EU-UK request on ecosystem considerations in the provision of single-stock advice for forage fish species

Service summary

The current ICES advice for forage fish species does include ecosystem effects on the assessed stocks through both variable predation mortality and qualitative ecosystem considerations.

ICES stock annexes clearly recognize the ecological significance of forage fish species such as sandeel, Norway pout, herring, and sprat as important food sources for seabirds, other fish species, and marine mammals. All the stock annexes document the implementation of natural mortality (M) and nearly all include predation mortality estimated from a multispecies model. The North Sea is one of very few regions worldwide where quantitatively based and often time-varying predation mortality is routinely included in forage species assessments. This is the primary way that predator–prey interactions are handled in assessments supporting advice. Other ecosystem considerations outlined for the studied stocks include description of conservation of spawning habitat (herring), potential habitat shifts (sprat), ecosystem drivers of larval survival (herring, sandeel), and the importance of maintaining diverse stock structure to promote population resilience (herring, sandeel). All of these are important to stock sustainability and therefore to sustaining the ecosystem services provided by forage stocks. Additional information is included on the bycatch of other fish species and protected species in forage fisheries for Norway pout and herring.

What is not conducted in the assessments is specific analysis of whether the forage fish biomass is kept high enough for specific predator requirements. Such an analysis would depend on the specifics of individual predator populations, and overall stock levels of forage fish are only part of the issue. Minke whales, for example, can move large distances to find food and are not limited by any local abundance, while nesting seabirds have a restricted feeding range. ICES advice on fishing opportunities is given at stock level and cannot function at the level of individual feeding grounds, which goes beyond the detail level of the stock assessment models. Therefore, a large part of the question of whether management is supporting ecosystem functions should occur at the level of national regulations, which is outside the scope of this technical service.

ICES advice framework distinguishes between stocks with relatively stable biomass for which advice is based on a target fishing mortality (herring) and those with variable biomass for which advice is based on an escapement strategy (sandeel, Norway pout, sprat). In both cases, the advice is consistent with the maximum sustainable yield approach, the aim of which is to have high stock sizes producing pretty good yields. It is possible that exploitation levels consistent with this framework would result in a high enough biomass required to sustain ecosystem services. However, it is also possible that the resulting biomasses may be too low. Although the ICES advice framework includes a provision to keep the stocks above a given precautionary level, there is no analysis of whether this precautionary level is sufficient to provide adequate food levels for individual predator populations. Such an analysis would need to take account of the interplay between ICES advice, national management measures, and the dynamics of a given predator population.

It is stressed that sandeel is currently undergoing a harvest control rule (HCR) evaluation process and that North Sea herring will undergo the same in 2024. Some of the conclusions of ICES advice could change once the new assessments and HCRs have been adopted. However, no big changes are expected in the *underlying concepts* (e.g. predation mortality and reference points rationale), in which case the conclusions would remain valid.

This request is responded to as a review of the ecosystem considerations in the provision of single-species advice for forage fish species. The response is based on two independent reviews based on the ICES most recent advice and the stock annexes for North Sea herring, Norway pout, sandeel (seven stocks), and sprat (two stocks) as well as supplementary scientific papers and reports.

Request

Request to ICES: (technical service request) Background: The EU and UK recognise the ecological significance of forage fish species such as sandeel, Norway pout, herring and sprat as an important food source for seabirds, other fish species and marine mammals. Their function and role should be considered when setting fishing opportunities, guided by the best available scientific advice.

Description of requested work: ICES is asked to clarify and describe how ecosystem considerations are factored in and applied in the provision of single stock advice for forage fish species. Particular reference should be made to the handling of predator-prey interactions and what considerations/provisions are made for the rebuilding of sensitive higher trophic level species such as certain seabirds.

Reviewer 1

This review concentrates on the ICES quota advice, which provides advice on overall fishing levels for each stock. The performance of a fishery and the ability of the exploited stock to provide ecosystem services rest both on the overall quota advice level and on local regulations, including closed areas, partially closed areas (by time and/or gear type), discard bans, and gear regulations. These local regulations are managed outside of ICES. Therefore, this review can only cover one pillar of the regimes which affect stock and ecosystem management. Furthermore, the review does not define exactly which ecosystem aspects are of particular interest.

The current ICES quota advice for the North Sea forage fish is set on the basis of maximum sustainable single-species yield, with an element of precautionarity to avoid going into recruitment overfishing given the uncertainties in the assessment. The advice therefore aims to keep the stock above a significantly higher level than the point at which recruitment is impaired. This is especially important for the escapement strategy stocks (sandeel, sprat, and Norway pout), where the stock can be fished down to the escapement biomass each year. It is possible that the buffer which gives this level of precautionarity is also sufficient to ensure that the ability of the stocks to sustain critical ecosystem services is also protected. However, the ability of the existing precautionary buffer to ensure ecosystem services has not been evaluated. No explicit provision is made in the current ICES quota advice to ensure the provision of such ecosystem services. As a result of the lack of evaluations, it is not possible to make a judgement as to whether or not the current quantitative quota advice for North Sea forage fish is able to sustain critical ecosystem services, specifically food availability for predators. The advice sheets do include information on ecosystem considerations, so there clearly is an element of ecosystem considerations in the advice. Furthermore, there is variable predation mortality, so predation-based ecosystem impacts on the stock being assessed are included explicitly in the assessments. What is not currently done is a qualitative analysis if the forage fish biomasses are kept high enough to provide adequate food supplies for particular predator populations. Such an analysis would be complex and would need to be conducted for specific predator populations, and may therefore be beyond the scope of an ICES quota advice. For nesting seabirds in particular, the local abundance of forage fish (especially sandeel) at specific times of the year is likely to matter more than the abundance in the North Sea as a whole (or even in a single management area). It is never going to be feasible for ICES to provide catch advice at a sufficiently fine scale to account for this local food requirement, and therefore the responsibility to ensure the provision of these local ecosystem services relies on national regulations (for example using permanent or timed closures or setting restricted quotas in given areas).

ICES quotas for sandeel, Norway pout, sprat, and herring in the North Sea are based on best available scientific assessments. If followed, this advice should ensure healthy levels of these stocks. For sandeel there is a state-of-the-art spatial management system, herring have a known stock structure (though the advice only partially accounts for this), sprat has high uncertainty over the stock structure, while for Norway pout an investigation concluded that detailed spatial management was not needed. Sandeel, sprat, and Norway pout are fished with escapement strategies (with maximum fishing levels termed F_{cap}), where the escapement biomass (biomass left after fishing, $B_{escapement}$) is tuned to protect against recruitment overfishing, raising the escapement buffer enough to account for uncertainties in the assessment. Herring use a standard ICES advice rule approach, with an F_{target} fishing mortality curtailed below some biomass level ($B_{trigger}$). The $B_{trigger}$ is designed to avoid the stock approaching recruitment overfishing. As mentioned above, these buffers (either via $B_{escapement}$ with a maximum F_{cap} or $B_{trigger}$) may or may not be high enough to ensure the provision of the ecosystem services associated with a given stock and a given predator. For sandeel in particular, the spatial structure of the management advice is likely sufficient to ensure that local depletions can be reversed by recruitment from elsewhere in the management region, whereas lesser levels of such protection for the herring components is a potential issue.

Introduction

The terms of reference for this review are for ICES to “clarify and describe how ecosystem considerations are factored in and applied in the provision of single stock advice for forage fish species”. There are two points to note here. The first is that the time allowed for the review is rather short, and the focus will be on sandeel in the North Sea, although other forage stocks in and around the North Sea (Norway pout, herring, and sprat) will also be touched on. A more fundamental issue is that the advice from ICES only covers part of the overall fisheries management system. ICES typically advises on overall catch levels. There are many other parts of the management which can matter as much (sometimes more) than the overall catch advice: factors such as permanent or temporary closures, gear restriction and regulation, minimum landing size and discard bans. Together these can (depending on the actual regulations) provide a high level of protection which is not apparent in the overall catch advice. Conversely advice which maintains a high overall biomass could still result in local depletion depending on other management measures. These measures are typically handled at the national level rather than through ICES and are therefore not covered in the terms of reference for this review, nor are the full details of the regulations readily accessible to this reviewer. In addition, it needs to be noted that North Sea sandeel is currently undergoing a revision process within ICES, with a benchmark to revise the assessment model and a management strategy evaluation (MSE) process to evaluate the HCRs. Herring will undergo a similar HCR revision in 2024. This review focuses on the existing advice, but this will obviously change in the near future.

The review is also not able to come to any judgement as to the degree of importance of sandeel or other forage fish to particular bird species and colonies. In general food availability will only be one of many multiple pressures on nesting bird colonies, and while there is a general perception that food availability is important, there is a lack of comprehensive data for many localities. Site- and species-specific studies would be required to ascertain what food supply is required in each case.

One further point to bear in mind is that stock assessment modelling is, of necessity, conducted at a large spatial scale. For herring, sprat, and Norway pout this scale is that of the entire North Sea. For sandeel there is spatial structure in the assessment, with the greater North Sea being split into seven areas. This represents one of the most detailed spatial structures of any assessment. However, the availability of prey to predators may be at a smaller scale. While some predators (e.g. minke whales) have a high degree of mobility and can forage over large areas, others (especially nesting seabirds) have a strictly limited foraging range. This means that, for some predators, it is the local concentration of prey that matters, at a scale below any feasible stock assessment.

Sandeel

Overview

Sandeel is a, perhaps the key forage species in the North Sea for many predators (Engelhard *et al*., 2014). It is critical to note that it may not be the total abundance of sandeel in the North Sea that is a driver for predator populations but rather the local abundance. Nesting seabirds in particular will be restricted in their feeding range. Engelhard *et al*. (2014) note a number of seabird species where there is evidence that breeding success is correlated with (local) sandeel abundance. Sandeel are also important prey for seals and minke whales, however, these species can forage over a wider area than nesting seabirds. Minke whales in particular are able to forage over large distances and are unlikely to be seriously affected by local depletion of a particular prey, while seals are likely intermediate between wide-ranging Minkes and locally dependent seabirds. Fish are also important predators on sandeel, but the evidence for their dependence on sandeel is more limited.

Sandeel are small fish, associated with the seabed and living in burrows in sand and gravel banks in clean, well-oxygenated water. The fish do not move far from the burrows, feeding and breeding in the immediate area. Sandeel are restricted to burrows in mud-free banks (as little as 2% fine particles can exclude sandeel, [Wright *et al*., 2000]), which produces a patchy distribution. In addition, larval abundance has been shown to the correlated with zooplankton abundance (Frederiksen *et al*., 2005), suggesting a localized bottom-up control on recruitment success. As a result, there is no "North Sea" population of sandeel, rather there is a network of separate grounds, with poorly unquantified links between them. An additional consequence of the requirement for grounds with clean water and free of small sediment means that sandeel are potentially vulnerable to non-fisheries pressures (e.g. influxes of fine sediment or oil pollution). The fish overwinter between August and April in their burrows, meaning that the fishery is concentrated in the summer months.

The sandeel stock annex does a good job of providing the fisheries and ecological background to the sandeel stocks. Overall, the assessment model and HCR seem appropriate, but this is under a process of review and is likely to be revised. One concern would be the degree to which the fishing has been restructured, and it is to be hoped that the revision will investigate the impacts of this on the model. The assessment is to be commended on the fact that considerable effort has been made to split the North Sea into areas based on larval transport, ensuring that any particular location within an area can repopulate from recruitment elsewhere in the area. The management is based on an escapement strategy, where a $B_{escapement}$ value is chosen for the biomass remaining after fishing to ensure full reproductive capacity in each area (accounting for the uncertainties in the assessment). This is an appropriate strategy for a short-lived species. In general, therefore the overall fishing advice is appropriate to conserve the stock levels at a large spatial scale. However, the $B_{escapement}$ has not been set to account for the ecosystem services that this fish provide, and it is therefore not possible to make any judgement as to the degree to which the overall fishing level impacts on these ecosystem services. The ICES advice does not in itself provide protection to locally important sites at a smaller scale than the assessment areas. The overall quota advice therefore needs to be part of an overall management regime to ensure that local food availability is preserved.

Fishery

The fishery is regulated by a TAC by area (since 2011), based on an escapement strategy. This allows a fixed amount of fish to survive to breed ($B_{escapement}$) and then sets a quota based on the biomass above that level, accounting for uncertainty in the assessment. The $B_{escapement}$ for each area is set based on the recruitment function, providing protection against recruitment impairment and stock collapse. The existing $B_{escapement}$ is not set based on the needs of predators and may or may not be appropriate for ensuring a good provision of ecosystem services. Such analysis is possible and has occurred as part of the management advice in other stocks (e.g. Atlantic menhaden and New England herring) but is not in the current management regime for North Sea sandeel.

In addition to the concentration of the fishing into the summer months, there are concentrated fishing grounds which vary somewhat between years. There has been a rapid consolidation of the fishing industry to use fewer, larger vessels over the last two decades. The individual assessment texts note that this change may have consequences for the accuracy of the assessment. The fishery has been managed by a TAC by area (see below for details) since 2011. In addition to an overall quota, there are technical regulations on permitted bycatch of non-target species (with gear regulations to reduce the bycatch), and a closed season for Danish vessels (which take approximately ¾ of the catch). There are also several closed areas, giving high levels of protection for specific areas (one on the Dogger Bank and one east of Scotland).

Assessment and advice

A significant amount of work has been conducted in attempting to split the individual sandeel grounds into different assessment areas. The assessments are still, of necessity, at a coarser scale than the individual sandeel habitats, but the ICES structure does attempt to match the main distribution of the sandeel grounds and specifically the larval transport. Two different methods have been used in the ICES division of areas, the biophysical model of larval transport of Christensen *et al*. (2008) was used in WKSAN (2010) and revised at the 2016 WKSAND benchmark using an alternative hydrodynamic model; HBM-ERGOM (Christensen *et al*., 2008). Each grid cell was examined to determine where it receives larvae from, and this information was used to divide the greater North Sea into seven assessment areas (with one split into two subareas). By using larval connectivity to divide the grounds in this way, there is a degree of ability to rebuild locally depleted stocks in any one location, providing that assessment area as a whole remains in good status. Larvae are assumed to be transported within the assessment area and can thus re-colonize any depleted section.

As always with attempting to assign fixed boundaries to a complex natural system there will be different possible ways of assigning boundaries. In some areas the distinction is clear, with both the hydrographic modelling and analysis of disparate stock trends indicating distinct subunits. In others there is more connectivity. However, overall the split into areas appears to be well justified.

It should be noted that this ability to reverse small-scale local depletion does not prevent that depletion from occurring. The recovery should occur within a year or two (given the short lifespan of the fish), but there could still be short-term impacts on food availability.

This review, based only available documents, cannot attempt to assess the quality of the assessment in the way that an interactive ICES benchmark would do. In any case, there is an ongoing benchmark process so any such assessment would be out of date for next year’s assessment. From an examination of the stock annex the assessment procedure appears to be appropriate given the nature of the stock and data availability, and my main concern would be the use of interannual

annual transfers rather than in the assessment itself. The assessment is based on a benchmark (full scale model revision) in 2016 and an interbenchmark (minor model revision) in 2020. Most areas use the SMS model, which is a multispecies model used to provide mortality estimates for the North Sea and Baltic stock assessments although it is run in single-species mode for this assessment. Areas 5 (Northeast) and 6 (Skagerrak and Kattegat) do not have assessments – area 5 has a zero quota based on low survey abundances, and area 6 has a low quota based on an ICES data-limited approach.

The tuning Is based on a survey, catch data, and a CPUE index. Although CPUE indices are not ideal (especially given the changes in the fleet), the use of CPUE series is common in the absence of other tuning data. It should also be noted that the sandeel stock annexes state that the "other issues" section was due to be updated at the 2017 assessment (in the ICES HAWG working group), but that this section is blank.

Where approximations were needed (for example in estimating the spatial distribution of catches in the early time-series) the method chosen appears reasonable. One key weakness is that the catch sampling appears to be inadequate in some of the areas (although note that this is based on the stock annex which lists sample size up to 2015, so this may or may not still be relevant).

The actual assessment uses variable natural mortality, based on recommendations from ICES multispecies WGSAM working group. There are clear differences in trends in the south and north, with an overall increasing mortality over time in the north.

One potential concern with the HCR is that the stock advice sheet for area 1 mentions interannual quota transfers. These are typical in F_{MSY} managed stocks, however they may be less appropriate for escapement strategy fisheries, where the stock can vary rapidly between years. The sandeel fishery is concentrated on a single year class (age one), and the appropriate quota may therefore vary considerably between years. This raises the possibility that transferring a quota from a high stock year to a low stock year could result in overfishing.

Norway pout

Norway pout is a small pelagic, predominantly found in the northern North Sea. In contrast to sandeel, ICES considers that there is no evidence to subdivide the stock and gives advice for the North Sea as a whole. This conclusion is based on extensive research rather than simply being a default in the absence of evidence. While the sandeel distribution is constrained by the requirement for mud-free shallow banks, the Norway pout distribution is depth limited, concentrating in depths of 150 m. The stock is highly variable, with strong variations in recruitment and the fish considered to spawn only once, mostly at age 2. Where the sandeel stock annex indicated significant effort to quantify the impacts of sandeel as a food source, the Norway pout stock annex concentrates on bycatch of fish as the main ecosystem impact. Norway pout is listed as being an important food source for predatory fish (largely gadids) rather than seabirds. Consequently, it can be expected that while the overall stock biomass can have implications for predators, the local abundance should be less significant. Furthermore, the high natural variability will limit the ability of predators to depend on Norway pout stock levels. A study by Nielsen *et al*. (2016) fits with this, indicating a moderate positive correlation between Norway pout and SSB of cod, but not for other predator biomasses. The existing stock annex bases the $B_{escapement}$ on protecting stock recruitment but notes that a higher level could be considered in the future in order to ensure providing sufficient food for predators. It would seem likely that Norway pout forms an important part of the overall food supply for predatory fish in the North Sea, without being an individually critical component. It is therefore important to protect the Norway pout biomass alongside other food sources in the North Sea.

The main catches are a directed fishery and bycatch in the blue whiting fishery, with the fish being used for fish oil and fishmeal. Sorting grids are in use to minimize the bycatch of large fish, but small gadoids are caught alongside the Norway pout. The stock annex indicates low rates of bycatch of most larger species and a decline over time.

For Norway pout, there is no clear spatial structure of the stock, so the management at a single unit is appropriate. Fishing is currently based on $B_{escapement}$ to protect recruitment, which may or may not also protect the role as a food source. However, in contrast to sandeel there is a less clear-cut link between biomass and predator success, with only moderate association with biomass of cod. The stock is highly variable, and therefore the predators cannot rely on Norway pout as key food source. It is therefore likely important to protect Norway pout as part of an overall food complex, rather than specifically focussing on this species.

Sprat

Sprat is another important food for many predators in the North Sea, with the multispecies SMS model estimating significant consumption for both fish (notably mackerel, whiting, and cod) and seabirds. In contrast to Norway pout the sprat are most common in the south of the North Sea and in adjacent waters. Sprat is fished with an escapement rule for sandeel and Norway pout, but with an upper bound on fishing mortality (F_{cap}). The sprat is assessed at the level of the greater North Sea. The distribution of the fish In Q3 is split into three distinct regions: in the south and central North Sea, in between Denmark and Sweden, and the northeast coast of Scotland. It is not clear from the documents provided if the treatment of these components as a single stock is reasonable. The assessment itself is a standard age-structured stock assessment, using the SMS model. The model accounts for variable predation mortality. A separate advice is given for the English Channel, although again the stock structure is not well known. Due to more limited data there is data-limited approach to giving advice, based on trends in a biomass index. There is a note in the stock annex that the distribution of shoals is variable, which would mean that there are impacts on food supply for site limited predators (e.g. seabirds) caused by variable distribution, over and above any overall stock level issues.

Herring

Herring is another important food species for many predators. Assessment for the North Sea herring is complicated by the complex dynamics, with different spawning sites and times giving different stock components, which nevertheless mix in the feeding areas. Given that there is evidence of separation into at least four components, it is important that management can protect each of these components. Each of the different components has risen and fallen with the overall stock biomass, but this does not in itself guarantee that the protection of each component, and there are spawning grounds which have not been recolonized after the herring collapse in the 1970s.

The assessment uses a state-space model, using a specialized version of the SAM model. The assessment model accounts for variable predation mortality (from the SMS model as is common in the North Sea). The model is a single-stock model, and advice is given for the combined stock. There is a specific region to protect herring from the western Baltic, and several subquotas to protect one substock (the Downs spawning component). However, the fact the herring from different components mix in the central North Sea makes protecting individual components difficult. The advice recommends that this level of substock specific protection should be revised at the next benchmark.

The stock annex notes briefly that herring are both an important food source, and a predator on fish early life stages. However, this information is not developed further or incorporated into the advice. The stock annex also discusses the bycatch of marine mammals and seabirds, concluding that there is no evidence for bycatch at levels which could have population level impacts. This is rather outside the scope of the review, but it is worth noting that there are ecosystem impacts beyond the provision of food.

Conclusions

Although all of the stock assessments have weakness, mostly to do with data availability, all are peer-reviewed and represent best available scientific information. For sandeel, the assessment and advice track area structure at the level at which larvae are distributed and therefore able to recolonize any locally depleted area. For Norway pout a detailed investigation was conducted and concluded that such detail was not needed. Sprat and herring both show some degree of stock structure which is not accounted fully accounted for in the assessment and advice. This represents a potential weakness, where overall biomass could be maintained while still harming one or more subcomponents. With the possible exception of the spawning components for herring, the assessments do seem to give best available scientific advice for single-species management based on good yield and low risk of stock collapse. The question then arises of whether this sufficient to also provide a basis for provision of ecosystem services.

The assessments do include ecosystem considerations in two places. Natural mortality includes predation estimates, allowing the mortality to vary as appropriate. The advice sheets include quantitative ecosystem considerations. What is not conducted is specific analysis of if the forage fish biomass is kept high enough for specific predator requirements. Such an analysis is not trivial; it would depend on the specifics of individual predator populations rather than being able to make a generic "good/bad" determination.

Ideally fishing at maximum sustainable yield levels will result in a high stock size producing good yield in all years. However, due to natural variability and assessment uncertainties, the stocks will vary. All of ICES advice therefore aims not only to produce good yield but also to maintain the stock above B_{lim}, the point at which recruitment impairment occurs. Because all assessments are uncertain, the advice actually includes a buffer level to maintain the stock at a higher level than the actual point at which recruitment is reduced. Stocks can be divided into ones with relatively stable biomass which are fished with a target fishing mortality (herring) and those fished with an escapement strategy (sandeel, Norway pout, sprat). For herring, there is a F_{MSY} approach, which should (on average) keep the stock in the region of B_{MSY} (the biomass which gives the highest yield), and the precautionary element should keep the stock above some lower biomass. It would be hoped that the stocks should be near B_{MSY} for most of the time, with the precautionary part only occasionally becoming important – but the occasional drops may be the most significant for ecosystem services. For the escapement strategy stocks (sandeel and Norway point) the stock is fished down to the escapement biomass (B_{lim} plus precautionary buffer) each year. In this case, the biomass of fish left after the fishery is dependent on the size of the precautionary buffer in $B_{escapement}$. Stocks with $B_{escapement}$ and an Fcap level (e.g. sprat) represent a hybrid of the two approaches.

It is possible that these levels (the $B_{MSY}/B_{trigger}$ combination or the $B_{escapement}$ level with or without an F_{cap}) are also sufficient to provide a high enough biomass-required ecosystem services. However, it is also possible that the resulting biomasses may be too low for one or more of the stocks covered here. Because ICES has not included these considerations in the analysis and provision of advice, it is not possible to make this evaluation from the available information. As mentioned above, it is unlikely that there would be a single answer here, rather there would need to be detailed analysis for any given predator population.

One potential issue with the management (especially of sandeel) is the potential to transfer quota between years. With highly variable stocks, this could result in transfers from a high stock year into a low stock year, resulting in overfishing. Without an evaluation of the risks of such interannual transfers it is not possible to say that such a practice is precautionary.

Overall stock levels of forage fish are only part of the issue, local abundance will matter for some predators. Minke whales, for example, can move large distances to find food and are not limited by local abundance, while nesting seabirds have a restricted feeding range. ICES quota advice cannot function at the level of individual feeding grounds, this level of detail goes beyond the ability of the stock assessment models. Therefore, a large part of the question of whether management is supporting ecosystem functions will occur at the level of national regulations, which is outside the scope of this review. There are several closed sandeel areas, and this is one possible example of measures to provide ecosystem services that sits alongside the overall quota. However, it would make sense to evaluate the degree to which such closures could be targeted to maximize the benefits while minimizing the costs.

Reviewer 2

It should be noted that there may be ecosystem considerations factored into advice and management that are described outside the review materials I was provided. For example, management measures such as seasonal or permanent fishery restriction or exclusion areas that may have been designed outside the assessment process cannot be included in this review if they were not mentioned in the stock annexes. It was assumed that the closed area included on maps in advice sheets for sandeel in assessment area 4 were implemented to mitigate potential impacts of fishery removals on predators based on descriptions in Searle *et al*. (2023). No information regarding the closure within sandeel Area 1 was available. These closed areas were not mentioned in either of the sandeel assessment stock annexes in those areas, likely because assessments are at the broader spatial level. Similarly, if any ICES MSE work was conducted to evaluate performance of management advice for ecosystem objectives beyond single-stock management, these were not accessible. Finally, it was noted that sandeel work is ongoing at present; however, no interim findings from that work that may address this request were available at present.

In addition, the request lacks specification of objectives for ecosystem considerations, predator–prey interactions (which ones? where and when?) and predator rebuilding (which predators, what are the rebuilding targets, what is the current predator population status, how much do they depend on the prey, what other factors affect predators?). Lacking these specifications, specific advice cannot be developed. Therefore, I will consider any mention of predator–prey interactions, predator considerations, or ecosystem considerations in general to be relevant to the request.

Given those caveats, two main points from the stock annexes related to the request can be drawn. First, all of the stock annexes include an “Ecosystem aspects” section with descriptive ecosystem considerations relevant to each stock, nearly all focused on predator–prey interactions. Based on this review, the stock annexes clearly recognize the ecological significance of forage fish species such as sandeel, Norway pout, herring, and sprat as important food sources for seabirds, other fish species, and marine mammals. Second, all of the stock annexes document the implementation of natural mortality (M) and nearly all include predation mortality estimated from a multispecies model. The North Sea is one of very few regions worldwide where quantitatively based and often time varying predation mortality is routinely included in forage species assessments. This is the primary way that predator–prey interactions are handled in assessments supporting advice. Each of these points are expanded upon in the below, concluding with other considerations.

Ecosystem aspects

The inclusion of a standardized “Ecosystem aspects” section across all of the stock annexes provides an opportunity to identify key predators and prey of each stock along with other ecosystem relationships or observations. All of the annexes with the exception of English Channel sprat discuss predator–prey interactions with the assessed stock. Predation mortality (discussed in the section below) is the primary ecosystem aspect that is quantitatively included in the assessments at present.

Other ecosystem considerations outlined for the stocks include descriptions of conservation of spawning habitat (herring), potential habitat shifts (sprat), ecosystem drivers of larval survival (herring, sandeel), and the importance of maintaining diverse stock structure to resilience (herring, sandeel). All of these are important to stock sustainability and therefore to sustaining ecosystem services provided by forage stocks. Additional information is included on bycatch of other fish species and protected species in forage fisheries for Norway pout and herring. However, since the request focuses on predator–prey interactions, I highlight those here.

Spatial distributions of forage stocks, fisheries, and predators define interactions but can be difficult to account for in spatially aggregated stock assessments. Sandeel assessment areas are based on the ecosystem consideration of larval transport and retention from a biophysical model and multiple other studies of spatially distinct size structure and condition. Spatial distribution of different sandeel predators is also described in relation to the changing distribution of the fishery. The sandeel assessment annexes include a detailed table of 25 predators, with information on whether they are immobile, immobile during breeding season, or mobile predators, the average percent of sandeel in diet, and documented impacts of low forage abundance on each predator. Seabirds are the most sensitive predators to changes in sandeel abundance, with terns and kittiwakes the most sensitive among seabirds.

The herring stock annex includes an ecosystem considerations section. It acknowledges a potential trade-off between fishery removals of herring and herring remaining in the sea to provide other ecosystem services. Literature is cited on replacement of herring by sandeel as prey when herring are low; interactions between herring and other fished stocks, with low herring biomass potentially limiting recovery of predator fish; and predators impacting herring populations. It is noted that GES may require a threshold level of herring biomass.

The Norway pout annex includes analyses investigating relationships of pout to predators along with hypotheses for species interactions between Norway pout, cod, whiting, haddock, saithe, and herring cited in peer-reviewed literature. Relationships between Norway pout and predator SSB were evaluated. Analyses attempting to relate mean weight at age for predators to Norway pout SSB found no relationship. Spatial and seasonal predation mortality derived from stomachs were evaluated. Herring predation on pout larvae is discussed. A relationship between Norway pout and saithe growth is discussed, as well as food limitation. Relationships between cod, pout, and temperature are also discussed.

Predation mortality

All of the stock annexes document how natural mortality (M) is implemented. This is an important parameter in any stock assessment and is often uninformed by data. North Sea forage assessments are exceptional in that M is informed by data on predator–prey interactions integrated within a multispecies assessment, North Sea SMS (ICES, 2021). Almost all of the reviewed assessment annexes *in some way* use M estimated from this multispecies model, with the exception of Norway pout, where M is estimated from survey information, and sandeel in area 6, which is outside the North Sea SMS model domain.

The value of M used in an assessment influences estimation of important outputs including biomass and recruitment, and therefore reference points based on the relationship between biomass and recruitment. Including quantitative information on predation mortality for forage species better accounts for both the level of M and potential changes in M over time. This should give a more complete picture of trends and status for the forage stock. The North Sea is one of very few regions worldwide where detailed time varying predation mortality is routinely included in forage species assessments.

Sandeel assessments in areas 1 and 3 use age specific three-year moving averages of North Sea SMS southern sandeel M estimates. The North Sea sprat assessment uses North Sea SMS sprat M estimates directly. The herring assessment uses smoothed and scaled time varying M estimates from North Sea SMS. Sandeel assessments in other areas use age specific M that is constant over time based on North Sea SMS. The Norway pout assessment analyses survey data to derive age-specific M estimates.

Ecosystem considerations are factored into North Sea stock assessments by including predation mortality estimated from multispecies models or other sources. This better accounts for mortality on managed stocks (forage and otherwise) but does not account for prey effects on predators. As noted in the Norway pout stock annex, predation mortality is not a measure of importance of the forage species in the predator's diet. Including predation mortality is not intended to evaluate the amount of prey needed by predators, only the amount removed by predators.

Other ecosystem considerations

Ecosystem considerations might be included within stock biomass reference points, as suggested in two of the stock annexes reviewed (herring and Norway pout). Fishery management maintaining stock biomass above a threshold where recruitment is impaired is the first step towards maintaining ecosystem services. Without this baseline level of management, stocks, their regional ecosystems, and dependent human communities tend to fare poorly (Hilborn *et al*., 2020). However, in regions with well-developed science and management such as northern Europe, it is possible to more directly address potential trade-offs between and among fleets and other ecosystem components.

Single-stock advice by definition rarely addresses rebuilding or maintenance of populations outside the assessment. However, there are examples of both HCRs and reference points developed for forage fish that address predator objectives (e.g. Deroba *et al*., 2018; Chagaris *et al*., 2020). These were not developed within an operational stock assessment advice process such as the examples reviewed for ICES, but rather in coordination with managers and stakeholder-driven management objectives.

Several excellent discussions are contained within stock annexes of how one might move forward with further quantitative integration of predator–prey considerations within advice, given management objectives. Both the Norway pout and herring assessment annexes mention the possibility of estimating a minimum level of forage to support predators and or ecosystem services. Estimation of this level would require analyses well beyond the scope of a typical stock assessment, as described below.

The Norway pout assessment ecosystem aspects section raises the excellent points that I would like to highlight here: for a comprehensive understanding of predator–prey interactions and resulting trade-offs in management, looking at individual forage species provides at best an incomplete picture. Reviewing the ecosystem aspects along with assessment results across all of these stocks has given me a better sense of overall forage and predator distributions in the North Sea. Evaluation across combined forage species and predators and including fisheries for all of the managed species (predators and prey) would be most likely to provide the best information for understanding impacts to sensitive predator species. Further, other factors affecting the sensitive predator species would need to be considered as well (e.g. high mortality on sensitive predators will negate any potential population benefits arising from a stable forage base). Clear specification of management objectives could identify which ecosystem drivers, forage species, and predators need to be assessed within a quantitative framework. A MICE model (Plagányi *et al*., 2014; Collie *et al*., 2016) would be best suited for this rather than a stock assessment.

Aside from the quantitative inclusion of predation mortality within M in assessments, it is difficult to tell whether/how other ecosystem considerations mentioned in stock annexes translate into advice. Conversely, some management measures are described in stock annexes that may have been designed to address ecosystem considerations, but the objectives of the measures are not described in the annex.

For example, sandeel Area 3 management in Norwegian waters includes areas closed to fishing until survey biomass is estimated at above 20 000 tonnes (not an official threshold), subareas within each open area are closed to prevent overexploitation, surveys and sampling from the fishery minimizes catch of age 0 fish, and a later season start is intended to preserve high condition, while an early end date is used to prevent catch of age 0 fish. The fishery starts assuming low recruitment, with TAC adjusted during season to reflect in-season survey results. These time and area in-season adjustments based on surveys may moderate any fishery interactions with predation, even if they were not specifically designed to do so.

However, supplemental material demonstrates that management measures designed to reduce fishery impacts on predators may not result in expected improvements to predator stock status. Searle *et al*. (2023) compare seabird colonies in the sandeel fishery closed area and open areas along the Scottish and English coasts of the North Sea. Kittiwake breeding success was poor during the sandeel fishery and improved during the 20-year closure, while three other species of seabirds in the same region did not have negative impacts from the fishery nor positive results from the closure. This highlights the complexities of predator–prey relationships and ecosystem considerations. Continued development of quantitative ecosystem considerations in advice products will likely require this level of detailed analysis, and analysis of trade-offs for different fishery scenarios will be essential to support informed decisions.

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