Including ecosystem information in U.S. fishery stock assessments: successes, challenges, and potential explanations

Stock assessments of federally managed fish species in U.S. waters include ecosystem information

High rates of inclusion of ecosystem information in stock assessments for federally managed fish species

We’re doing it already: high rates of inclusion for ecosystem information in stock assessments

US stock assessments include ecosystem information with broader definition of EBFM

EBFM advances depend on definition of EBFM

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**Abstract**

The appetite for ecosystem-based fisheries management approaches has grown, but the perception persists that implementation is slow. Here, we synthesize progress towards implementing EBFM in the United States through one potential avenue: expanding fish stock assessments to include ecosystem considerations and interactions between species, fleets, and sectors. We synthesized over 200 stock assessments and assessed how the stock assessment reports included information about system influences on the population. Our goals were to: 1) quantify how assessments incorporated broader system-level considerations, and 2) explore factors that might contribute to the use of system-level information. Interactions among fishing fleets (technical interactions) were more commonly included than biophysical interactions (species, habitat, climate) interactions within the physical environment (habitat climate) were included twice as often as interactions among species (predation, X out of Y). Many assessment reports included ecological interactions as background or qualitative considerations, however without incorporating them in the assessment model. Our analyses suggested that ecosystem characteristics are more likely to be included when the species was overfished (stock status), diet information is available, and life history characteristics of the stock suggest it is likely to be influenced by the physical environment, habitat, or predation mortality (short-lived species, sessile benthic species, or low trophic-level species). Our results demonstrate that significant progress has been made to use best available science and data to expand single-species assessment, particularly when a broad definition of EBFM is applied. Data availability continues to limit the inclusion of predation mortality in stock assessments, and more guidance is needed on best practices for the prioritization of when and how biophysical information should be considered.

**Introduction**

Over the past several decades, support for ecosystem-based fisheries management has grown along with recognition of the multidimensional context surrounding fisheries. Management bodies around the world have developed frameworks and policies that broaden considerations in fisheries management decisions to include the human and biophysical systems in which fisheries operate (NOAA 2016; FAO 2003; Marine Strategy Framework Directive 2008). Despite these policy shifts, many have argued that the practice of EBFM has lagged (Essington et al. 2016; Arkema, Abramson, and Dewsbury 2006; Berkes 2012; Cowan et al. 2012; Pitcher et al. 2009). Some authors suggest lags are caused by a need to develop new data sources, analytical tools, and models (Ray Hilborn 2011; Cowan et al. 2012) and a need for institutional and governance changes to support EBFM (Leslie et al. 2015; Ray Hilborn 2011; Olsson, Folke, and Hughes 2008).

However, Patrick and Link (2015a) argue that these challenges to EBFM have largely been resolved in developed countries, and now persist only as “myths”. At least in the U.S. fisheries management system, decision-makers and stakeholders in several regions are open to these ideas (Biedron and Knuth 2016). One key challenge is communication about and definition of EBFM. Some authors have said that EBFM is just “good practice” in many cases. In these cases, perhaps more EBFM is occurring than has received attention because they may be mis-categorized as conventional management.

One area of active research that hased conventional management approaches is the data and models used for stock assessment. In most developed countries, many fisheries are managed by setting effort or output controls that are informed by stock assessments. Stock assessment models estimate stock status (biomass) relative to reference points using data that may include catch and survey time series, information on life history parameters, and expert knowledge. Output from these models inform decisions about annual catch limits, and as such they are subjected to a great deal of scrutiny from scientists, managers, and stakeholders. Research to expand approaches for modelling fish population and estimating their status includes ecosystem considerations such as environmental relationships or predation mortality (Maunder and Watters 2003; Methot and Wetzel 2013; Kuparinen et al. 2012). However, we don’t know exactly how much of this published work has made it into assessment models used for management.

A recent global review of stock assessment models found that very few (2 percent) incorporated data or parameters representing external drivers of productivity (Skern-Mauritzen et al. 2016). However, productivity is only one avenue through which stocks are connected to their environment, and parameters and data in the final assessment model is only one line of evidence in support of considering ecosystem context. Any review of how broader system information is used needs to identify all possible ways such information might be included in management advice in general, and stock assessments in particular. On one end of the continuum is explicit inclusion of external parameters driving key population vital rates into assessment models, such as a predation mortality parameter or environmental driver of recruitment. On the other hand, is broader qualitative considerations that inform model development in unknown ways. Qualitative data could influence management decisions, or quantitative information may be used indirectly in the stock assessment process. For example, Zador et al. (2017) outlined how ecosystem assessments have qualitatively informed decisions by the North Pacific Council.

We sought to document how frequently ecosystem information has been incorporated and understand the conditions under which uptake of ecosystem information into stock assessment models has occurred. Not all stock assessment models can or should incorporate environmental drivers of recruitment, for example, especially given their often poor performance as predictors when re-evaluated later (Myers 1998). But, patterns of uptake and use of ecosystem considerations may indicate persistent barriers to implementing EBFM. To that end, we developed three hypotheses about which stock assessments were likely to incorporate ecosystem considerations.

First, we hypothesized that assessments for stocks that were in an overfished status would be more likely to include additional ecosystem interactions. We suppose that overfished status could lead to a sense of urgency, which has been suggested to increase the receptiveness to EBFM (Olsson, Folke, and Hughes 2008). Or, overfished stocks may simply receive higher priority for development of a new assessment. New assessments may create opportunities to update older models, and an overfished status may lead to a desire to understand what caused the stock decline (or lack of recovery) and exploration of causative drivers within the stock assessment model. Furthermore, when stocks collapse, it is often due to combined effects of fishing and environmental variability (Pinsky and Byler 2015).

Second, we hypothesized that data availability may be a barrier to including ecosystem considerations in assessments. The lack of data is a commonly described barrier to implementing EBFM (Cowan et al. 2012; Ray Hilborn 2011; Mace 2001). A full assessment of data availability for all stocks considered in this analysis would be outside the scope of this paper. Instead, we investigated one specific kind of data that can inform species interactions: diet data. We focus on diet data because it provides information on one of the most common justifications of EBFM, namely that predator-prey interactions change population productivity and reference points (J. Link 2002; J. S. Link 2010).

Third, we suspected that certain fish species life history characteristics lend themselves to including ecosystem considerations more than others. For example, forage species are typically short-lived, highly linked to the physical environment, and may be influenced by predation from higher trophic levels (Pikitch et al. 2012). Therefore, we might expect that stock assessments for forage species would be more likely to include information about environmental drivers or predation than a stock assessment for a high trophic level, longer-lived, generalist piscivorous predator.

Documenting EBFM “success stories” helps to demonstrate the effectiveness of EBFM, a key part of building a case for it (Tallis et al. 2010; Christie et al. 2007; de Young, Charles, and Hjort 2008). The goals of our synthesis are to gauge the current status of the use of ecosystem considerations in U.S. assessments, provide examples that can serve as a reference for others seeking to expand the scope of assessments, and consider more broadly how ecosystem information can be used in the institutional context in which assessments occur. We suspect that all of these contextual factors could influence how stock assessment models for fish species evolve as EBFM continues to advance.

**Methods**

We reviewed over 200 stock assessments conducted by NOAA Fisheries. We obtained a list of the most recent stock assessment for each Council-managed stock in federal waters through a data request to the NOAA Species Information System (SIS) database (a simplified public version of the portal is available at https://www.st.nmfs.noaa.gov/sisPortal/). The SIS database contains metadata on stock assessment models and stock status from 2000 to present. We controlled for variation in model complexity by evaluating reports that had, at a minimum, some sort of production model (assigned level 3 or higher in the database).

We examined the extent to which each stock assessment report incorporated information about the interaction of the target stock with its ecosystem and other fisheries. We characterized six types of interactions: interactions with habitat or habitat requirements, environmental or climate interactions, interactions with prey, interactions with predators, bycatch of the target species in other fisheries, and bycatch of other species within the target species fishery. These topic areas cover a range of factors that could influence recruitment, growth, movement, or mortality, which are the processes that affect stock biomass and thus most likely to be included in assessments.

We scored each category of ecosystem information on an ordinal scale from 1 to 3. A score of 1 was given when the topic was mentioned in the stock assessment report as background information on the species. We scored a report with a 2 for two cases: when quantitative data on the interaction were included in the report, but not used in any analyses, or when the author made an explicit link between the ecosystem category and assessment parameters or output. For example, including numerical data from diet studies on the target species would receive a score of 2, as would discussing a link between sea surface temperature and recruitment predictions. The highest score, 3, was given in cases when the category was explicitly included in the assessment model through data inputs or estimated parameters.

It is unlikely that any report would score high in every category. Given the step-wise progression of most assessment models, new components are generally only added as needed, or desired, by the assessment working group or the stock assessment author. Moreover, higher scores are not intended to be a judgement of the quality of an assessment. In some cases, an initial screening of the available environmental variables may be sufficient to determine that inclusion of these variables in the stock assessment would not improve model performance. Thus, a model that includes these variables, which would receive a score of 3, is not necessarily more accurate or less biased than a model that does not (Punt et al. 2014).

In some cases, ecosystem interactions were included in exploratory model runs, but not the final model used to develop management advice. Our scores reflect the level of consideration given to each category of ecosystem interaction as reflected in the final stock assessment report, not whether the final model used for decision-making included any of these factors. We did this out of a desire to record the consideration of new topics, not track the review process of new components of assessment models.

*Potential explanatory factors: stock status, availability of diet data, life history types, and revenue*

We explored how characteristics of the target stocks and the context surrounding their management might influence their stock assessments by exploring four aspects. First, we categorized stock status based on its designation during the period from 2001 to 2005. We chose this period because NOAA’s Fish Stock Sustainability Index (FSSI) began tracking overfished status in 2001, and the oldest assessment in our database was from 2006. If the stock was given an overfished status designation during any one of those years, we considered it “overfished” for the purposes of this analysis. Second, we explored the role of data availability on the potential to be able to include information on predators and prey of target stocks in assessment reports by characterizing the general availability of diet information by region. The Northeast Fisheries Science Center and Alaska Fisheries Science Center have long-standing stomach contents analysis programs and sampling as part of their annual surveys, while the other science centers have more opportunistic sampling and support for diet studies, if any. Third, we categorized each target stock as one of four ecological “types” that combine information about taxonomy, habitat, and functional role in the ecosystem: small pelagics, groundfish, benthic invertebrates, or medium/large pelagics.

**Results**

The quality and quantity of inclusion of ecosystem interactions into 206 recent stock assessments varied dramatically (Figure 1). Bycatch of the target species (40 percent of assessments) was the most common interaction included in quantitative approaches. Explicit and quantitative incorporation of other interactions into assessments was less common, but 24 percent of assessment reports included at least one ecosystem factor quantitatively. Eleven percent of stock assessments included habitat, 14 percent included environmental or oceanographic conditions, while 1 percent included the effects of predation. Bycatch of other species and competition were never incorporated quantitatively.

Most assessments that scored a 3 in one or more categories included ecosystem information to filter or correct observations of the assessed species in fishery dependent or independent surveys (Table S1). Of 22 assessments that included habitat, 18 used habitat factors to filter observations or correct catchability. In those assessments, habitat was characterized by bottom depth, bottom type, or the presence of co-occurring species. Three assessments for invertebrate bivalves (Atlantic surfclam, ocean quahog, sea scallop) included total habitat area to inform the biomass estimate. One assessment (Gulf of Alaska demersal shelf rockfish) used the area of rocky habitat as a multiplier for densities observed in the survey.

Twenty-nine assessment models quantitatively included climate, and did so in more diverse ways than for habitat. About half used temperature as a covariate for catchability or an index of abundance. Four salmon stock assessments used environmental covariates to forecast returns. Five assessments used temperature or other environmental indices to predict recruitment. Growth was modeled as temperature-dependent in one assessment (Bering Sea-Aleutian Islands yellowfin sole), and in another growth was time-varying with PDO regimes (Southern Pacific Coast chilipepper rockfish). Gulf of Mexico Gag uses an environmentally driven mortality parameter to account for red-tide events. Catches were assigned to U.S. or Mexican fleets based on temperature (which influences spatial distribution of the stock) in the Pacific sardine assessment.

Predation was included quantitatively in three assessment reports. Time-varying natural mortality informed by predator abundance was investigated for butterfish and Atlantic herring (but was not retained in the final model for either stock). Predator abundance was used as an indicator of year-class strength for shortbelly rockfish. The Atlantic herring assessment also investigated an index of an egg predator to predict recruitment.



**Figure 1**. Inclusion of ecosystem interactions across interaction types. Each bar represents the proportion of assessment reports that received each score across topics (n=206). Shading increases with scores: background information (1), qualitative inclusion of information (2), or quantitative inclusion (3).

Qualitative inclusion of ecosystem considerations were more common than quantitative for some categories, but not all. Incorporating ecosystem considerations qualitatively occurred more frequently than quantitatively for diet, predation, and bycatch of other species. Quantitative approaches were more common than qualitative for habitat, climate, and bycatch of the target species (Figure 1).

Including ecosystem interactions as background information was the most common approach in all categories except for bycatch of the assessed species. Habitat (68 percent) and predation (49 percent) interactions were most frequently included in background information. Bycatch of other species was mentioned in 30 percent of assessment reports and environmental interactions were mentioned in 23 percent of the reports. Competition was rarely mentioned (5 percent), and we did not include it in the remaining graphs.

*Stock status*

Our hypothesis that overfished status may lead to increased inclusion of ecosystem information was supported for some ecosystem and fishery interactions, but not others. Bycatch of the target species was more frequently included in assessments for overfished species (Figure 2). Qualitative (but not quantitative) inclusion of climate influences was more common for overfished stocks We saw little difference in the inclusion of habitat, predation, or diet in stock assessments for overfished stocks.



**Figure 2.** Stocks that were in an overfished state for some part of 2001-2005 had relatively higher scores on their assessments for accounting for bycatch of the target species, habitat interactions, and environmental/climate interactions. Bar plots show the proportion of scores within each category (None= 0, Background = 1, Qualitative = 2, Quantitative=3)

*Availability of diet data*

We found support for our hypothesis that data availability may be reflected in what information is considered in stock assessments. When we grouped assessment scores by the availability of an on-site stomach contents lab, we saw higher scores for the inclusion of diet and predation interactions into stock assessments in those science centers that had long histories of supporting research on trophic interactions (Alaska and Northeast, Figure 3). A score of 2 or above for diet occurred in 2 assessments coming out of fisheries science centers without stomach contents labs and 23 assessments from centers with stomach contents labs. For predation, 22 assessments had scores of 2 or above from centers with stomach contents labs. Only four assessments from centers without stomach contents labs had scores of 2 or above for predation. However, even in centers with stomach contents labs, quantitative incorporation of predation in assessment models was rare (X out of Y assessments).

  
**Figure 3**. The incorporation of prey and predation into stock assessments may be explained by data availability. Bar plots show the proportion of assessments that received each score as a function of the co-occurrence of a stomach contents lab at the science center where the assessment was done.

*Target species life history*

We hypothesized that life history characteristics may influence what types of ecosystem interactions are considered in assessments, and found support for this for predation but not other categories (Figure 4). Predation was included quantitatively only for the X species we categorized as forage, and over 50 percent of assessments for forage species incorporated predation at least qualitatively. Quantitative inclusion of climate factors was also highest for forage species, but the proportion of assessments scored 2 or higher was similar across forage, demersal, and benthic invertebrate species. Habitat considerations followed a similar pattern, but were most frequent for invertebrates. Pelagic species had the lowest levels of inclusion of ecosystem and fishery interactions across all types.



**Figure 4**. Assessment scores for six categories of fishery system information, separated by the ecological type of the assessed species. Legend as in Fig 2.

**Discussion**

Our review of over 200 U.S. stock assessments demonstrates progress on incorporating interactions among fisheries and with the biophysical environment into the stock assessment process. Assessments included more interactions among fisheries (technical interactions) than interactions within the biophysical system. One quarter of the assessment models included at least one type of interaction between the assessed species and its biophysical system. Of those, more assessment models included interactions with physical drivers of habitat and climate than species interactions (diet and predation). The level of inclusion of biophysical linkages was greatest where data were available and life history characteristics of the species suggested strong interactions were likely. Together, these findings suggest that current modeling tools used for stock assessments are capable of supporting EBFM.

We found support for our hypothesis that overfished status may contribute to greater inclusion of ecosystem interactions, particularly for interactions with oceanographic conditions. This congruence lends potential support to the idea that fishery collapses are often caused by a combination of overfishing and environmental changes (Pinsky and Byler 2015; Essington et al. 2015). However, overfished status may also lead to additional scrutiny and a sense of urgency, ultimately supporting innovation of methods or data during the development of subsequent assessment models for that species. Research in product innovation suggests that creating a sense of urgency is a critical component in team dynamics that leads to higher levels of creativity and more competitive new technologies (Im, Montoya, and Workman 2013).

While complex modeling and data requirements may not be the dominant barrier to operationalizing EBFM (Patrick and Link 2015a), we found support for our hypothesis that data availability limits what types of ecosystem considerations stock assessments can include. The more frequent inclusion of information related to physical than biological linkages also suggests that data on ecological processes maybe particularly limiting. Of course, understanding the consequences of predator-prey interactions is inherently challenging because they can change seasonally, from year to year, and across a region. Moreover, we cannot discern whether predation interactions are a more dominant part of the ecosystem in the regions where diet data are collected, or of the science culture in these regions. But we can say, in regions where large-scale federally sponsored stomach content sampling does not occur, trophic interactions have not been included in assessments.

Fish life history has likely played a role in determining how ecosystem information has been used to date. Higher scores for assessments of forage species and benthic invertebrates suggest that life histories are taken into account in the assessment process for at least some of these species. Increased attention on forage fish in the science and conservation communities over the past decade may also be reflected in the assessment reports (e.g., Pikitch et al. 2012; Dickey-Collas et al. 2013; Smith et al. 2011).

We found a greater degree of inclusion of ecosystem considerations than the global review by Skern-Mauritzen et al. (2016), using our broader definitions of inclusion and ecosystem information types. The context surrounding ecosystem considerations in European (ICES) assessments they described is similar to what we found in the U.S. context, however. Skern-Mauritzen et al. (2016) noted that inclusion of interactions has been primarily a bottom-up process, driven first by scientific support in the literature, then data availability, and then interest and inclusion in the assessment model. They also found that qualitative inclusion of ecosystem effects on stock productivity was more common than quantitative inclusion, although they did not quantify those differences. Their results and ours suggest that there are likely more opportunities to include and evaluate relationships between harvested species and their ecosystems moving forward.

Given the examples we identified in U.S. assessments for expanding assessment models to include more ecosystem considerations, an important next step will be to identify how and when to include ecosystem data. Including additional ecosystem information in assessment models does not always improve the accuracy or predictive capacity of models (Punt et al. 2014). However, a risk analysis and prioritization framework could be used to triage species most likely to benefit from greater consideration of fishery and ecosystem interactions. For example, NOAA’s recent Stock Assessment Improvement Plan (NOAA 2017) recommends a very simple framework for scoring species based on their ecosystem importance (trophic linkages), recruitment variability (likelihood of being linked to environmental driver), and habitat associations. Implementing this kind of approach may be useful for NMFS and their Council partners to quickly screen species to identify candidates for expanding assessments.

Governance and institutional challenges are often referred to as barriers to implementing EBFM (Bundy et al. 2008; R. Hilborn, Orensanz, and Parma 2005; Olsson, Folke, and Hughes 2008) and some of these may occur within the stock assessment process itself, limiting further inclusion of ecosystem considerations in assessment models. For example, skepticism about new approaches is inherent to the process of science and particularly to EBFM (Ray Hilborn 2011). Moreover, fisheries science has been strongly influenced by statistical inference, where the goal is to describe observed data with as simple a model as possible (Kuparinen et al. 2012; Burnham and Anderson 1998). Any new models, data, or tools are also subject to reviews by Fishery Management Councils Science and Statistical Committee and outside reviewers. Together, these factors protect an important process influencing management decisions and ensure the use of “best available science.” An unintended consequence may be that this high burden of proof presents an obstacle to even positive changes.

Developing new stock assessment models and data sources to inform them is a complex and creative scientific process. Creativity research suggests that negative emotions (such as those created by negative feedback from reviewers, or fears generated by large changes in stock status) can motivate improvement, for which creativity is required (Rasulzada 2014). But, stress (such as that created by being asked to produce results under very tight deadlines and in a public arena) can also reduce creativity by reducing cognitive resources (Fredrickson 2004). Bureaucratic climates can threaten employee creativity by fostering a fear of failure and risk avoidance (Ford 1996). Considering the institutional context surrounding stock assessments could create opportunities to improve the process. For example, exploring potential ecosystem expansions to assessment models first using management strategy evaluations can provide some breathing room from the management decisions on catch-levels. Including ecosystem scientists on assessment teams is another way to encourage broader ecosystem considerations. Some regions have developed terms of reference for assessments that recommend consulting with or including ecosystem scientists (eg. Pacific Council, 2017, others?) or explicitly require ecosystem factors to be considered. For example, the 2014 butterfish assessment included the following term of reference: “3. Characterize oceanographic and habitat data as it pertains to butterfish distribution and availability. If possible, integrate the results into the stock assessment (TOR-5).”

One productive approach to expanding the use of ecosystem considerations in stock assessments is to develop separate “research” and “operational” tracks for stock assessments. Research track assessments would have greater flexibility to innovate without being constrained by the tight timelines and need for demonstrated robustness associated with operational assessments and their formal review process. A mechanism would be needed to move successful innovations from the research track into the operational assessment. Currently, “benchmark” assessments provide some opportunity to innovate, but they are still constrained by the existing review process and intense assessment schedule.

Expanding stock assessments to include more consideration of fishery and ecosystem interactions is only one way these considerations can influence the management process. Others may be equally or more influential. Stock assessments estimate stock status relative to reference points, which in turn influences the recommended catch. This influence of estimated status on recommended catch is made explicit in harvest control rules. The form of the control rule (how catch should change with biomass), and reference points (targets or limits) are another target for including ecosystem information (e.g., Holsman et al. 2016; Patrick and Link 2015b; Punt et al. 2014). For example, the control rule for Pacific sardine depends on temperature (CPS FMP). Moreover, a control rule translates biomass into allowed catch (ABC- allowable biological catch), but actually setting catch limits (TAC- total allowable catch) is a separate decision, which could also be influenced qualitative or quantitatively by ecosystem status (e.g. Zador et al. 2017) or other biophysical or human system considerations (Patrick and Link 2015b; Levin 2014).

Our analysis provides a summary of the current state of stock assessments in the U.S. with respect to ecosystem science, and highlights numerous examples where broader considerations have been included qualitatively and quantitatively. We identified potential data-gaps and also opportunities for further expansion of assessments moving forward. Our results can inform future decisions about developing guidelines for prioritizing assessments and funding opportunities to improve ecosystem-based fisheries management.

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**References**

Arkema, Katie K., Sarah C. Abramson, and Bryan M. Dewsbury. 2006. “Marine Ecosystem-Based Management: From Characterization to Implementation.” *Frontiers in Ecology and the Environment* 4 (10):525–532.

Berkes, Fikret. 2012. “Implementing Ecosystem-Based Management: Evolution or Revolution?” *Fish and Fisheries* 13 (4):465–76. https://doi.org/10.1111/j.1467-2979.2011.00452.x.

Biedron, Ingrid S., and Barbara A. Knuth. 2016. “Toward Shared Understandings of Ecosystem-Based Fisheries Management among Fishery Management Councils and Stakeholders in the U.S. Mid-Atlantic and New England Regions.” *Marine Policy* 70 (Supplement C):40–48. https://doi.org/10.1016/j.marpol.2016.04.010.

Bundy, Alida, Ratana Chuenpagdee, Svein Jentoft, and Robin Mahon. 2008. “If Science Is Not the Answer, What Is? An Alternative Governance Model for the World’s Fisheries.” *Frontiers in Ecology and the Environment* 6 (3):152–155.

Burnham, K.P., and D.R. Anderson. 1998. *Model Selection and Inference: A Practical Information-Theoretic Approach*. New York: Springer-Verlag.

Christie, Patrick, David L. Fluharty, Alan T. White, Liza Eisma-Osorio, and William Jatulan. 2007. “Assessing the Feasibility of Ecosystem-Based Fisheries Management in Tropical Contexts.” *Marine Policy* 31 (3):239–50. https://doi.org/10.1016/j.marpol.2006.08.001.

Cowan, James H., Jake C. Rice, Carl J. Walters, Ray Hilborn, Timothy E. Essington, John W. Day, and Kevin M. Boswell. 2012. “Challenges for Implementing an Ecosystem Approach to Fisheries Management.” *Marine and Coastal Fisheries* 4 (1):496–510. https://doi.org/10.1080/19425120.2012.690825.

Dickey-Collas, M., G. H. Engelhard, A. Rindorf, K. Raab, S. Smout, G. Aarts, M. van Deurs, et al. 2013. “Ecosystem-Based Management Objectives for the North Sea: Riding the Forage Fish Rollercoaster.” *ICES Journal of Marine Science*. https://doi.org/10.1093/icesjms/fst075.

Essington, T. E., P. S. Levin, K.N. Marshall, L. E. Koehn, L.G. Anderson, A. Bundy, Courtney Carothers, et al. 2016. “Building Effective Fishery Ecosystem Plans: A Report from the Lenfest Fishery Ecosystem Task Force.” Washington, D.C.: Lenfest Ocean Program.

Essington, T. E., P. E. Moriarty, H. E. Froehlich, E. E. Hodgson, L. E. Koehn, K. L. Oken, M. C. Siple, and C. C. Stawitz. 2015. “Fishing Amplifies Forage Fish Population Collapses.” *Proc Natl Acad Sci U S A* 112 (21):6648–52. https://doi.org/10.1073/pnas.1422020112.

FAO. 2003. “Fisheries Management. 2. The Ecosystem Approach to Fisheries.” 4 Suppl. 2. FAO Technical Guidelines for Responsible Fisheries. Rome, Italy.

Ford, Cameron M. 1996. “A Theory of Individual Creative Action in Multiple Social Domains.” *Academy of Management Review* 21 (4):1112–1142.

Fredrickson, Barbara L. 2004. “The Broaden-and-Build Theory of Positive Emotions.” *Philosophical Transactions of the Royal Society B: Biological Sciences* 359 (1449):1367.

Hilborn, R., J.M. Orensanz, and A.M. Parma. 2005. “Institutions, Incentives and the Future of Fisheries.” *Philosophical Transactions of the Royal Society of London, Series B: Biological Sciences* 360:47–57.

Hilborn, Ray. 2011. “Future Directions in Ecosystem Based Fisheries Management: A Personal Perspective.” *Fisheries Research* 108 (2):235–239.

Holsman, Kirstin K., James Ianelli, Kerim Aydin, Andre E. Punt, and Elizabeth A. Moffitt. 2016. “A Comparison of Fisheries Biological Reference Points Estimated from Temperature-Specific Multi-Species and Single-Species Climate-Enhanced Stock Assessment Models.” *Deep-Sea Research Part Ii-Topical Studies in Oceanography* 134 (December):360–78. https://doi.org/10.1016/j.dsr2.2015.08.001.

Im, Subin, Mitzi M. Montoya, and John P. Workman. 2013. “Antecedents and Consequences of Creativity in Product Innovation Teams.” *Journal of Product Innovation Management* 30 (1):170–185.

Kuparinen, Anna, Samu Mäntyniemi, Jeffrey A. Hutchings, and Sakari Kuikka. 2012. “Increasing Biological Realism of Fisheries Stock Assessment: Towards Hierarchical Bayesian Methods.” *Environmental Reviews* 20 (2):135–51. https://doi.org/10.1139/a2012-006.

Leslie, Heather, Leila Sievanen, Tara Gancos Crawford, Rebecca Gruby, H. Cristina Villanueva-Aznar, and Lisa M. Campbell. 2015. “Learning from Ecosystem-Based Management in Practice.” *Coastal Management* 43 (5):471–97. https://doi.org/10.1080/08920753.2015.1051424.

Levin, Phillip S. 2014. “New Conservation for the Anthropocene Ocean.” *Conservation Letters*. http://onlinelibrary.wiley.com/doi/10.1111/conl.12108/abstract.

Link, J. 2002. “What Does Ecosystem-Based Management Mean?” *Fisheries* 27 (4):18–21.

Link, J. S. 2010. *Ecosystem-Based Fisheries Management: Confronting Tradeoffs*. Cambridge: Cambridge University Press.

Mace, Pamela M. 2001. “A New Role for MSY in Single-Species and Ecosystem Approaches to Fisheries Stock Assessment and Management.” *Fish and Fisheries* 2 (1):2–32.

Marine Strategy Framework Directive. 2008. “Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 Establishing a Framework for Community Action in the Field of Marine Environmental Policy.” *Official Journal of the European Union L* 164:19–40.

Maunder, M.N., and G. M. Watters. 2003. “A General Framework for Integrating Environmental Time Series into Stock Assessment Models: Model Descriptions, Simulation Testing and Example.” *Fisheries Bulletin* 101:89–99.

Methot, Richard D., and Chantell R. Wetzel. 2013. “Stock Synthesis: A Biological and Statistical Framework for Fish Stock Assessment and Fishery Management.” *Fisheries Research* 142:86–99.

Myers, Ransom A. 1998. “When Do Environment–recruitment Correlations Work?” *Reviews in Fish Biology and Fisheries* 8 (3):285–305. https://doi.org/10.1023/a:1008828730759.

NOAA. 2016. “NOAA Fisheries Ecosystem-Based Fisheries Management Road Map.” https://www.st.nmfs.noaa.gov/ecosystems/ebfm/creating-an-ebfm-management-policy.

Olsson, P., C. Folke, and T.P. Hughes. 2008. “Navigating the Transition to Ecystem-Based Management of the Great Barrier Reef, Australia.” *Proceedings of the National Academy of Science of the United States of America* 105:9489–94.

Patrick, Wesley S., and Jason S. Link. 2015a. “Myths That Continue to Impede Progress in Ecosystem-Based Fisheries Management.” *Fisheries* 40 (4):155–160.

———. 2015b. “Hidden in Plain Sight: Using Optimum Yield as a Policy Framework to Operationalize Ecosystem-Based Fisheries Management.” *Marine Policy* 62 (December):74–81. https://doi.org/10.1016/j.marpol.2015.08.014.

Pikitch, E. K., P.D. Boersma, I. L. Boyd, D. O. Conover, P. Cury, T.E. Essington, S. S. Heppell, et al. 2012. “Little Fish, Big Impact: Managing a Crucial Link in Ocean Food Webs.” Washington D.C.: Lenfest Ocean Program. http://www.oceanconservationsicence.org/foragefish.

Pinsky, Malin L., and David Byler. 2015. “Fishing, Fast Growth and Climate Variability Increase the Risk of Collapse.” In *Proc. R. Soc. B*, 282:20151053. The Royal Society. http://rspb.royalsocietypublishing.org/content/282/1813/20151053.abstract.

Pitcher, Tony J., Daniela Kalikoski, Katherine Short, Divya Varkey, and Ganapathiraju Pramod. 2009. “An Evaluation of Progress in Implementing Ecosystem-Based Management of Fisheries in 33 Countries.” *Marine Policy* 33 (2):223–232.

Punt, André E., Teresa A’mar, Nicholas A. Bond, Douglas S. Butterworth, Carryn L. de Moor, José AA De Oliveira, Melissa A. Haltuch, Anne B. Hollowed, and Cody Szuwalski. 2014. “Fisheries Management under Climate and Environmental Uncertainty: Control Rules and Performance Simulation.” *ICES Journal of Marine Science: Journal Du Conseil* 71 (8):2208–2220.

Rasulzada, Farida. 2014. “Creativity at Work and Its Relation to Well-Being.” *Creativity Research: An Interdisciplinary and Multidisciplinary Research Handbook*, 171–190.

Skern-Mauritzen, Mette, Geir Ottersen, Nils Olav Handegard, Geir Huse, Gjert E. Dingsør, Nils C. Stenseth, and Olav S. Kjesbu. 2016. “Ecosystem Processes Are Rarely Included in Tactical Fisheries Management.” *Fish and Fisheries* 17 (1):165–75. https://doi.org/10.1111/faf.12111.

Smith, A. D., C. J. Brown, C. M. Bulman, E. A. Fulton, P. Johnson, I. C. Kaplan, H. Lozano-Montes, et al. 2011. “Impacts of Fishing Low-Trophic Level Species on Marine Ecosystems.” *Science* 333 (6046):1147–50. https://doi.org/10.1126/science.1209395.

Tallis, Heather, Phillip S. Levin, Mary Ruckelshaus, Sarah E. Lester, Karen L. McLeod, David L. Fluharty, and Benjamin S. Halpern. 2010. “The Many Faces of Ecosystem-Based Management: Making the Process Work Today in Real Places.” *Marine Policy* 34 (2):340–348.

Young, C de, A Charles, and A Hjort. 2008. “Human Dimensions of the Ecosystem Approach to Fisheries: An Overview of Context, Concepts, Tools and Methods.” 489. FAO Fisheries Technical Paper. Rome: FAO.

Zador, Stephani G., Kirstin K. Holsman, Kerim Y. Aydin, and Sarah K. Gaichas. 2017. “Ecosystem Considerations in Alaska: The Value of Qualitative Assessments.” *ICES Journal of Marine Science* 74 (1):421–30. https://doi.org/10.1093/icesjms/fsw144.

Table S1. Stock assessment reports that included ecosystem interactions quantitatively

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| --- | --- | --- | --- | --- |
| **Species and Stock** | **Year Assessed** | **Managing Council** | **NOAA Science Center** | **Ecosystem interaction** |
| Gag Gulf of Mexico | 2014 | GMFMC | SEFSC | climate |
| Yellowedge grouper Gulf of Mexico | 2011 | GMFMC | SEFSC | habitat |
| Vermilion Snapper - Gulf of Mexico | 2006 | GMFMC | SEFSC | habitat |
| Red Grouper - Gulf of Mexico | 2006 | GMFMC | SEFSC | habitat |
| Tilefish Gulf of Mexico | 2011 | GMFMC | SEFSC | habitat |
| Ocean quahog | 2009 | MAFMC | NEFSC | habitat |
| Longfin inshore squid Atlantic Coast | 2010 | MAFMC | NEFSC | habitat |
| Atlantic surfclam - Mid-Atlantic Coast | 2013 | MAFMC | NEFSC | habitat |
| Yellowtail flounder- Southern New England / Mid-Atlantic | 2012 | NEFMC | NEFSC | climate |
| Winter flounder - Southern New England / Mid-Atlantic | 2011 | NEFMC | NEFSC | climate |
| black sea bass | 2009 | NEFMC | NEFSC | climate |
| Silver Hake | 2006 | NEFMC | NEFSC | climate |
| Winter flounder - George's Bank | 2011 | NEFMC | NEFSC | climate |
| Pollock - Gulf of Maine / George's Bank | 2010 | NEFMC | NEFSC | climate |
| Butterfish | 2014 | NEFMC | NEFSC | climate, predation |
| Atlantic herring | 2012 | NEFMC | NEFSC | climate, predation |
| Sea Scallop Georges Bank / Mid-Atlantic Bight | 2014 | NEFMC | NEFSC | habitat |
| Red King Crab Bristol Bay | 2013 | NPFMC | ADFG | climate |
| Flathead sole (BSAI) | 2014 | NPFMC | AFSC | climate |
| Tanner Crab Bering Sea | 2013 | NPFMC | AFSC | climate |
| Alaska Plaice | 2014 | NPFMC | AFSC | climate |
| Kamchatka flounder (BSAI) | 2014 | NPFMC | AFSC | climate |
| Arrowtooth flounder BSAI | 2014 | NPFMC | AFSC | climate |
| Northern rock sole Eastern Bering Sea and Aleutian Islands | 2012 | NPFMC | AFSC | climate |
| Yellowfin sole BSAI | 2014 | NPFMC | AFSC | climate |
| Red King Crab Pribilof Islands | 2013 | NPFMC | AFSC | climate |
| Demersal shelf rockfish complex (GOA - includes Yelloweye) | 2014 | NPFMC | AFSC | habitat |
| Chilipepper - Southern Pacific Coast | 2007 | PFMC | NW-SW | climate |
| Coho salmon - Oregon Production Index Area: Oregon Coast Natural | 2014 | PFMC | NW-SW | climate |
| Coho salmon - Puget Sound: Skagit | 2014 | PFMC | NW-SW | climate |
| Chinook salmon - Puget Sound: Snohomish Summer/Fall | 2014 | PFMC | NW-SW | climate |
| Chinook salmon - Puget Sound: Stillaguamish Summer/Fall | 2014 | PFMC | NW-SW | climate |
| Sablefish Pacific Coast | 2011 | PFMC | NW-SW | climate |
| Starry Flounder off CA., OR., and WA. | 2005 | PFMC | NW-SW | habitat |
| Black rockfish - Southern Pacific Coast | 2007 | PFMC | NW-SW | habitat |
| shortbelly rockfish pacific coast | 2007 | PFMC | NW-SW | predation |
| Pacific Sardine | 2014 | PFMC | SWFSC | climate |
| Goliath Grouper | 2011 | SA-GM | SEFSC | habitat |
| Hogfish Gulf of Mexico and South Atlantic | 2013 | SA-GM | SEFSC | habitat |
| Yellowtail Snapper Southern Atlantic Coast | 2012 | SA-GM | SEFSC | habitat |
| Black Grouper Gulf of Mexico and South Atlantic | 2010 | SA-GM | SEFSC | habitat |
| Yellowtail Snapper - Gulf of Mexico | 2012 | SA-GM | SEFSC | habitat |
| Spiny lobster - Southeast US | 2005 | SA-GM | SEFSC | habitat |
| Mutton Snapper - South Atlantic and Gulf of Mexico | 2008 | SA-GM | SEFSC | habitat, climate |
| Vermilion Snapper - South Atlantic | 2008 | SAFMC | SEFSC | climate |
| King Mackerel South Atlantic | 2014 | SAFMC | SEFSC | climate |
| Hogfish - Southeast Florida | 2013 | SAFMC | SEFSC | habitat |
| Black Sea Bass - South Atlantic | 2011 | SAFMC | SEFSC | habitat |
| Tilefish - South Atlantic | 2011 | SAFMC | SEFSC | habitat |
| Red grouper South Atlantic | 2010 | SAFMC | SEFSC | habitat, climate |