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

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**Abstract**

The appetite for ecosystem-based fisheries management approaches has grown, but implementation has been 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. We found that including interactions among fishing fleets (technical interactions) was far more common than including biophysical (species, habitat, climate) interactions in stock assessment models. Within the biophysical realm, including interactions with the physical environment (habitat, climate) was occurred twice as often as including ecological interactions (predation). Many assessment reports included ecological interactions as background or qualitative considerations, however. Our analyses suggested that whether the species was overfished (stock status), the availability of diet information, and life history characteristics may influence how and when broader considerations were included. Our results demonstrate that significant progress has been made to expand single-species assessment and technical capacity exists to do so. Continuing challenges are the availability of some types of data to support expanded stock assessments, and guidance 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; Directive 2008). Even though there is general agreement surrounding such policies, the practice of EBFM has often lagged (Essington et al. 2016; Arkema, Abramson, and Dewsbury 2006; Berkes 2012; Cowan et al. 2012; Pitcher et al. 2009). Some purported barriers to implementing EBFM have included lags associated with developing data collection, analytical tool, and models (Hilborn 2011; Cowan et al. 2012) and a remaining need for institutional and governance changes to support EBFM (Leslie et al. 2015; Hilborn 2011; Olsson, Folke, and Hughes 2008). However Patrick and Link (2015a) argue that these challenges to EBFM have been resolved in developed countries, and now persist only as “myths”.

Stock assessments and the process surrounding their review and acceptance by regional fishery management councils are at the heart of fisheries management in the United States and other developed countries. Stock assessment models estimate biomass of a targeted species (in some cases, species groups) based on data from catches and surveys 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. A growing body of work extends the scope of stock assessment modelling tools to include ecosystem considerations such as environmental relationships or predation mortality (Maunder and Watters 2003; Methot and Wetzel 2013; Kuparinen et al. 2012). The stock assessment process is only one of many ways through which broader ecosystem considerations can influence management decisions. Here, we use stock assessments and the reports communicating their findings to managers as a microcosm to investigate progress towards implementing EBFM in the U.S.

A recent global review of stock assessment models found that very few (2 percent) incorporated data or parameters representing 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. We sought broader definitions of both. 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 why uptake of ecosystem information into stock assessment models has occurred the way it has. Not all stock assessment models can or should incorporate environmental drivers of recruitment, for example. But, patterns of uptake and use of ecosystem considerations may be indicative of continuing 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, changes in status may simply shift the prioritization 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 continues to 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; 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.

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 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 implement extended assessments, and consider more broadly how ecosystem information can be used as well as 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 and reviewed by the regional fishery management councils. We obtained a list of the most recent stock assessment for each Council-managed stock in federal waters from the NOAA Species Information System (SIS) database (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. We chose these topic areas because we presumed they were the most relevant potential types of ecosystem interactions that would affect stock biomass and were therefore 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 technical scientific review committee 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).

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 labs 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 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 were not retained in the final model). 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 inclusion of climate influences was more common for overfished stocks, but not for quantitative approaches. We saw little difference in the inclusion of habitat, predation, or diet in stock assessments regardless of overfished status.



**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 diet 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 diet labs and 23 assessments from centers with diet labs. For predation, 22 assessments had scores of 2 or above from centers with diet labs. Only four assessments from centers without diet labs had scores of 2 or above for predation.

  
**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 diet 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 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 were 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 interactions 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 supports the idea that fishery collapses are often caused by a combination of overfishing and environmental changes (Pinsky and Byler 2015; Essington et al. 2015). 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 significant data on trophic interactions do not exist, 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. Recent attention on forage fish over the past decade may also be reflected in the assessments for these species. Differential inclusion of ecosystem considerations among life history types may be a good area developing prioritizations. As an example, NOAA’s recent Stock Assessment Improvement Plan includes recommendations for how to prioritize which assessments should be expanded (NOAA 2017). General guidance on life history types could be part of this prioritization, given what is already known in the literature and in practice . the inclusion of ecosystem info…. history types are more likely to lend themselves to ecosystem info—this could be used for prioritization of which assessments to target for expanstion (see parallels in NOAA SAIP)

Given the patterns we observed, what can lessons can be drawn about potential for continuing to expand stock assessments and what are remaining barriers? Governance and institutional challenges have been cited as a barrier for the broadscale implementation of EBFM, and some of these may be applicable to the process surrounding stock assessment modeling and review. In particular, how different types of information included in assessments can be considered a creative process, and thus informed by research on creativity and innovation andTherefore, we can use research on creativity to inform a discussion of why these factors are or are not included. Negative emotions can motivate improvements—for which creativity is required (George and Zhou 2002, martin and stoner 1996, Schwarz 2002, Rasulzada 2014). But, stress can also reduce creativity by reducing cognitive resources (Fredricksen 2001). Questioning prevailing truths—can be seen as a threat. Bureaucratic climate can threaten employee creativity—fear of taking risks because fear of failure. Leads to risk avoidance ford 1996

1. Zador et al. make a case for the use of qualitative information—report cards influence decisions implicitly and explicitly—these could influence assessment authors as they prepare their model for review, or could influence review panels as they evaluate assessment panels. Helps to bound uncertainty and consider what additional information could inform the most uncertain parameters (e.g., natural mortality or steepness)
2. Stock assessment as risk assessment? Evaluating evidence that contributes to the trends in the data, and evaluating weights and causes—lots of weight of evidence research. What if the data stream isn’t comparable to the others—can’t evaluate it…

Ecosystem information can only be used when it exists and is in a form readily available to assessment authors. Have to make it easy. Burden on assessment authors is high. (many data streams)

Ways to improve the process—include teams with ecologists to help with the lift. (SSC TOR for pcouncil stock assessment 2017-2018)

Recognize other pathways to influencing decisions re: catch besides assessment models. Eco info could influence decisiosn about setting the catch level, outside the control rule – control rule determines MSY. But OY is based on a bunch of other considerations. Zador paper

Track inclusion of eco info into process, whether or not it ultimately influences the stock assessment model.

For example, it is common among scientists (and others) not directly involved with stock assessments to lament the rigidity of the models, assumptions, and process and review required to change parameters in a model, let alone model structure, to reflect ecological understanding such as mortality rates that change through time as a function of predator abundance. On the other side, stock assessment scientists are quick to recognize data limitations and weak stationarity associated with many recruitment-environment relationships, and the high burden of proof required to add even incrementally add new kinds of information to assessments.

Overcoming barriers to EBFM

Bycatch of target species, which is not surprising, because accounting for all catches of the target species can be considered a requirement of proper single species assessment.

UNDER CONSTRUCTION-Compare these findings with Skern-Mauritzen study noting that inclusion of interactions has been 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, which suggests that more data, or at least intuition, exists to include and evaluate these relationships.

Extended stock assessment models are one way to begin to operationalize EBFM. There are others. For example, our review did not include ecosystem considerations in single species control rules or reference points, both of which are areas of ongoing research (e.g., Holsman et al. 2016; Patrick and Link 2015b; Punt et al. 2014). Further, ecosystem reference points and control rules are also outside the scope of our review (e.g., Moffitt et al. 2015; Dolan, Patrick, and Link 2016).

This analysis provides a summary of the current state of stock assessments with respect to ecosystem science, and also highlights potential data-gaps and chokepoints for information that could be used in stock assessments, but isn’t currently. Our results can inform future decisions about developing guidelines for assessments and funding opportunities to improve ecosystem-based fisheries management.

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