analytical framework. The evolving nature of the ACLIM framework ensures improved understanding of system responses and feedbacks are considered within the projections and that the fishing scenarios continue to reflect the management objectives of the regional fisheries management bodies. The multi-model approach used for projection of biological responses, facilitates the quantification of the relative contributions of climate forcing scenario, fishing scenario, parameter, and structural uncertainty with and between models. Ensemble means and variance within and between models inform risk assessments under different future scenarios. The first phase of projections of climate conditions to the end of the 21st century is complete, including projections of catch for core species under baseline (status quo) fishing conditions and two alternative fishing scenarios are discussed. The ACLIM modeling framework serves as a guide for multidisciplinary integrated climate impact and adaptation decision making in other large marine ecosystems.

* Daniel Howell, Amy M. Schueller, Jacob W. Bentley, Andre Buchheister, David Chagaris, Matthew Cieri, Katie Drew, Mathieu G. Lundy, Debbi Pedreschi, David G. Reid, Howard Townsend. 2021. **Combining Ecosystem and Single-Species Modeling to Provide Ecosystem-Based Fisheries Management Advice Within Current Management Systems**. Frontiers in Marine Science. 7, <https://doi.org/10.3389/fmars.2020.607831>

Although many countries have formally committed to Ecosystem-Based Fisheries Management (EBFM), actual progress toward these goals has been slow. This paper presents two independent case studies that have combined strategic advice from ecosystem modeling with the tactical advice of single-species assessment models to provide practical ecosystem-based management advice. With this approach, stock status, reference points, and initial target F are computed from a single-species model, then an ecosystem model rescales the target F according to ecosystem indicators without crossing pre-calculated single-species precautionary limits. Finally, the single-species model computes the quota advice from the rescaled target F, termed here Feco. Such a methodology incorporates both the detailed population reconstructions of the single-species model and the broader ecosystem perspective from ecosystem-based modeling, and fits into existing management schemes. The advocated method has arisen from independent work on EBFM in two international fisheries management systems: (1) Atlantic menhaden in the United States and (2) the multi species fisheries of the Irish Sea, in the Celtic Seas ecoregion. In the Atlantic menhaden example, the objective was to develop ecological reference points (ERPs) that account for the effect of menhaden harvest on predator populations and the tradeoffs associated with forage fish management. In the Irish Sea, the objective was to account for ecosystem variability when setting quotas for the individual target species. These two exercises were aimed at different management needs, but both arrived at a process of adjusting the target F used within the current single-species management. Although the approach has limitations, it represents a practical step toward EBFM, which can be adapted to a range of ecosystem objectives and applied within current management systems.

* Peter DF Isles, Francesco Pomati. 2021. **An operational framework for defining and forecasting phytoplankton blooms**. Frontiers in Ecology and the Environment. fee.2376, <https://doi.org/10.1002/fee.2376>

NA

* Michael G. Jacox, Michael A. Alexander, Samantha Siedlecki, Ke Chen, Young Oh Kwon, Stephanie Brodie, Ivonne Ortiz, Desiree Tommasi, Matthew J. Widlansky, Daniel Barrie, Antonietta Capotondi, Wei Cheng, Emanuele Di Lorenzo, Christopher Edwards, Jerome Fiechter, Paula Fratantoni, Elliott L. Hazen, Albert J. Hermann, Arun Kumar, Arthur J. Miller, Douglas Pirhalla, Mercedes Pozo Buil, Sulagna Ray, Scott C. Sheridan, Aneesh Subramanian, Philip Thompson, Lesley Thorne, Hariharasubramanian Annamalai, Kerim Aydin, Steven J. Bograd, Roger B. Griffis, Kelly Kearney, Hyemi Kim, Annarita Mariotti, Mark Merrifield, Ryan Rykaczewski. 2020. **Seasonal-to-interannual prediction of North American coastal marine ecosystems: Forecast methods, mechanisms of predictability, and priority developments**. Progress in Oceanography. 183, <https://doi.org/10.1016/j.pocean.2020.102307>

Marine ecosystem forecasting is an area of active research and rapid development. Promise has been shown for skillful prediction of physical, biogeochemical, and ecological variables on a range of timescales, suggesting potential for forecasts to aid in the management of living marine resources and coastal communities. However, the mechanisms underlying forecast skill in marine ecosystems are often poorly understood, and many forecasts, especially for biological variables, rely on empirical statistical relationships developed from historical observations. Here, we review statistical and dynamical marine ecosystem forecasting methods and highlight examples of their application along U.S. coastlines for seasonal-to-interannual (1–24 month) prediction of properties ranging from coastal sea level to marine top predator distributions. We then describe known mechanisms governing marine ecosystem predictability and how they have been used in forecasts to date. These mechanisms include physical atmospheric and oceanic processes, biogeochemical and ecological responses to physical forcing, and intrinsic characteristics of species themselves. In reviewing the state of the knowledge on forecasting techniques and mechanisms underlying marine ecosystem predictability, we aim to facilitate forecast development and uptake by (i) identifying methods and processes that can be exploited for development of skillful regional forecasts, (ii) informing priorities for forecast development and verification, and (iii) improving understanding of conditional forecast skill (i.e., a priori knowledge of whether a forecast is likely to be skillful). While we focus primarily on coastal marine ecosystems surrounding North America (and the U.S. in particular), we detail forecast methods, physical and biological mechanisms, and priority developments that are globally relevant.

* Sunny L. Jardine, Mary C. Fisher, Stephanie K. Moore, Jameal F. Samhouri. 2020. **Inequality in the Economic Impacts from Climate Shocks in Fisheries: The Case of Harmful Algal Blooms**. Ecological Economics. 176, <https://doi.org/10.1016/j.ecolecon.2020.106691>

Climate impacts disproportionately affect people that are most vulnerable and least able to adapt. The extent to which these equity impacts extend to fishing communities in the developed world is a question that has received surprisingly little attention. Here we explore the distributional impacts of a climate shock in one of the largest and most valuable fisheries on the West Coast of the United States. Specifically, we examine whether a series of two harmful algal blooms (HABs), occurring during the 2014–2016 Northeast Pacific Marine Heatwave, differentially affected small and large vessels in the commercial California Dungeness crab fishery. The HAB events were managed with localized fishery closures in response to elevated levels of the HAB toxin, domoic acid, in crab tissue. We find evidence that large vessels had a greater ability to mitigate losses from the HAB events. Thus, the proportion of total revenue going to small-vessel operators and the proportion of small-vessel participation in the fishery fell in response to the HAB events in several California fishing ports. Our results, therefore, offer empirical evidence that climate impacts on fishing communities are not uniform and offer insights into potential alternative adaptation strategies for different ocean user groups.

* Isaac C. Kaplan, Cecilie Hansen, Hem Nalini Morzaria-Luna, Raphael Girardin, Kristin N. Marshall. 2020. **Ecosystem-Based Harvest Control Rules for Norwegian and US Ecosystems**. Frontiers in Marine Science. 7, <https://doi.org/10.3389/fmars.2020.00652>

Management strategy evaluation (MSE) provides a simulation framework to test the performance of living marine resource management. MSE has now been adopted broadly for use in single-species fishery management, often using a relatively simple “operating model” that projects population dynamics of one species forward in time. However, many challenges in ecosystem-based management involve tradeoffs between multiple species and interactions of multiple stressors. Here we use complex operating models, multi-species ecosystem models of the California Current and Nordic and Barents Seas, to test threshold harvest control rules that explicitly address the linkage between predators and prey, and between the forage needs of predators and fisheries. Specifically, within Atlantis ecosystem models we focus on how forage (zooplankton) availability affects the performance of harvest rules for target fish, and how these harvest rules for fish can account for environmentally-driven fluctuations in zooplankton. Our investigation led to three main results. First, consistent with studies based on single-species operating models, we found that compared to constant F = FMSY policies, threshold rules led to higher target stock biomass for Pacific hake (Merluccius productus) in the California Current and mackerel (Scomber scombrus) in the Nordic and Barents Seas. Performance in terms of catch of these species varied depending partly on the biomass and recovery trajectory for the simulated stock. Secondly, the multi-species operating models and the harvest control rules that linked fishing mortality rates to prey biomass (zooplankton) led to increased catch variability; this stemmed directly from the harvest rule that frequently adjusted Pacific hake or mackerel fishing rates in response to zooplankton, which are quite variable in these two ecosystems. Thirdly, tests suggested that threshold rules that increased fishing when productivity (zooplankton) declined had the potential for strong ecosystem effects on other species. These effects were most apparent in the Nordic and Barents Seas simulations. The tests of harvest control rules here do not include uncertainty in monitoring of fish and zooplankton, nor do they include uncertainty in stock assessment and implementation; these would be required for full MSE. Additionally, we intentionally chose target fish with strong mechanistic links to particular zooplankton groups, with the simplifying assumption that zooplankton biomass followed a forced time series. Further developing and testing of ecosystem-level considerations can be achieved with end-to-end ecosystem models, such as the Atlantis models applied here, which have the added benefit of tracking the follow-on effects of the harvest control rule on the broader ecosystem.

* Isaac C. Kaplan, Gregory D. Williams, Nicholas A. Bond, Albert J. Hermann, Samantha A. Siedlecki. 2016. **Cloudy with a chance of sardines: Forecasting sardine distributions using regional climate models**. Fisheries Oceanography. 25, 15-27, <https://doi.org/10.1111/fog.12131>

Despite the significant advances in making monthly or seasonal forecasts of weather, ocean hypoxia, harmful algal blooms and marine pathogens, few such forecasting efforts have extended to the ecology of upper trophic level marine species. Here, we test our ability to use short-term (up to 9 months) predictions of ocean conditions to create a novel forecast of the spatial distribution of Pacific sardine, Sardinops sagax. Predictions of ocean conditions are derived using the output from the Climate Forecast System (CFS) model downscaled through the Regional Ocean Modeling System (ROMS). Using generalized additive models (GAMs), we estimated significant relationships between sardine presence in a test year (2009) and salinity and temperature. The model, fitted to 2009 data, had a moderate skill [area under the curve (AUC) = 0.67] in predicting 2009 sardine distributions, 5-8 months in advance. Preliminary tests indicate that the model also had the skill to predict sardine presence in August 2013 (AUC = 0.85) and August 2014 (AUC = 0.96), 4-5 months in advance. The approach could be used to provide fishery managers with an early warning of distributional shifts of this species, which migrates from the U.S.-Mexico border to as far north as British Columbia, Canada, in summers with warm water and other favorable ocean conditions. We expect seasonal and monthly forecasts of ocean conditions to be broadly useful for predicting spatial distributions of other pelagic and midwater species.

* Isaac C. Kaplan, Kristin N. Marshall. 2016. **A Guinea pig’s tale: Learning to review end-to-end marine ecosystem models for management applications**. ICES Journal of Marine Science. 73, 1715-1724, <https://doi.org/10.1093/icesjms/fsw047>

A shift towards ecosystem-based management in recent decades has led to new analytical tools such as end-to-end marine ecosystem models. End-to-end models are complex and typically simulate full ecosystems from oceanography to foodwebs and fisheries, operate on a spatial framework, and link to physical oceanographic models. Most end-to-end approaches allow multiple ways to implement human behaviours involving fishery catch, fleet movement, or other impacts such as nutrient loading or climate change effects. Though end-to-end ecosystem models were designed specifically for marine management, their novelty makes them unfamiliar to most decision makers. Before such models can be applied within the context of marine management decisions, additional levels of vetting will be required, and a dialogue with decision makers must be initiated. Here we summarize a review of an Atlantis end-to-end model, which involved a multi-day, expert review panel with local and international experts, convened to challenge models and data used in the management context. We propose nine credibility and quality control standards for end-to-end models intended to inform management, and suggest two best practice guidelines for any end-to-end modelling application. We offer our perspectives (as recent test subjects or {“}Guinea pigs{”}) on how a review could be motivated and structured and on the evaluation criteria that should be used, in the most specific terms possible.

* Stefan Koenigstein, Matthias Ruth, Stefan Gößling-Reisemann. 2016. **Stakeholder-informed ecosystem modeling of ocean warming and acidification impacts in the barents sea region**. Frontiers in Marine Science. 3, <https://doi.org/10.3389/fmars.2016.00093>

Climate change and ocean acidification are anticipated to alter marine ecosystems, with consequences for the provision of marine resources and ecosystem services to human societies. However, considerable uncertainties about future ecological changes and ensuing socio-economic impacts impede the identification of societal adaptation strategies. In a case study from the Barents Sea and Northern Norwegian Sea region, we integrated stakeholder perceptions of ecological changes and their significance for societies with the current state of scientific knowledge, to investigate the marine-human system under climate change and identify societal adaptation options. Stakeholders were engaged through personal interviews, two local workshops, and a web based survey, identifying the most relevant ecosystem services potentially impacted and developing an integrated system dynamics model which links climate change scenarios to the response of relevant species. Stakeholder perceptions of temperature-dependent multiannual fluctuations of fish stocks, interactions among fish, marine mammal, and seabird populations, and ecological processes such as primary production are represented in the model. The model was used for a discourse-based stakeholder evaluation of potential ecosystem changes under ocean warming and acidification scenarios, identifying shifts in ecosystem service provision and discussing associated societal adaptation options. The results pointed to differences in adaptive capacity among user groups. Small-scale fishers and tourism businesses are potentially more affected by changing spatial distribution and local declines in marine species than industrial fisheries. Changes in biodiversity, especially extinctions of polar species, and ecosystem functioning were a concern from an environmental conservation viewpoint. When considering potential additional impacts of ocean acidification, changes observed in the model projections were more uniformly valued as negative, and associated with an increased potential for conflicts among user groups. The stakeholder-informed ecosystem modeling approach has succeeded in driving a discussion and interchange among stakeholder groups and with scientists, integrating knowledge about climate change impacts in the social-ecological system and identifying important factors that shape societal responses. The approach can thus serve to improve governance of marine systems by incorporating knowledge about system dynamics and about societal uses and values.

* Fiona Nicholson, Rikke Krogshave Laursen, Rachel Cassidy, Luke Farrow, Linda Tendler, John Williams, Nicolas Surdyk, Gerard Velthof. 2020. **How can decision support tools help reduce nitrate and pesticide pollution from agriculture? A literature review and practical insights from the EU FAIRWAY project**. Water (Switzerland). 12, <https://doi.org/10.3390/w12030768>

The FAIRWAY project reviewed approaches for protecting drinking water from nitrate and pesticide pollution. A comprehensive assessment of decision support tools (DSTs) used by farmers, advisors, water managers and policy makers across the European Union as an aid to meeting CAP objectives and targets was undertaken, encompassing paper-based guidelines, farm-level and catchment level software, and complex research models. More than 150 DSTs were identified, with 36 ranked for further investigation based on how widely they were used and/or their potential relevance to the FAIRWAY case studies. Of those, most were farm management tools promoting smart nutrient/pesticide use, with only three explicitly considering the impact of mitigation methods on water quality. Following demonstration and evaluation, 12 DSTs were selected for practical testing at nine diverse case study sites, based on their pertinence to local challenges and scales of interest. Barriers to DST exchange between member states were identified and information was collected about user requirements and attitudes. Key obstacles to exchange include differences in legislation, advisory frameworks, country-specific data and calibration requirements, geo-climate and issues around language. Notably, DSTs from different countries using the same input data sometimes delivered very different results. Whilst many countries have developed DSTs to address similar problems, all case study participants were able to draw inspiration from elsewhere. The support and advice provided by skilled advisors was highly valued, empowering end users to most effectively use DST outputs.

* Erik Olsen, Isaac C. Kaplan, Cameron Ainsworth, Gavin Fay, Sarah Gaichas, Robert Gamble, Raphael Girardin, Cecilie H. Eide, Thomas F. Ihde, Hem Nalini Morzaria-Luna, Kelli F. Johnson, Marie Savina-Rolland, Howard Townsend, Mariska Weijerman, Elizabeth A. Fulton, Jason S. Link. 2018. **Ocean futures under ocean acidification, marine protection, and changing fishing pressures explored using a worldwide suite of ecosystem models**. Frontiers in Marine Science. 5, <https://doi.org/10.3389/fmars.2018.00064>

Ecosystem-based management (EBM) of the ocean considers all impacts on and uses of marine and coastal systems. In recent years, there has been a heightened interest in EBM tools that allow testing of alternative management options and help identify tradeoffs among human uses. End-to-end ecosystem modeling frameworks that consider a wide range of management options are a means to provide integrated solutions to the complex ocean management problems encountered in EBM. Here, we leverage the global advances in ecosystem modeling to explore common opportunities and challenges for ecosystem-based management, including changes in ocean acidification, spatial management, and fishing pressure across eight Atlantis (atlantis.cmar.csiro.au) end-to-end ecosystem models. These models represent marine ecosystems from the tropics to the arctic, varying in size, ecology, and management regimes, using a three-dimensional, spatially-explicit structure parametrized for each system. Results suggest stronger impacts from ocean acidification and marine protected areas than from altering fishing pressure, both in terms of guild-level (i.e., aggregations of similar species or groups) biomass and in terms of indicators of ecological and fishery structure. Effects of ocean acidification were typically negative (reducing biomass), while marine protected areas led to both {“}winners{”} and {“}losers{”} at the level of particular species (or functional groups). Changing fishing pressure (doubling or halving) had smaller effects on the species guilds or ecosystem indicators than either ocean acidification or marine protected areas. Compensatory effects within guilds led to weaker average effects at the guild level than the species or group level. The impacts and tradeoffs implied by these future scenarios are highly relevant as ocean governance shifts focus from single-sector objectives (e.g., sustainable levels of individual fished stocks) to taking into account competing industrial sectors’ objectives (e.g., simultaneous spatial management of energy, shipping, and fishing) while at the same time grappling with compounded impacts of global climate change (e.g., ocean acidification and warming).

* Christophe Orazio, Rebeca Cordero Montoya, Margot Régolini, José G. Borges, Jordi Garcia-Gonzalo, Susana Barreiro, Brigite Botequim, Susete Marques, Róbert Sedmák, Róbert Smreček, Yvonne Brodrechtová, Vilis Brukas, Gherardo Chirici, Marco Marchetti, Ralf Moshammer, Peter Biber, Edwin Corrigan, Ljusk Ola Eriksson, Matteo Favero, Emil Galev, Geerten M. Hengeveld, Marius Kavaliauskas, Gintautas Mozgeris, Rudolf Navrátil, Maarten Nieuwenhuis, Ivan Paligorov, Davide Pettenella, Andrius Stanislovaitis, Margarida Tomé, Renats Trubins, Ján Tuček, Matteo Vizzarri, Ida Wallin, Hans Pretzsch, Ola Sallnäs. 2017. **Decision support tools and strategies to simulate forest landscape evolutions integrating forest owner behaviour: A review from the case studies of the European project, INTEGRAL**. Sustainability (Switzerland). 9, <https://doi.org/10.3390/su9040599>

For forest sustainability and vulnerability assessment, the landscape scale is considered to be more and more relevant as the stand level approaches its known limitations. This review, which describes the main forest landscape simulation tools used in the 20 European case studies of the European project {“}Future-oriented integrated management of European forest landscapes{”} (INTEGRAL), gives an update on existing decision support tools to run landscape simulation from Mediterranean to boreal ecosystems. The main growth models and software available in Europe are described, and the strengths and weaknesses of different approaches are discussed. Trades-offs between input efforts and output are illustrated. Recommendations for the selection of a forest landscape simulator are given. The paper concludes by describing the need to have tools that are able to cope with climate change and the need to build more robust indicators for assessment of forest landscape sustainability and vulnerability.

* Mark R. Payne, Alistair J. Hobday, Brian R. MacKenzie, Desiree Tommasi, Danielle P. Dempsey, Sascha M.M. Fässler, Alan C. Haynie, Rubao Ji, Gang Liu, Patrick D. Lynch, Daniela Matei, Anna K. Miesner, Katherine E. Mills, Kjersti O. Strand, Ernesto Villarino. 2017. **Lessons from the first generation of marine ecological forecast products**. Frontiers in Marine Science. 4, <https://doi.org/10.3389/fmars.2017.00289>

Recent years have seen a rapid expansion in the ability of earth system models to describe and predict the physical state of the ocean. Skilful forecasts ranging from seasonal (3 months) to decadal (5-10 years) time scales are now a reality. With the advance of these forecasts of ocean physics, the first generation of marine ecological forecasts has started to emerge. Such forecasts are potentially of great value in the management of living marine resources and for all of those who are dependent on the ocean for both nutrition and their livelihood; however, this is still a field in its infancy. We review the state of the art in this emerging field and identify the lessons that can be learnt and carried forward from these pioneering efforts. The majority of this first wave of products are forecasts of spatial distributions, possibly reflecting the inherent suitability of this response variable to the task of forecasting. Promising developments are also seen in forecasting fish-stock recruitment where, despite well-recognized challenges in understanding and predicting this response, new process knowledge and model approaches that could form a basis for forecasting are becoming available. Forecasts of phenology and coral-bleaching events are also being applied to monitoring and industry decisions. Moving marine ecological forecasting forward will require striking a balance between what is feasible and what is useful. We propose here a set of criteria to quickly identify {“}low-hanging fruit{”} that can potentially be predicted; however, ensuring the usefulness of forecast products also requires close collaboration with actively engaged end-users. Realizing the full potential of marine ecological forecasting will require bridging the gaps between marine ecology and climatology on the one-hand, and between science and end-users on the other. Nevertheless, the successes seen thus far and the potential to develop further products suggest that the field of marine ecological forecasting can be expected to flourish in the coming years.

* Frank Pennekamp, Alison C. Iles, Joshua Garland, Georgina Brennan, Ulrich Brose, Ursula Gaedke, Ute Jacob, Pavel Kratina, Blake Matthews, Stephan Munch, Mark Novak, Gian Marco Palamara, Björn C. Rall, Benjamin Rosenbaum, Andrea Tabi, Colette Ward, Richard Williams, Hao Ye, Owen L. Petchey. 2019. **The intrinsic predictability of ecological time series and its potential to guide forecasting**. Ecological Monographs. 89, <https://doi.org/10.1002/ecm.1359>

Successfully predicting the future states of systems that are complex, stochastic, and potentially chaotic is a major challenge. Model forecasting error (FE) is the usual measure of success; however model predictions provide no insights into the potential for improvement. In short, the realized predictability of a specific model is uninformative about whether the system is inherently predictable or whether the chosen model is a poor match for the system and our observations thereof. Ideally, model proficiency would be judged with respect to the systems’ intrinsic predictability, the highest achievable predictability given the degree to which system dynamics are the result of deterministic vs. stochastic processes. Intrinsic predictability may be quantified with permutation entropy (PE), a model-free, information-theoretic measure of the complexity of a time series. By means of simulations, we show that a correlation exists between estimated PE and FE and show how stochasticity, process error, and chaotic dynamics affect the relationship. This relationship is verified for a data set of 461 empirical ecological time series. We show how deviations from the expected PE–FE relationship are related to covariates of data quality and the nonlinearity of ecological dynamics. These results demonstrate a theoretically grounded basis for a model-free evaluation of a system’s intrinsic predictability. Identifying the gap between the intrinsic and realized predictability of time series will enable researchers to understand whether forecasting proficiency is limited by the quality and quantity of their data or the ability of the chosen forecasting model to explain the data. Intrinsic predictability also provides a model-free baseline of forecasting proficiency against which modeling efforts can be evaluated.

* Jonathan C.P. Reum, Julia L. Blanchard, Kirstin K. Holsman, Kerim Aydin, Anne B. Hollowed, Albert J. Hermann, Wei Cheng, Amanda Faig, Alan C. Haynie, André E. Punt. 2020. **Ensemble Projections of Future Climate Change Impacts on the Eastern Bering Sea Food Web Using a Multispecies Size Spectrum Model**. Frontiers in Marine Science. 7, <https://doi.org/10.3389/fmars.2020.00124>

Characterization of uncertainty (variance) in ecosystem projections under climate change is still rare despite its importance for informing decision-making and prioritizing research. We developed an ensemble modeling framework to evaluate the relative importance of different uncertainty sources for food web projections of the eastern Bering Sea (EBS). Specifically, dynamically downscaled projections from Earth System Models (ESM) under different greenhouse gas emission scenarios (GHG) were used to force a multispecies size spectrum model (MSSM) of the EBS food web. In addition to ESM and GHG uncertainty, we incorporated uncertainty from different plausible fisheries management scenarios reflecting shifts in the total allowable catch of flatfish and gadids and different assumptions regarding temperature-dependencies on biological rates in the MSSM. Relative to historical averages (1994–2014), end-of-century (2080–2100 average) ensemble projections of community spawner stock biomass, catches, and mean body size (±standard deviation) decreased by 36% (±21%), 61% (±27%), and 38% (±25%), respectively. Long-term trends were, on average, also negative for the majority of species, but the level of trend consistency between ensemble projections was low for most species. Projection uncertainty for model outputs from ∼2020 to 2040 was driven by inter-annual climate variability for 85% of species and the community as a whole. Thereafter, structural uncertainty (different ESMs, temperature-dependency assumptions) dominated projection uncertainty. Fishery management and GHG emissions scenarios contributed little (<10%) to projection uncertainty, with the exception of catches for a subset of flatfishes which were dominated by fishery management scenarios. Long-term outcomes were improved in most cases under a moderate “mitigation” relative to a high “business-as-usual” GHG emissions scenario and we show how inclusion of temperature-dependencies on processes related to body growth and intrinsic (non-predation) natural mortality can strongly influence projections in potentially non-additive ways. Narrowing the spread of long-term projections in future ensemble simulations will depend primarily on whether the set of ESMs and food web models considered behave more or less similarly to one another relative to the present models sets. Further model skill assessment and data integration are needed to aid in the reduction and quantification of uncertainties if we are to advance predictive ecology.

* Jörn O. Schmidt, Steven J. Bograd, Haritz Arrizabalaga, José L. Azevedo, Steven J. Barbeaux, John A. Barth, Tim Boyer, Stephanie Brodie, Juan José Cárdenas, Scott Cross, Jean Noël Druon, Agneta Fransson, Jason Hartog, Elliott L. Hazen, Alistair Hobday, Michael Jacox, Johannes Karstensen, Sven Kupschus, Jon Lopez, Lauro A.S.P. Madureira, José E. Martinelli Filho, Patricia Miloslavich, Catarina P. Santos, Kylie Scales, Sabrina Speich, Matthew B. Sullivan, Amber Szoboszlai, Desiree Tommasi, Douglas Wallace, Stephani Zador, Paulo Antônio Zawislak. 2019. **Future Ocean Observations to Connect Climate, Fisheries and Marine Ecosystems**. Frontiers in Marine Science. 6, <https://doi.org/10.3389/fmars.2019.00550>

Advances in ocean observing technologies and modeling provide the capacity to revolutionize the management of living marine resources. While traditional fisheries management approaches like single-species stock assessments are still common, a global effort is underway to adopt ecosystem-based fisheries management (EBFM) approaches. These approaches consider changes in the physical environment and interactions between ecosystem elements, including human uses, holistically. For example, integrated ecosystem assessments aim to synthesize a suite of observations (physical, biological, socioeconomic) and modeling platforms [ocean circulation models, ecological models, short-term forecasts, management strategy evaluations (MSEs)] to assess the current status and recent and future trends of ecosystem components. This information provides guidance for better management strategies. A common thread in EBFM approaches is the need for high-quality observations of ocean conditions, at scales that resolve critical physical-biological processes and are timely for management needs. Here we explore options for a future observing system that meets the needs of EBFM by (i) identifying observing needs for different user groups, (ii) reviewing relevant datasets and existing technologies, (iii) showcasing regional case studies, and (iv) recommending observational approaches required to implement EBFM. We recommend linking ocean observing within the context of Global Ocean Observing System (GOOS) and other regional ocean observing efforts with fisheries observations, new forecasting methods, and capacity development, in a comprehensive ocean observing framework.

* Beth A. Stauffer, Holly A. Bowers, Earle Buckley, Timothy W. Davis, Thomas H. Johengen, Raphael Kudela, Margaret A. McManus, Heidi Purcell, G. Jason Smith, Andrea Vander Woude, Mario N. Tamburri. 2019. **Considerations in harmful algal bloom research and monitoring: Perspectives from a consensus-building workshop and technology testing**. Frontiers in Marine Science. 6, <https://doi.org/10.3389/fmars.2019.00399>

Recurrent blooms of harmful algae and cyanobacteria (HABs) plague many coastal and inland waters throughout the United States and have significant socioeconomic impacts to the adjacent communities. Notable HAB events in recent years continue to underscore the many remaining gaps in knowledge and increased needs for technological advances leading to early detection. This review summarizes the main research and management priorities that can be addressed through ocean observation-based approaches and technological solutions for harmful algal blooms, provides an update to the state of the technology to detect HAB events based on recent activities of the Alliance for Coastal Technologies (ACT), offers considerations for ensuring data quality, and highlights both ongoing challenges and opportunities for solutions in integrating HAB-focused technologies in research and management. Specifically, technological advances are discussed for remote sensing (both multispectral satellite and hyperspectral); deployable in situ detection of HAB species on fixed or mobile platforms (based on bulk or taxa-specific biomass, images, or molecular approaches); and field-based and/or rapid quantitative detection of HAB toxins (via molecular and analytical chemistry methods). Suggestions for addressing challenges to continued development and adoption of new technologies are summarized, based on a consensus-building workshop hosted by ACT, including dealing with the uncertainties in investment for HAB research, monitoring, and management. Challenges associated with choosing appropriate technologies for a given ecosystem and/or management concern are also addressed, and examples of programs that are leveraging and combining complementary approaches are highlighted.

* Desiree Tommasi, Yvonne deReynier, Howard Townsend, Chris J. Harvey, William H. Satterthwaite, Kristin N. Marshall, Isaac C. Kaplan, Stephanie Brodie, John C. Field, Elliott L. Hazen, Stefan Koenigstein, Joshua Lindsay, Kathleen Moore, Barbara Muhling, Lisa Pfeiffer, James A. Smith, Jonathan Sweeney, Brian Wells, Michael G. Jacox. 2021. **A Case Study in Connecting Fisheries Management Challenges With Models and Analysis to Support Ecosystem-Based Management in the California Current Ecosystem**. Frontiers in Marine Science. 8, <https://doi.org/10.3389/fmars.2021.624161>

One of the significant challenges to using information and ideas generated through ecosystem models and analyses for ecosystem-based fisheries management is the disconnect between modeling and management needs. Here we present a case study from the U.S. West Coast, the stakeholder review of NOAA’s annual ecosystem status report for the California Current Ecosystem established by the Pacific Fisheries Management Council’s Fisheries Ecosystem Plan, showcasing a process to identify management priorities that require information from ecosystem models and analyses. We then assess potential ecosystem models and analyses that could help address the identified policy concerns. We screened stakeholder comments and found 17 comments highlighting the need for ecosystem-level synthesis. Policy needs for ecosystem science included: (1) assessment of how the environment affects productivity of target species to improve forecasts of biomass and reference points required for setting harvest limits, (2) assessment of shifts in the spatial distribution of target stocks and protected species to anticipate changes in availability and the potential for interactions between target and protected species, (3) identification of trophic interactions to better assess tradeoffs in the management of forage species between the diet needs of dependent predators, the resilience of fishing communities, and maintenance of the forage species themselves, and (4) synthesis of how the environment affects efficiency and profitability in fishing communities, either directly via extreme events (e.g., storms) or indirectly via climate-driven changes in target species availability. We conclude by exemplifying an existing management process established on the U.S. West Coast that could be used to enable the structured, iterative, and interactive communication between managers, stakeholders, and modelers that is key to refining existing ecosystem models and analyses for management use.

* Desiree Tommasi, Charles A. Stock, Alistair J. Hobday, Rick Methot, Isaac C. Kaplan, J. Paige Eveson, Kirstin Holsman, Timothy J. Miller, Sarah Gaichas, Marion Gehlen, Andrew Pershing, Gabriel A. Vecchi, Rym Msadek, Tom Delworth, C. Mark Eakin, Melissa A. Haltuch, Roland Séférian, Claire M. Spillman, Jason R. Hartog, Samantha Siedlecki, Jameal F. Samhouri, Barbara Muhling, Rebecca G. Asch, Malin L. Pinsky, Vincent S. Saba, Sarah B. Kapnick, Carlos F. Gaitan, Ryan R. Rykaczewski, Michael A. Alexander, Yan Xue, Kathleen V. Pegion, Patrick Lynch, Mark R. Payne, Trond Kristiansen, Patrick Lehodey, Francisco E. Werner. 2017. **Managing living marine resources in a dynamic environment: The role of seasonal to decadal climate forecasts**. Progress in Oceanography. 152, 15-49, <https://doi.org/10.1016/j.pocean.2016.12.011>

Recent developments in global dynamical climate prediction systems have allowed for skillful predictions of climate variables relevant to living marine resources (LMRs) at a scale useful to understanding and managing LMRs. Such predictions present opportunities for improved LMR management and industry operations, as well as new research avenues in fisheries science. LMRs respond to climate variability via changes in physiology and behavior. For species and systems where climate-fisheries links are well established, forecasted LMR responses can lead to anticipatory and more effective decisions, benefitting both managers and stakeholders. Here, we provide an overview of climate prediction systems and advances in seasonal to decadal prediction of marine-resource relevant environmental variables. We then describe a range of climate-sensitive LMR decisions that can be taken at lead-times of months to decades, before highlighting a range of pioneering case studies using climate predictions to inform LMR decisions. The success of these case studies suggests that many additional applications are possible. Progress, however, is limited by observational and modeling challenges. Priority developments include strengthening of the mechanistic linkages between climate and marine resource responses, development of LMR models able to explicitly represent such responses, integration of climate driven LMR dynamics in the multi-driver context within which marine resources exist, and improved prediction of ecosystem-relevant variables at the fine regional scales at which most marine resource decisions are made. While there are fundamental limits to predictability, continued advances in these areas have considerable potential to make LMR managers and industry decision more resilient to climate variability and help sustain valuable resources. Concerted dialog between scientists, LMR managers and industry is essential to realizing this potential.

* Désirée Tommasi, Charles A. Stock, Kathleen Pegion, Gabriel A. Vecchi, Richard D. Methot, Michael A. Alexander, David M. Checkley. 2017. **Improved management of small pelagic fisheries through seasonal climate prediction:**. Ecological Applications. 27, 378-388, <https://doi.org/10.1002/eap.1458>

Populations of small pelagic fish are strongly influenced by climate. The inability of managers to anticipate environment-driven fluctuations in stock productivity or distribution can lead to overfishing and stock collapses, inflexible management regulations inducing shifts in the functional response to human predators, lost opportunities to harvest populations, bankruptcies in the fishing industry, and loss of resilience in the human food supply. Recent advances in dynamical global climate prediction systems allow for sea surface temperature (SST) anomaly predictions at a seasonal scale over many shelf ecosystems. Here we assess the utility of SST predictions at this {“}fishery relevant{”} scale to inform management, using Pacific sardine as a case study. The value of SST anomaly predictions to management was quantified under four harvest guidelines (HGs) differing in their level of integration of SST data and predictions. The HG that incorporated stock biomass forecasts informed by skillful SST predictions led to increases in stock biomass and yield, and reductions in the probability of yield and biomass falling below socioeconomic or ecologically acceptable levels. However, to mitigate the risk of collapse in the event of an erroneous forecast, it was important to combine such forecast-informed harvest controls with additional harvest restrictions at low biomass.

* Howard Townsend, Chris J. Harvey, Yvonne deReynier, Dawn Davis, Stephani G. Zador, Sarah Gaichas, Mariska Weijerman, Elliott L. Hazen, Isaac C. Kaplan. 2019. **Progress on Implementing Ecosystem-Based Fisheries Management in the United States Through the Use of Ecosystem Models and Analysis**. Frontiers in Marine Science. 6, <https://doi.org/10.3389/fmars.2019.00641>

Worldwide fisheries management has been undergoing a paradigm shift from a single-species approach to ecosystem approaches. In the United States, NOAA has adopted a policy statement and Road Map to guide the development and implementation of ecosystem-based fisheries management (EBFM). NOAA’s EBFM policy supports addressing the ecosystem interconnections to help maintain resilient and productive ecosystems, even as they respond to climate, habitat, ecological, and social and economic changes. Managing natural marine resources while taking into account their interactions with their environment and our human interactions with our resources and environment requires the support of ecosystem science, modeling, and analysis. Implementing EBFM will require using existing mandates and approaches that fit regional management structures and cultures. The primary mandate for managing marine fisheries in the United States is the Magnuson-Stevens Fishery Conservation and Management Act. Many tenets of the Act align well with the EBFM policy, however, incorporating ecosystem analysis and models into fisheries management processes has faced procedural challenges in many jurisdictions. In this paper, we review example cases where scientists have had success in using ecosystem analysis and modeling to inform management priorities, and identify practices that help bring new ecosystem science information into existing policy processes. A key to these successes is regular communication and collaborative discourse among modelers, stakeholders, and resource managers to tailor models and ensure they addressed the management needs as directly as possible.

* Elisabeth Van Beveren, Hugues P. Benoît, Daniel E. Duplisea. 2021. **Forecasting fish recruitment in age-structured population models**. Fish and Fisheries. <https://doi.org/10.1111/faf.12562>

Recruitment in age-structured stock assessment models can be forecasted using a variety of algorithms to provide advice on the anticipated consequences of different possible management actions. Selecting one method over another usually involves some subjectivity, yet can be consequential to the provision of advice. Extensive case-specific testing is not always feasible. We evaluated the forecast skill in 3-, 5- and 10-year forecasts of 16 recruitment forecasting methods under various circumstances to provide a broad evaluation and general guidelines on the reliability of forecasts. We used 31 operating models based on existing stock assessment models applied to a diversity of stocks with empirical data, which we show to be generally representative of assessed stocks worldwide. Although no single best-performing method could be identified, we found that time-series methods were most likely to perform poorly. Both forecast skill across all methods and forecast sensitivity to the selected method were linked to the properties of the stock or assessment: age at maturity and recruitment autocorrelation in 3-year forecasts and previous long-term recruitment variability in 10-year forecasts. In some situations, all forecasting methods resulted in systematic over- or underestimation of spawning stock biomass. The simulation approach employed here to assess forecast performance, rooted directly in the predictions of existing stock assessment models, can be a complementary tool to existing simulation approaches which generate alternative sets of population dynamics or observations and we discussed the advantages and limitations.

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

The influence of climate on marine populations is important for predicting stock abundance of marine fishes, and has led to increasing interest in environment-based forecasts (EBFs) for harvest management. While some climate indices have proven useful for explaining fluctuations in Pacific salmon stock abundance, there have also been sudden failures of EBF models. I analyzed temporal patterns in prediction skill for a variety of climate and ecosystem indicators as predictors of marine survival for a coastal coho salmon stock by computing prediction skill for 29 climate and ecosystem indices across multiple time scales to explore patterns of skill across time. Results demonstrate that predictive skill of EBF models is often ephemeral, arising and falling suddenly across time. This behavior can be explained both on a statistical basis and as a consequence of complex interactions between climate, ecosystems, and populations involving both climate regime shifts and ecosystem phase transitions. Forecast failures are problematic for traditional forecast-dependent harvest management approaches. Solutions for this problem may include improved forecast models and improved climate and ecosystem indicators, but developing management systems that are robust to forecast uncertainty would provide a more reliable response to expected rapid ecosystem changes in response to climate.

* Ethan P. White, Glenda M. Yenni, Shawn D. Taylor, Erica M. Christensen, Ellen K. Bledsoe, Juniper L. Simonis, S. K.Morgan Ernest. 2019. **Developing an automated iterative near-term forecasting system for an ecological study**. Methods in Ecology and Evolution. 10, 332-344, <https://doi.org/10.1111/2041-210X.13104>

Most forecasts for the future state of ecological systems are conducted once and never updated or assessed. As a result, many available ecological forecasts are not based on the most up-to-date data, and the scientific progress of ecological forecasting models is slowed by a lack of feedback on how well the forecasts perform. Iterative near-term ecological forecasting involves repeated daily to annual scale forecasts of an ecological system as new data becomes available and regular assessment of the resulting forecasts. We demonstrate how automated iterative near-term forecasting systems for ecology can be constructed by building one to conduct monthly forecasts of rodent abundances at the Portal Project, a long-term study with over 40 years of monthly data. This system automates most aspects of the six stages of converting raw data into new forecasts: data collection, data sharing, data manipulation, modelling and forecasting, archiving, and presentation of the forecasts. The forecasting system uses R code for working with data, fitting models, making forecasts, and archiving and presenting these forecasts. The resulting pipeline is automated using continuous integration (a software development tool) to run the entire pipeline once a week. The cyberinfrastructure is designed for long-term maintainability and to allow the easy addition of new models. Constructing this forecasting system required a team with expertise ranging from field site experience to software development. Automated near-term iterative forecasting systems will allow the science of ecological forecasting to advance more rapidly and provide the most up-to-date forecasts possible for conservation and management. These forecasting systems will also accelerate basic science by allowing new models of natural systems to be quickly implemented and compared to existing models. Using existing technology, and teams with diverse skill sets, it is possible for ecologists to build automated forecasting systems and use them to advance our understanding of natural systems.

* George A. Whitehouse, Kerim Y. Aydin, Anne B. Hollowed, Kirstin K. Holsman, Wei Cheng, Amanda Faig, Alan C. Haynie, Albert J. Hermann, Kelly A. Kearney, André E. Punt, Timothy E. Essington. 2021. **Bottom–Up Impacts of Forecasted Climate Change on the Eastern Bering Sea Food Web**. Frontiers in Marine Science. 8, <https://doi.org/10.3389/fmars.2021.624301>

Recent observations of record low winter sea-ice coverage and warming water temperatures in the eastern Bering Sea have signaled the potential impacts of climate change on this ecosystem, which have implications for commercial fisheries production. We investigate the impacts of forecasted climate change on the eastern Bering Sea food web through the end of the century under medium- and high-emissions climate scenarios in combination with a selection of fisheries management strategies by conducting simulations using a dynamic food web model. The outputs from three global earth system models run under two greenhouse gas emission scenarios were dynamically downscaled using a regional ocean and biogeochemical model to project ecosystem dynamics at the base of the food web. Four fishing scenarios were explored: status quo, no fishing, and two scenarios that alternatively assume increased fishing emphasis on either gadids or flatfishes. Annual fishery quotas were dynamically simulated by combining harvest control rules based on model-simulated stock biomass, while incorporating social and economic tradeoffs induced by the Bering Sea’s combined groundfish harvest cap. There was little predicted difference between the status quo and no fishing scenario for most managed groundfish species biomasses at the end of the century, regardless of emission scenario. Under the status quo fishing scenario, biomass projections for most species and functional groups across trophic levels showed a slow but steady decline toward the end of the century, and most groups were near or below recent historical (1991–2017) biomass levels by 2080. The bottom–up effects of declines in biomass at lower trophic levels as forecasted by the climate-enhanced lower trophic level modeling, drove the biomass trends at higher trophic levels. By 2080, the biomass projections for species and trophic guilds showed very little difference between emission scenarios. Our method for climate-enhanced food web projections can support fisheries managers by informing strategic guidance on the long-term impacts of ecosystem productivity shifts driven by climate change on commercial species and the food web, and how those impacts may interact with different fisheries management scenarios.

## Meteorology Forecasting

## Health Forecasting

## Financial Forecasting

## Energy Forecasting

## Political/Elections Forecasting and Sports Forecasting

## Commodity Production Forecasting