Review Article

Inclusion of ecosystem information in US fish stock assessments suggests progress toward ecosystem-based fisheries management

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The appetite for ecosystem-based fisheries management (EBFM) approaches has grown, but the perception persists that implementation is slow. Here, we synthesize progress toward 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 reviewed over 200 stock assessments and assessed how the stock assessment reports included information about system influences on the assessed stock. Our goals were to quantify whether and how assessments incorporated broader system-level considerations, and to 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). Many assessment reports included ecological interactions only as background or qualitative considerations, rather than 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), the assessment is conducted at a science centre with a longstanding stomach contents analysis program, and/or the species life history characteristics 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). Regional differences in stomach contents analysis programs may 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. However, our results demonstrate that significant progress has been made to use best available science and data to expand single-species stock assessments, particularly when a broad definition of EBFM is applied.

Keywords: ecosystem-based fisheries management, ecosystem considerations, stock assessment

Introduction

Although ecosystem-based fisheries management (EBFM) is increasingly identified as a way to improve management outcomes, there is little consensus as to the extent to which management decisions are based on, or informed by, EBFM principles. On one hand, 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 (FAO, 2003; Marine Strategy Framework Directive, 2008; NOAA, 2016). Even so, many have argued that the practice of EBFM has lagged despite the proliferation of EBFM frameworks (Arkema *et al.*, 2006; Pitcher *et al.*,

2009; Berkes, 2012; Cowan *et al.*, 2012; Essington *et al.*, 2016). Here we use the EBFM definition of Essington *et al.* (2016), "a holistic, place-based framework that seeks to sustain fisheries and other services that humans want and need by maintaining healthy, productive and resilient fishery systems."

Some authors suggest lags between the generation of EBFM thought and action are caused by a need to develop new data sources, analytical tools, and models (Hilborn, 2011; Cowan *et al.*, 2012). 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 US federal fisheries management system, decision-makers and stakeholders in several regions are open to implementing EBFM (Biedron and Knuth, 2016) and the federal fisheries management agency, National Oceanic and Atmospheric Administration, has committed to doing so (NOAA, 2016). Thus, it is possible that EBFM is occurring more often than typically acknowledged, but does not receive attention because it now part of "good practice". That is, conventional management has incrementally evolved to include ecosystem considerations, but has not labelled such evolution as EBFM. We examine this thesis here.

The data and models used for stock assessment, a cornerstone of conventional fisheries management in many areas of the world, have greatly expanded in scope and complexity, and may be one way in which ecosystem considerations inform management. Stock assessment models estimate stock abundance relative to reference points using data such as catch, abundance, life history parameters, and expert knowledge. Output from these models informs decisions about annual catch limits, and as such they are subjected to a great deal of scrutiny from scientists, managers, and stakeholders. While some fisheries scientists have developed approaches for estimating the status of fish stocks that includes environmental relationships or predation mortality (Maunder and Watters, 2003; Kuparinen *et al.*, 2012; Methot and Wetzel, 2013), the degree to which this research has been transferred to assessment models used for management is unknown. We note that expanding single species assessment models to include more environmental context may be considered by some as an ecosystem approach to fisheries management (EAFM), rather than EBFM, which requires consideration of interacting fisheries or fish stocks (Patrick and Link, 2015a). However, in this article we include EAFM under the broader definition of EBFM and do not differentiate between them.

A recent global review of stock assessment models found that very few (2%) 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 end, is broader qualitative considerations that inform model development in less obvious 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 in stock assessment reports in the United States and understand the conditions under which uptake of ecosystem information has occurred. We undertook this exercise aware that it is not reasonable to expect all stock assessment models to include all ecological drivers; the performance of stock assessments and management strategies that include such drivers are highly variable (Myers, 1998; Punt *et al.*, 2014). Nonetheless, exploring cases where ecosystem information has not been included may indicate persistent barriers to implementing EBFM. To that end, we developed three hypotheses describing conditions that we thought could lead to stock assessment reports including ecosystem considerations.

First, we hypothesized that assessments for stocks that were in an overfished status would be more likely to include additional ecosystem interactions. Our reasoning is that overfished status could lead to a sense of urgency, which has been suggested to increase the receptiveness to EBFM (Olsson *et al.*, 2008). Additionally, 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 (Essington *et al.*, 2015; Pinsky and Byler, 2015).

Second, we hypothesized that regional differences among National Marine Fisheries Service Fishery Science Centers conducting the assessments may influence how ecosystem information is considered. For example, centres that have longstanding stomach contents analysis programs may be more likely to produce assessments in which predation and diet information are included. Or, centres that have strong oceanography programs may be more likely to produce assessments with climate information. If data limit the development of ecosystem models (Mace, 2001; Hilborn, 2011; Cowan *et al.*, 2012), the availability of such data may spur development of assessments that include novel information. A full assessment of data availability for all stocks considered in this analysis would be outside the scope of this article, however. We focus on regional differences in stomach contents programs because diet data provide information on one of the most common justifications of EBFM, namely that predator–prey interactions change population productivity and reference points (Link, 2002, 2010).

Third, we suspected that inclusion of ecosystem considerations will depend on the life history characteristics of stocks. 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.

The goals of our synthesis are to gauge the current status of the use of ecosystem considerations in US 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 206 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). Simple index-based assessments or per-recruit analyses which lacked an underlying population model were excluded.

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 (hereafter referred to as diets), 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 of information 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 stomach contents data, and life history types

We explored how characteristics of the target stocks and the context surrounding their management might influence their stock assessments by exploring three aspects. First, we categorized stock status based on its designation by NOAA 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 (defined on a stock by stock basis) during any one of those years, we considered it "overfished" for the purposes of this analysis. Second, we explored how regional differences in stomach contents analysis programs influenced the potential to include information on predation and diets of target stocks in assessment reports. The Northeast Fisheries Science Center (NEFSC, https://www.nefsc.noaa.gov/femad/pbb/fwdp/databases.html) and Alaska Fisheries Science Center (AFSC, https://access.afsc.noaa.gov/REEM/WebDietData/DietDataIntro.php) have long-standing stomach contents analysis programs and sampling as part of their annual surveys, while the other science centres 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 pelagic fishes, groundfish, benthic invertebrates, or medium/large pelagic fishes. We evaluated statistical support for our hypotheses by comparing the number of stock assessment reports with scores of 2 or higher with the number of reports scoring 1 or lower in each category using non-parametric one-sided Mann-Whitney U-tests. Differences between the four ecological types were described by Wilcoxon Rank Sum tests and post-hoc two-sided tests with Bonferonni corrections for multiple comparisons.

Results

The quality and quantity of inclusion of the six fishery and ecosystem interactions within the 206 recent stock assessments varied dramatically (Figure 1). Fishery interactions, specifically bycatch of the target species (40% of assessments), were the most common interaction included in quantitative approaches. Quantitative incorporation of other interactions into assessments was less common. Twenty-four percent of assessment reports included at least one of the other ecosystem factors quantitatively: 11% of stock assessments included habitat, 14% included environmental or oceanographic conditions, and 1% 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 (Supplementary Table S1). Of 23 assessments that included habitat, 19 used habitat factors to filter survey 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 surf-clam, 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
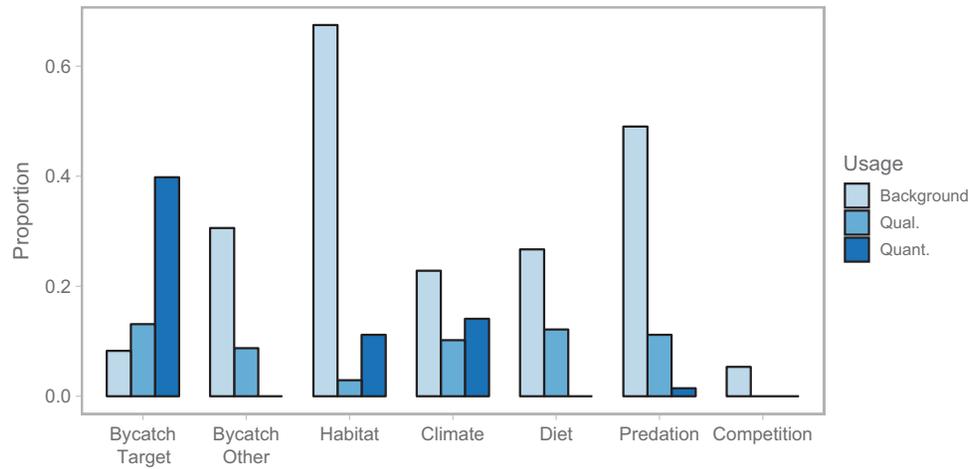
Figure 1. Inclusion of fishery and ecosystem interactions across interaction types. Each bar represents the proportion of assessment reports that received each score across topics ($n = 206$). Shading increases with scores: background information (1), qualitative inclusion of information (2), or quantitative inclusion (3).

half used temperature as a covariate for catchability or an index of abundance. Four salmon stock assessments used environmental covariates to forecast returns of adult fish. Five assessments used temperature or other environmental indices to predict recruitment. Growth was modelled as temperature dependent in one assessment (Bering Sea-Aleutian Islands yellowfin sole), and in another growth was time varying with phases of the Pacific Decadal Oscillation (PDO) (Southern Pacific Coast chilipepper rockfish). The Gulf of Mexico Gag assessment used an environmentally driven mortality parameter to account for red-tide events. Catches were assigned to the United States 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.

Fishery and ecosystem considerations in stock assessment reports were both qualitative and quantitative in nature. Qualitative elements were more common for diet, predation, and bycatch of other species. Quantitative approaches were more common for habitat, climate, and bycatch of the target species (Figure 1). For most of the categories, ecosystem interactions were most commonly incorporated as background. Habitat (68%) and predator (49%) interactions were most frequently included in background information. Bycatch of other species was mentioned in 30% of assessment reports and climate interactions were mentioned in 23% of the reports. Competition was rarely mentioned (5%), 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 only partly supported (Figure 2). Bycatch of the target species appeared more often in assessments for overfished species ($U = 2655$, $p = 0.002$).

Inclusion of climate interactions was more common for overfished stocks ($U = 2825$, $p = 0.004$). Overfished status did not contribute to the inclusion of bycatch of other species, habitat, predation, or diet in stock assessment reports.

Availability of diet data
We found support for our hypothesis that information considered in stock assessments may reflect availability of data (Figure 3). The number of assessment reports scoring 2 or higher for diet and predation was greater in regions that have a long-standing on-site stomach contents lab. Diet was included at a score of 2 or higher in 23 assessments from science centres from these two regions compared with only 2 from elsewhere ($U = 3706$, $p < 0.001$). Predation was included at a score of 2 or higher in 22 assessments from Alaska and Northeast compared with 4 from elsewhere ($U = 3849.5$, $p < 0.001$). Quantitative incorporation of predation in assessment models was rare (3 out of 206 assessments).

Target species life history
Of all of the fishery and ecosystem interactions that might be included in stock assessments, only habitat, diet, and predation showed any relationship to stock life history characteristics (Figure 4). Habitat interactions were included more frequently for small pelagic species, demersal species, and invertebrate species compared with large pelagic species (statistics presented in Supplementary Table S2). Assessment reports for demersal species included diet information at a level 2 significantly more often than assessment reports on large pelagic species (Supplementary Table S2). Over 50% of assessments for small pelagic species incorporated predation at least qualitatively (though predation was included quantitatively for only three of these species). The proportion of assessments scoring 2 or higher was significantly higher for small pelagic species compared with demersal or large pelagic species (Supplementary Table S2). Assessment reports for large pelagic fishes had the lowest levels of inclusion of ecosystem and fishery interactions across all types.
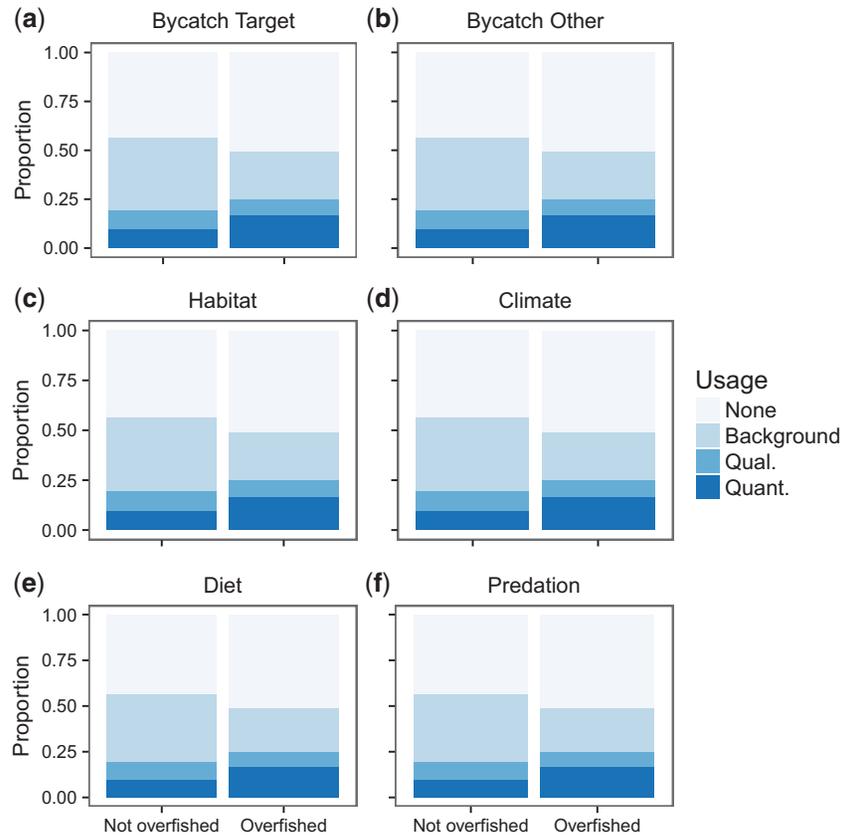
Figure 2. Stock assessments for species that were in an overfished status for some part of 2001–2005 had relatively higher scores on their assessments for accounting for bycatch of the target species and including climate interactions. Panels show scores by fishery or ecosystem interaction type: bycatch of the target species (a), bycatch of other species (b), habitat (c), climate (d), diet (e), and predation (f). Stacked bars show the proportion of scores within each category, with increased shading for higher scores (none = 0, background = 1, qualitative = 2, quantitative = 3).
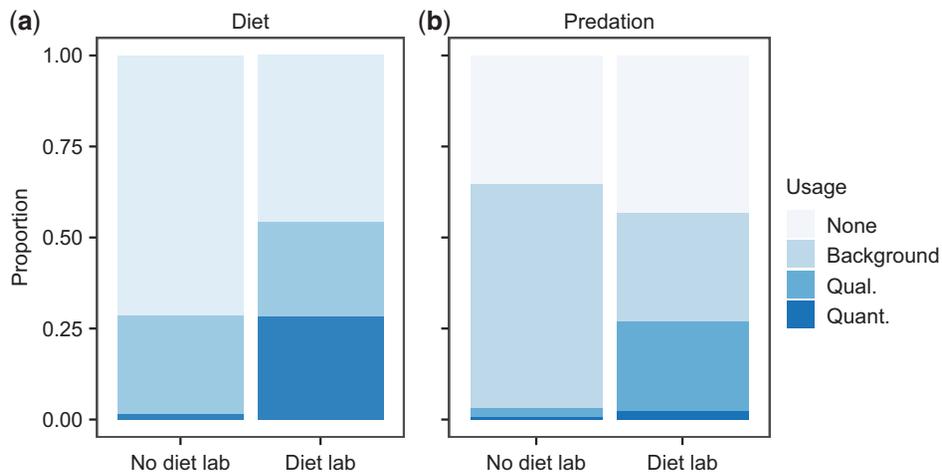

Figure 3. The incorporation of diets and predation into stock assessments may be explained by data availability. Bar plots show the proportion of assessments that received each score as a function of the co-occurrence of a stomach contents lab at the science centre where the stock assessment was done. Panels show scores by fishery or ecosystem interaction type: diet (a) and predation (b). Stacked bars show the proportion of scores within each category, with increased shading for higher scores (none = 0, background = 1, qualitative = 2, quantitative = 3).
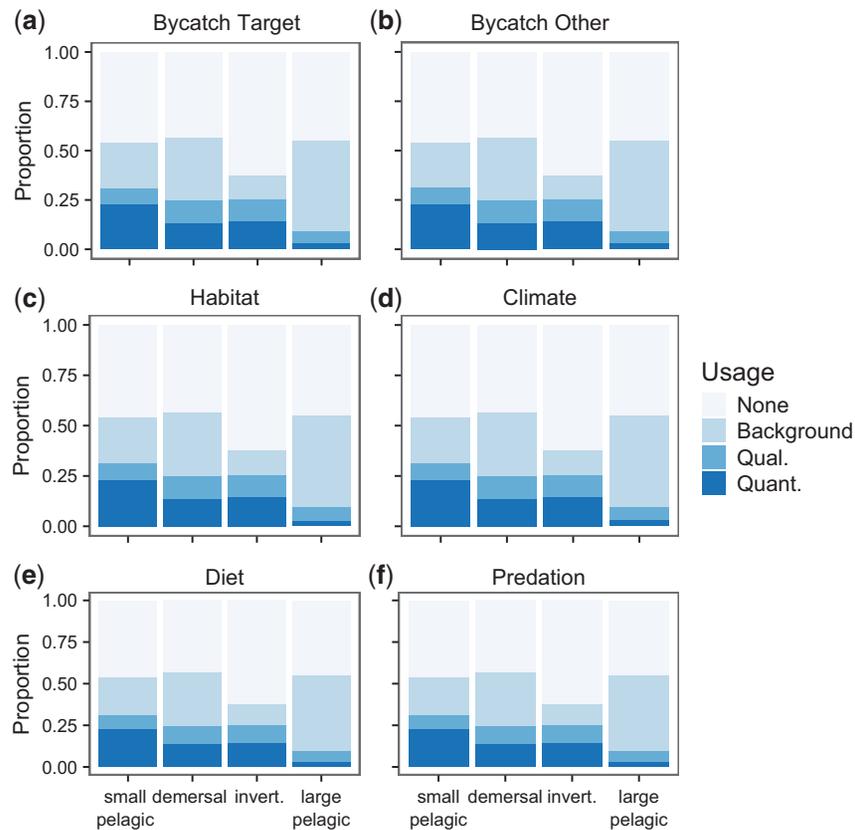
Figure 4. Assessment scores for six categories of fishery and ecosystem interactions, separated by the ecological type of the assessed species. Panels show scores by fishery or ecosystem interaction type: bycatch of the target species (a), bycatch of other species (b), habitat (c), climate (d), diet (e), and predation (f). Stacked bars show the proportion of scores within each category, with increased shading for higher scores (none = 0, background = 1, qualitative = 2, quantitative = 3).

Discussion

Our review of over 200 US stock assessments demonstrates more widespread inclusion of interactions among fisheries and with the ecosystem into the stock assessment process than previously reported. One quarter of the assessment models included at least one type of interaction between the assessed species and its ecosystem, especially physical drivers of habitat and climate. Diets and predation were less common, likely because of the paucity of detailed data on fish feeding in many areas of the United States. Together, these findings suggest that ecosystem factors are being considered in the stock assessment process, even if those factors are not specifically called out as EBFM. Moreover, when interactions are included quantitatively, they often involved the influence of habitat or environmental factors on catchability rather than trying to predict recruitment.

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 US 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 the United States for expanding assessments to include more ecosystem considerations, an important next step will be to develop more formal recommendations for how and when to include ecosystem data and relationships. Identifying where and when specific assessments and management advice could be improved by ecosystem information will be case specific. Including ecosystem information in assessment models does not always improve the accuracy or predictive capacity of models (Punt *et al.*, 2014). However, our findings on current uses of ecosystem information in assessments lead to some preliminary recommendations.

Overfished species may be a universally higher needs category of assessment report that could benefit from ecosystem information. Failure of overfished stocks to recover is in some cases tied to overoptimistic assessment results, which can be the result of unaccounted for shifts in productivity. We found support for our hypothesis that overfished status may contribute to greater inclusion of ecosystem interactions, particularly for interactions with other fisheries (bycatch) and oceanographic conditions. Beyond environmental information, identifying other potentially changing sources of mortality could improve the understanding of the

causes of population decline. Increasing predator abundance could lead to increasing trends in natural mortality, and documenting patterns of predation could lead to inferences about time-varying natural mortality, even if only qualitatively. 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 *et al.* 2013).

For species that are not overfished, one way to select assessments for potential inclusion of ecosystem information is a risk analysis and prioritization framework. This approach could triage species most likely to benefit from greater consideration of fishery and ecosystem interactions. For example, NOAA's recent Stock Assessment Improvement Plan (NOAA 2018) recommends a simple framework for scoring species based on their ecosystem importance (trophic linkages), recruitment variability (likelihood of being linked to environmental driver), and habitat associations. Higher ecosystem importance scores would be given for top predators and dominant forage species, identifying their potential outsized importance in food web dynamics (Heithaus *et al.*, 2008; Smith *et al.*, 2011). High recruitment variability or changes in average recruitment (especially coinciding with high steepness values) may imply that recruitment processes are linked to environmental conditions (Szuwalski *et al.*, 2015). Strong habitat associations might identify the potential for habitat covariates to improve how the observation process is modelled (e.g. catchability). These categories cover similar characteristics as the life history types we characterized, but in a more explicit process-oriented way (e.g. demersal species may have high or low recruitment variability, and some, but not all, have strong habitat associations). Implementing a qualitative scoring approach in each region may be useful to quickly screen species and identify the highest priority candidates for expanding the scope of assessments.

A second phase of a risk analysis approach would be to add "ecosystem considerations" sections to assessment reports for those species identified as having high scores in the areas identified above. These sections are already standard for all species in some regions (e.g. AFSC). An ecosystem considerations section could describe the qualities of the stock that make its assessment and management likely to benefit from the inclusion of ecosystem information and identify potential data sources or indicators that could be explored for inclusion in the assessment model or to qualitatively inform the structure of the model and/or discussions on setting annual catch levels. This second phase could also identify data needs where information would be useful but is not currently available. For example, a productive, abundant forage fish with high recruitment variability identifies a potential need for ecosystem information, but environmental data or information on predators and their diets may or may not be available in that region. A third phase of fitting assessment models with new covariates or datasets would then only be employed in the limited set of cases where a potential need was identified and data available to inform the models.

Governance and institutional challenges are identified as barriers to implementing EBFM (Hilborn *et al.*, 2005; Bundy *et al.*, 2008; Olsson *et al.*, 2008) and some of these may occur within the stock assessment process itself, limiting further inclusion of ecosystem considerations in assessment models. For example, scepticism about new approaches is inherent to the process of science and particularly to EBFM (Hilborn, 2011). Moreover, fisheries science has been strongly influenced by statistical inference, where the goal is frequently to describe observed data with as simple a model as possible (Burnham and Anderson, 1998; Kuparinen *et al.*, 2012). 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 are designed to 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. Research on creativity 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).

Consideration of 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 (e.g. Punt *et al.*, 2014) can provide some breathing room from the pressure associated with decisions on catch levels. Creating assessment teams that add scientists with expertise in ecological interactions, climate, habitat ecosystem to those with expertise in population dynamics will also encourage broader consideration of ecosystem information. Some regions have developed terms of reference for assessments that recommend consulting with or including ecosystem scientists (e.g. PFMC, 2016) or explicitly require ecosystem factors to be considered. For example, the 2014 butterfish assessment included the following term of reference (TOR): "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)." This TOR has two characteristics that we believe are helpful. First, it specifies a priority for inclusion of ecosystem information—in this case, "oceanographic and habitat data." Second, it urges quantitative integration of these factors into the stock assessment model, but ultimately leaves the decision to include these factors in the final model up to the assessment scientists and working group. Because inclusion of ecosystem information and the associated additional parameters does not always make for a more a robust and reliable assessment (Myers 1988, Punt *et al.*, 2014), the technical decision of whether it is best to include it should be left to the appropriate experts.

One productive approach to expanding the use of ecosystem information 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 ecosystem 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 influence 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 additional targets for including ecosystem information (Punt *et al.*, 2014; Patrick and Link, 2015b; e.g. Holsman *et al.*, 2016). For example, the control rule for Pacific sardine depends on temperature (PFMC, 2018). 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 qualitatively or quantitatively by ecosystem status (e.g. Zador *et al.* 2017) or other fishery or ecosystem considerations (Levin, 2014; Patrick and Link, 2015b).

Our analysis provides a summary of the current state of stock assessments in the United States 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. Successful examples of where fishery and ecosystem interactions have been included in stock assessment reports can inform future guidelines for prioritizing which assessments to target for further expansion and funding opportunities to improve data collection for EBFM.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Acknowledgements

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