Evaluating forage fisheries and their impacts on marine predators: results and recommendations for management from the Lenfest Forage Fish Task Force

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ABSTRACT

Forage fish are small to medium-sized species that include anchovies, herring, menhaden, sardines, and, in some ecosystem models, krill. Direct catch of forage fish makes up more than one-third of the world's marine fish catch and has contributed to the collapse of some forage fish populations. In the most comprehensive global analysis of forage fish management to date, the Lenfest Forage Fish Task Force found that conventional management can be risky for forage fish because it does not adequately account for their wide population swings and high catchability. It also fails to capture the critical role of forage fish as food for marine mammals, seabirds, and commercially important fish such as tuna, salmon, and cod. The report recommends cutting catch rates in half relative to conventional fisheries management targets and doubling the minimum biomass of forage fish that must be left in the water. Even more stringent measures are advised when important biological information is missing. Although the Task Force took a broad view of the role of forage species in marine ecosystems worldwide and did not focus on cetaceans, many of the findings, model results, and management recommendations are directly relevant to IWC's continued effort to promote ecosystem-based management policies.

This paper is an abridged version of the Lenfest Forage Fish Task Force Report, "Little Fish, Big Impact" and its Appendices, available on the web at http://www.lenfestocean.org/foragefish. (Pikitch et al *2011). Specific chapter references for that report are noted as LFFTF Chapter X. Some additional comments and references pertaining to cetaceans have been added by the presenting author.*

INTRODUCTION

Forage fisheries target small to medium-sized fish species that include anchovies, herring, menhaden, and sardines, as well as krill. Direct catch of forage fish makes up more than one-third of the world's marine fish catch and has contributed to the collapse of some forage fish populations. With the support of the Lenfest Ocean Program, the Institute for Ocean Conservation Science at Stony Brook University convened the Lenfest Forage Fish Task Force, a panel of thirteen preeminent marine and fisheries scientists from around the world. The primary purpose of assembling the Lenfest Forage Fish Task Force (LFFTF) was to provide practical, science-based advice for the management of forage fishes through an ecosystem-based fisheries management approach. Our task force conducted original research and synthesis to advance scientific understanding and to inform our management recommendations. While the relationships between cetaceans and forage species and the impacts of forage fisheries on whales was not an explicit objective of our analyses, cetaceans were key forage fish predators in many of the models we examined, and our meta-analyses of ecosystem models (Ecopath and Ecopath-with-EcoSim, EwE) also included krill as a forage species. Our general results and recommendations apply to fisheries that indirectly impact whales in all marine ecosystems.

Forage fish are the foundation prey of marine food webs in many ecosystems. They are the primary food source for many marine mammals, seabirds, and larger fish. Feeding in large part on plankton, forage fish transfer energy from the pelagic realm to larger predators, performing a crucial ecological function in the marine environment (Figure 1). Forage fish play this intermediate role in many marine ecosystems, including estuaries, shelf seas, and upwelling oceanic systems from the tropics to the Earth's poles. For some predators, forage fish constitute the majority of prey upon which they depend. Such highly dependent species may be iconic or ecologically important, while others may be commercially or recreationally valuable species. In some cases, highly dependent predators may even include threatened or endangered species, including cetaceans.

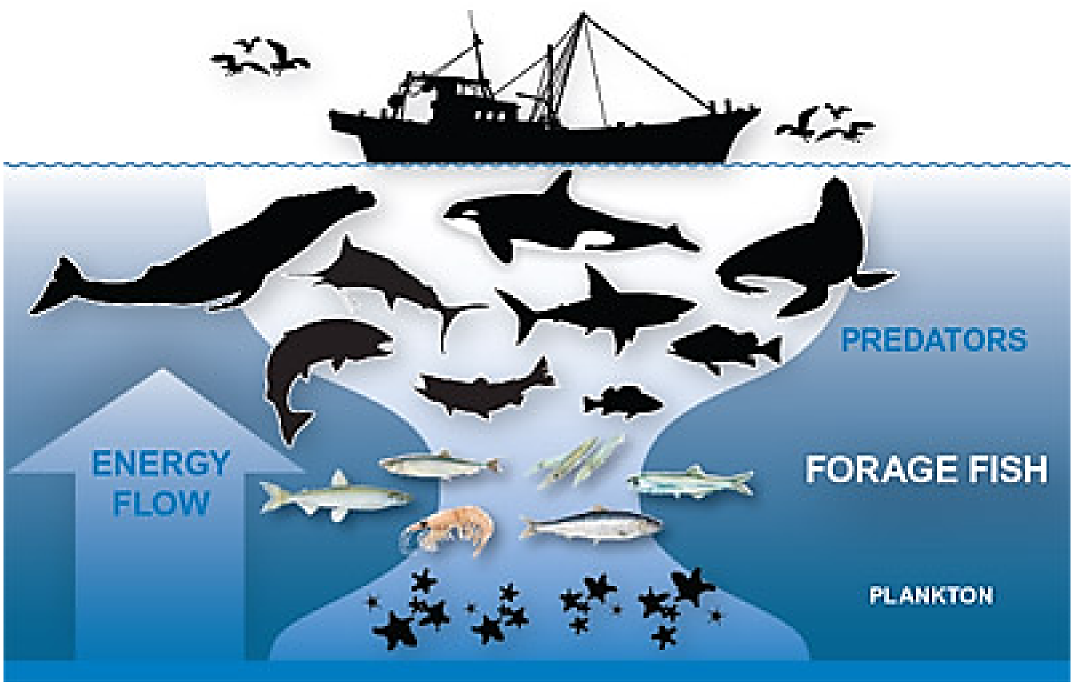

Figure 1. General schematic of the position of forage species in marine food webs. From Pew Environment Group, http://www.pewenvironment.org/news-room/other-resources/little-fish-big-deal-see-what-we-mean-by-forage-fish-85899378401

A reduction in available forage fish—due to fishing, environmental conditions, or a combination of both—can have direct and lasting impacts and can fundamentally change the structure and functioning of an ecosystem. The magnitude of this impact depends strongly on the number of predator species that rely on those species as their primary prey. We restricted our analyses to forage species that are plankton feeders and serve the key role of transferring energy from the plankton to higher trophic levels throughout their life history, including herring, smelt, sardine, anchovy, sandlance, capelin, and large euphausids (krill). We did not include squid or juvenile fishes that serve the role of foundation prey in many marine ecosystems, due to the multiple trophic roles that these animals play (but see Hunsicker *et al.* 2010).

Conventional wisdom has suggested that forage fish populations are resilient to fishing-induced and environmental changes because they are functionally more like weeds than trees in marine systems. That is, they are capable of reproducing (or replenishing themselves) early in life and their biomass can rise to high levels. Some populations have rebounded even after rapid and large declines; however, a recent study (Pinsky *et al*. 2011) has demonstrated that small, low trophic-level fish species are just as likely to collapse as long-lived, upper trophic-level species when fished at unsustainable levels.

The resilience of some forage fish populations may have been overestimated and the effects that their depletion may have on other species have generally been ignored. Much of the scientific research and management advice has centered on maintaining the forage population alone, without explicitly addressing the ecosystem impacts that may result from their removal. Even in cases where forage fish are well-managed from a single-species perspective (i.e. the stock is not overfished; overfishing is not occurring), depleted abundance of forage fish may negatively affect the ecosystem (Pikitch *et al*. 2004). This phenomenon has been called "ecosystem overfishing" and occurs when the harvesting of prey species impairs the long-term viability of other ecologically important species (Murawski 2000; Coll *et al*. 2008). In simple terms, a strategy that would seem optimal for managing one fish population may be insufficient when accounting for ecosystem considerations such as predator-prey interactions. With a few exceptions, such as in South Africa (Barange *et al*. 2009) or Antarctica (Constable *et al*. 2000, Reid *et al*. 2005), an ecosystem-based approach that considers ecosystem overfishing in management of forage fish has yet to be applied.

Ecosystem-based fishery management of forage fish is especially important because they are strongly interconnected with so many other species, and because their dynamics often closely track the climate-driven, biophysical environment in which they reside. Forage fish abundances fluctuate naturally, in step with changes in environmental variables, notably ocean temperature. Accounting for such factors in devising management strategies for forage fish can provide a buffer against overfishing during periods when populations are naturally low. And because forage fish play such a central role in marine food webs, even minor removals of a forage species may cause ripple effects, especially to highly dependent species (LFFTF Chapter 6; Smith *et al.* 2011). Our report is meant to begin a dialog among fisheries scientists, ecosystem scientists, managers, and stakeholders to develop standards for ecosystem-based management for forage fish and provide specific guidance for managers and policymakers in the future.

METHODS

Review of Existing Theory and Practice

In developing our recommendations, we reviewed existing principles that have been used in the management forage fisheries and examined current applications around the world. We reviewed a large number of papers describing the biological and ecological characteristics of forage fishes, as well as management considerations relevant to forage fisheries. Of relevance to cetacean management and conservation is our review of documented relationships between forage fish abundance and predator abundance or vital rates (LFFTF Chapter 2 and Appendix B), although quantitative metrics for impacts of forage fish depletion on cetacean species are rare.

Considerations for forage species management include issues of catchability, the resilience and rebound potential of populations, natural mortality rates, and localized depletion. We summarized alternative assessment methodologies and management strategies, including target and limit reference points derived from stock assessments, "potential biological removal"-like management approaches, and empirically based management methods. We also discuss the advantages of time- and space-based approaches to forage fish management. Many of these management strategies are already in use. We provide nine ecosystem case studies, each of which includes one or more predominant forage fish species (LFFTF Chapter 4).

Quantitative Methods

We used two types of food web models of marine ecosystems in our analyses, relying on existing models from the literature. The first, Ecopath (Polovina 1984; Christensen and Pauly 1992), is the most widely used food web models in fisheries (Essington 2007) with over 200 Ecopath models developed as of 2010 (Fulton 2010). Ecopath creates static models or "ecosystem snapshots" (Christensen *et al*. 2005), which can be used to analyze the biomass of ecosystem elements and the flow of energy between these elements. The second model, Ecosim (Walters *et al*. 1997), was developed in 1997 to be used in conjunction with Ecopath. The Ecopath with Ecosim software allows for time dynamic modeling and is commonly used to explore the impact of different fishery management strategies on ecosystem elements (Christensen *et al*. 2005). Each of the specific models we used was obtained from the published literature or from the scientific teams that developed them.

By conducting a meta-analysis of 72 Ecopath models from ecosystems worldwide (Figure 2), we were able to quantify the value of forage fish both as an economic commodity and as ecological support for other species in the ecosystem. For Ecopath models to be included in our analysis they needed to: (1) represent a marine or estuarine ecosystem within the last 40 years and (2) have all necessary data and parameters freely available. Furthermore, it was important that all data were collected from Ecopath models and not other modeling software. This ensured that differences between ecosystems were the result of the respective ecosystem parameters and not an artifact of the modeling framework. We estimated the portion of every predator's production supported by forage fish for all forage fish predators and across all ecosystem models using modified equations from Hunsicker *et al*. (2010) (LFFTF Appendix D).

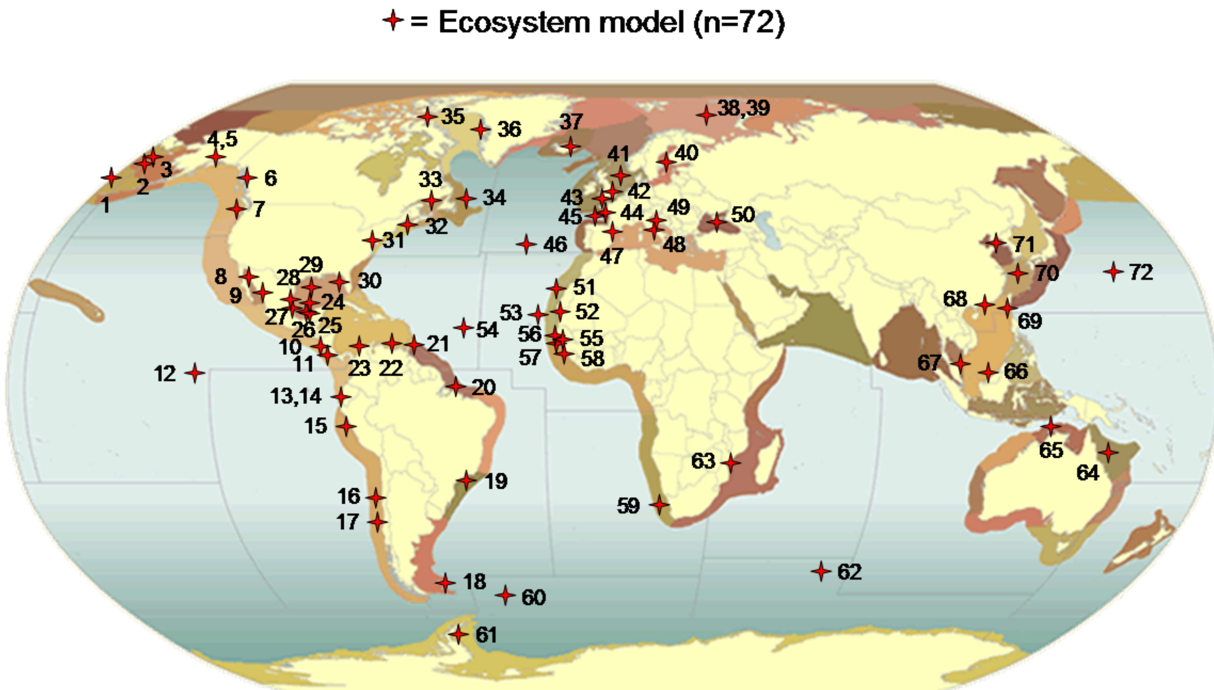

Figure 2. Locations of the 72 published Ecopath models used in the Lenfest Forage Fish Task Force meta-analysis of the direct and indirect contributions of forage fish to ecosystems and fisheries worldwide. Shading indicates the locations of Large Marine Ecosystems (LMEs; http://www.lme.noaa.gov/).

For our evaluation of different forage fish management strategies, we simulated what happens to forage fish and their predators using ten independently published Ecopath with EcoSim models (EwE; Christensen & Walters 2004). These models represent a variety of ecosystem types around the world ranging from coastal upwelling systems to semi-enclosed seas: Aleutian Islands and Southeast Alaska (Guenette *et al.* 2006), Baltic Sea (Hansson *et al.* 2007), Barents Sea (Blanchard *et al.* 2002), Chesapeake Bay (Christensen *et al.* 2009), Gulf of Mexico (Walters *et al* 2008), Humboldt Current (Taylor *et al.* 2008), Northern California Current (Field *et al.* 2006), North Sea (Mackinson and Daskalov 2007), and the Western English Channel (Araujo 2005). We used the models without modifications from the published papers. Although other multispecies trophic models exist (e.g. Osmose, Atlantis), we used EwE exclusively because we wanted to critically evaluate alternative harvest control rules across many ecosystems using a consistent model format and a significant number of models. EwE is the most widely used marine ecosystem modeling platform, is available to the public, and is particularly effective and capable of testing multiple harvest control rules involved in different management strategies (Fulton 2010).

The Management Strategy Evaluation module for EwE is an external spreadsheet that allows for multiple runs of a model to occur at once, with all output compiled into external comma-separated values (CSV) files. The runs may represent different fishing mortalities, different yields, and/ or different upper and lower thresholds for the step and hockey stick management strategies. The runs may also be different simulations, given a pre-specified error variance, of the same strategy. This variance is given as a coefficient of variation, and provides both observation error and process error as the same value. The module treated the user-defined fixed fishing mortalities as targets to set annual quotas. For each year of the EwE model, the fishing quota was updated using predicted biomass from a stock assessment model. The stock assessment models added recruitment based on the biomass of the previous year and the stock recruitment curves. The CV term for the observation and process error was included in this annual stock assessment. For each time step of EwE, the module set the target fishing mortality for the year by capping the fishing effort using the biomass from the current time step. The possible output files include biomasses, yields, consumption levels, feeding times, the realized fishing mortalities, and the realized predation rates.

RESULTS (Summary)

Characteristics of Forage Fishes and their Predators

Previous research on forage fish biology, behavior, and life history has revealed commonalities that allow some generalizations of their population dynamics and responses to environmental change and fishing pressure. Although forage species are highly productive, their short life spans can result in sudden changes in population size. Due to shoaling behavior and predictable migratory pathways, the catchability of many forage fish stocks can remain high despite decreases in population size, leading to a greater chance for collapse. When fishing mortality is high, a larger spawning stock must be maintained to minimize the risk of collapse. Forage fish mortality from nonhuman sources is variable because of changes in predation and plankton production.

Depletion of forage fish can affect predators that depend on them as prey, particularly at local scales; this predation requirement must be taken into account when estimating allowable fishery catches. There is a strong theoretical basis indicating a relationship between indices of foraging success in marine predators and the state of their food supply, especially for forage fish (Cairns 1987). An example is shown in Figure 3 and there is increasing empirical support for the existence of these types of relationships between predator responses such as population size or key vital rates that are linked to fitness, such as annual reproductive success (e.g., Boyd and Murray 2001; Furness 2002; Kitayski *et al*. 2010; Field *et al*. 2010).

It becomes possible to create new approaches to the management of forage fish by using these types of relationships (Richerson *et al.* 2010). Predators often have considerable existence value and in many places where forage fish are harvested there is also legislation to protect and maintain populations of predators like seabirds and marine mammals. Consequently, knowledge of the functional relationship between predator responses and forage fish population size means that it should be possible to develop management strategies that help to maintain forage fish populations above the threshold at which rapid declines in predator responses are likely to occur (e.g., Cury *et al*. 2011). For example, efforts to link management thresholds to observed changes in predator abundance or reproductive rates have been proposed for Antarctic krill fisheries. Establishing harvest rules that use this approach could be the key to delivering the levels of fishing that minimize ecological impacts.

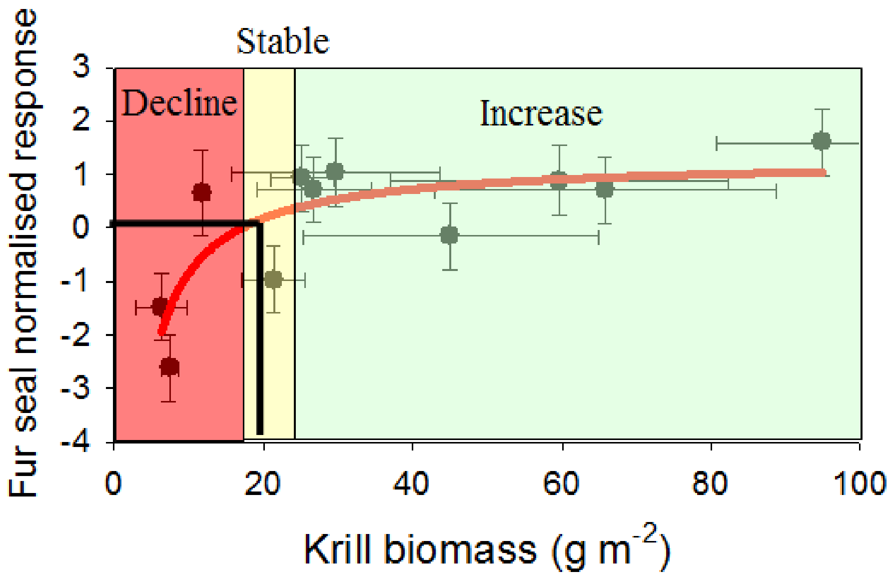

Figure 3. Example of a predator response to changes in forage biomass. Antarctic fur seals show a marked reduction in reproductive rates when their primary food source, krill, drops below critical levels, leading to population decline. From Boyd 2002.

Review of existing management strategies and case studies

Examples of precautionary and ecosystem based management measures already exist for some forage species. Ecosystem considerations such as predator needs can be incorporated into single-species stock assessments, although the result may be a simple buffer to the allowable catch. However, fishery harvest limits based on MSY for single species may not be appropriate for forage species due to their high variability and effects on dependent predators. More sustainable forage fish management has been achieved with minimum biomass thresholds (or "cutoffs") for forage fish fishing. Using gradated fishing mortality for stock sizes above the threshold ("hockey stick" control rule) may be even more effective.

Our case studies were selected to illustrate a variety of forage fish and the wide range of issues surrounding their management. Three ecosystems (California Current, Humboldt Current, and Benguela Current) occur within major eastern boundary current upwelling systems and exemplify forage-fish dominant, so-called "wasp-waist" functional attributes of these systems (Cury et al. 2000). Forage fish catch rates in these systems are among the highest in the world (Alder and Pauly 2006). Two ecosystems are situated in high latitudes (Antarctic and Barents Sea), the former representing a diverse system with krill (*Euphausia superba*) as the foundation prey for many higher-level dependent predators and the latter representing a low diversity system in which capelin (*Mallotus villosus*) plays the central role in a tightly coupled food web. The final four ecosystems include a semi-enclosed sea (North Sea) where there has been considerable fishing effort over many years; a large estuary (Chesapeake Bay) where there are many ecosystem services provided by forage fishes that conflict with forage fisheries; a brackish water sea (Baltic Sea) that represents an 'impoverished' environment; and a large, semi-enclosed embayment (Gulf of Maine) in which forage fish provide critical support for the lobster (*Homarus americanus*) fishery—the dominant socioeconomic driver in the region. In all, these case studies illustrate key concepts in forage fishery management that we found relevant and that provide broader context and insight into the questions posed than would be possible based solely on results of food web modelling analyses.

Evaluation of the Direct and Supportive Roles of Forage Fish

We performed an analysis of 72 Ecopath models to measure the importance of forage fish to marine systems and economies. We examined direct catch value, indirect support of non-forage fish fisheries, as well as forage fish importance to other ecosystem predators (Figure 4). Forage fish provide the largest proportion of their support value to ecosystem predators in high latitude systems (>58° North and South).

Forage fish contribute an estimated total of $16.9 billion (ex-vessel value in 2006 USD) to global fisheries annually. According to our analysis, the direct catch value is approximately one-third of that total. The economic value of forage fish is highest in upwelling ecosystems, with the largest catch and value generated by the Humboldt current where the Peruvian anchoveta fishery occurs. Catch and catch value generally decreased at higher latitudes. The value of forage fish as supporters of other commercially fished species is also highest in upwelling ecosystems and exceeds the value of direct catch in 30 of the ecosystems we studied.

Because of the limited time available, we did not account for the potential economic value of forage fish to recreational fisheries, to ecotourism (e.g. the global potential for the whale watching industry is estimated at $2.5 billion 2009 USD annually (Cisneros-Montemayor et al. 2010), as bait for fisheries, and to the provision of other ecosystem services such as water filtration. Thus, we feel that our calculations of forage fish indirect value are conservative.

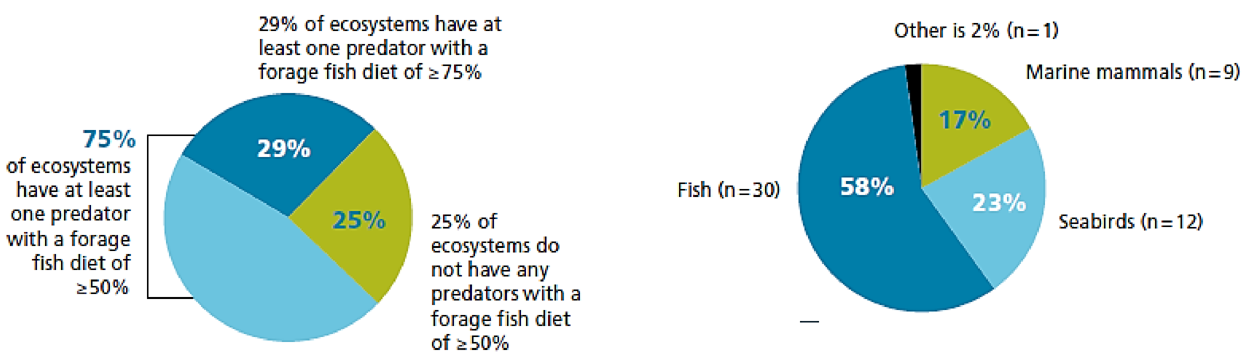

Figure 4. Summary of forage fish dependency among predators, including marine mammals, in 72 reviewed Ecopath models evaluated by the Lenfest Forage Fish Task Force.

Comparison of Fisheries Management Strategies and Ecosystem Responses to the Depletion of Forage Fish

We assessed the ecological impacts of forage fish fishing on whole ecosystems by examining the responses of organisms to variations in the harvest rate for forage species in ten Ecopath with Ecosim models. Diet dependency plays a critical role in the effects of forage fish removals on top predators. Significant reductions in dependent predators can occur with forage fish removals of greater than 20 percent of the biomass predicted by the ecosystem model when there is no fishing (example shown in Figure 5). We found that harvesting at a constant rate based on Maximum Sustainable Yield (MSY) led to the largest and most variable reductions in forage fish and predator biomass. Fishing with a conservative "cutoff" and gradual increase in harvest rate with forage fish biomass had much lower impacts on the ecosystem and a lower probability of stock collapse.

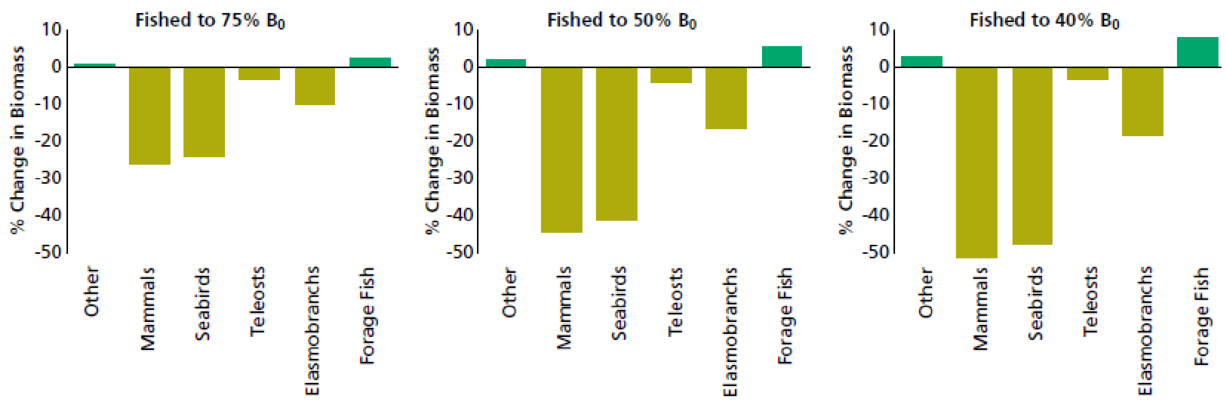

Figure 5. Example of model predicted predator response to a reduction in forage fish. Plots show predator responses to 3 levels of biomass reduction of sand eel (*Ammodytes* spp) biomass, relative to an unfished condition (B_0), in the EwE model for the North Sea (Mackinson and Daskalov 2007).

We synthesized the results from all model runs via a meta-analysis to predict the level of predator depletion expected from various levels of forage fish depletion. Preliminary analyses suggested that either a linear or log-linear model would describe the response of predators across all systems reasonably adequately. From first principles, we expected that the decline will be near zero for species that do not consume the forage fish and for all species whenever forage fish have not been subjected to fishing pressure. Eqn. (1) accounts for this and relates predator response, measured as the biomass decline R of the predator, to a given level of forage fish depletion and predator diet dependence D. The biomass decline R is the percentage decline from the predator's CUB value, and the diet dependence D is the fraction of the predator's diet that is composed of the target forage fish. Model simulations were used to fit the equation:

$$R = \rho D^{\alpha}\left(1 - \frac{B}{B_0}\right)^{\beta} \qquad (1)$$

Where ρ, α and β are estimated model parameters which control the shape of the function, and $\frac{B}{B_0}$ is the relative depletion level of forage fish. Some species will increase as $\frac{B}{B_0}$ declines, but these are generally competitors or predators that specialize on forage fish competitors, and Eq. (1) does not consider these types of responses.

We estimated general, system-specific and trophic level specific values of the parameters by taking logarithms of both sides of Eq. (1) and applying linear mixed effects model regression techniques. The data used to estimate the parameters involved multiple predators from each ecosystem and considered multiple depletion levels for each target forage fish, hence the need for mixed effects. The resulting parameter estimates for the model, which we named the Predator Response to Exploitation of Prey (PREP), are given in Table 1 for all species combined and for individual taxonomic groups. A description of the formulation and parameterization of the PREP equation, as well as the model error structure, see LFFTF Appendix H.

Table 1 can be used to find the forage fish biomass level that will ensure avoidance of large declines in predator abundance. For example, if we wanted to be very certain (i.e., have a 95% chance of success) that 75% of the predators in the ecosystem would not decline by 50% or more, then forage fish should be maintained at 88% of B_0 or higher. We note that because of their generality, these results are likely to be conservative for any specific system. Their value is in providing robust benchmarks for systems for which we do not have EwE models already in place.

Table 1. Parameter estimates for the Predator Response to Exploitation of Prey (PREP) model (Equation 1), based on regressions of predator responses to reductions in prey biomass for 10 EwE models.

Par.	All	Teleosts	Birds	Mammals	Elasmobranchs	Invertebrates
α	0.62 (0.01)	0.58 (0.01)	0.74 (0.03)	0.68 (0.03)	0.76 (0.02)	0.99 (0.05)
β	0.91 (0.01)	0.83 (0.02)	0.88 (0.03)	0.85 (0.04)	0.91 (0.03)	0.99 (0.06)
$\ln(\rho)$	4.49 (0.04)	4.30 (0.05)	4.92 (0.08)	4.44 (0.10)	4.93 (0.09)	5.32 (0.22)
R^2	0.62	0.60	0.85	0.58	0.81	0.75

In our model simulations, hockey stick control rules, which employ both a hard lower biomass limit below which fishing is prohibited and reduces fishing as the limit is approached, performed much better at maintaining forage fish biomass and preventing impacts to dependent species than constant F policies, especially at fishing mortality rates exceeding 0.5 F_{MSY} (Chapter 6).

Our model results also indicate that, in general, fishing mortality should not exceed half of the rate that would be commonly recommended for forage fish $F=0.5F_{MSY}$ (or about half the species' natural mortality rate F=0.5 M), to ensure with high probability (75 – 95% probability) that forage fish fishing will not place dependent predators at jeopardy of extinction (according to international standards). Overall, our results support setting much more conservative targets and limits for forage fish fishery management than have been commonly recommended and applied in the past.

DEVELOPING CONCLUSIONS AND RECOMMENDATIONS

We drew upon various sources of information when developing our conclusions and recommendations. Our approaches included synthesizing existing literature, examining current and past management practices for forage fish including case studies, and generating novel quantitative modeling approaches and results. We also sought out empirical evidence that could provide insights into impacts on ecosystem dynamics from fisheries and predator dependence of forage fish. We used this information and our informed scientific judgment to recommend both specific management measures and general rules that are operationally defined and thus could be implemented immediately:

- Forage fisheries should be managed to sustain both forage fish and predators. Managers should set catch levels that protect forage populations from collapse and, with high probability, do not make predator species vulnerable to extinction.
- Managers should use greater caution when there is less information on forage fish and their interactions with predators and the environment. The Task Force proposes "information tiers" to aid in this (LFFTF Chapter 7).
- The Task Force expects that most forage fisheries now considered as well-managed will fall into the "intermediate" information tier. For these fisheries, fishing mortality should be at most half the conventional rate (half of F_{MSY}) and the amount of fish left in the ocean should be at least twice as large (40 percent of B_0).

Because forage fishes experience high variability in abundance and distribution, detailed monitoring and adaptive management are important components of any harvest strategy. Models used to evaluate criteria should be updated regularly with new information from the fishery and fishery independent sampling of the target species and dependent predators.

We believe that the management advice presented in this report provides a set of robust, precautionary standards, management targets and biomass thresholds that can be used broadly to support the maintenance of forage fish populations as an important feature of marine ecosystems. We understand that every ecosystem is unique and would benefit from solutions that account for individual characteristics, management structure, and research capacity tailored to that system; however, the guidance provided herein will be useful in providing a basis for ecosystem-based management of forage fisheries. In addition, we illustrate how management actions and research priorities might vary among ecosystems according to the level of information available (LFFTF Chapter 7). The results and recommendations contained within this report both advance the scientific discussion on forage fish and provide necessary and credible guidance as to how to apply an ecosystem approach to these species.

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