

# A framework for ecosystem impacts assessment using an indicator approach

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Assessment of the historical, present, and future states of marine ecosystems and the effects that humans and climate have on the state of an ecosystem are crucial to the scientific advice required to implement an ecosystem-based fishery management system. Management of federal groundfish fisheries in Alaska considers not just the target fishery, but also the possible impact those fisheries might have on other species and the ecosystem. Management actions have ranged from providing protection of endangered species in the region to preventing new fisheries from starting on key foodweb components such as forage fish. A scientific framework for providing ecosystem-based advice that puts the ecosystem first has been evolving over the past few years. This framework provides a way of assessing ecosystem factors that influence target species, the impact the target fishery may have on associated species, and ecosystem-level impacts of fishing. An indicator approach that describes ecosystem status, and trends and measures of human and climate influence has been developed to provide advice to fishery managers. This approach is now being expanded to utilize a variety of models to predict possible future trends in various ecosystem indicators. Future implementation challenges include the refinement of these predictive models, and the inclusion of climate into the models. Identification of sensitive and meaningful ecosystem indicators is also required before a more formalized decision-making process, one that includes ecosystem considerations, can be developed. Most important, the culture of fishery management and research organizations needs to change to embrace the ecosystem-based protections already mandated by various laws.

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## Introduction

Recent, worldwide calls for an ecosystem-based approach to fisheries management imply that the necessary framework for protecting ecosystem components, structure, and function has been lacking in present-day fishery management systems. However, such protection has been mandated in the United States by a number of environmental protection laws that have been in existence for more than 20 years (Table 1). These legislative mandates include those specific to fisheries management, such as the Magnuson-Stevens Fisheries Conservation and Management Act (MSA, last amended in 1996), to broader mandates such as the National Environmental Policy Act (NEPA, instituted in 1969). Historically, marine research

and management under each of these laws has tended to be somewhat separate. Although marine fishery managers attempted to meet the requirements of the NEPA, the production of environmental assessments and impact statements under the law were viewed more as an administrative task than as a useful tool for scientific evaluation of ecosystem impacts of fisheries that would provide useful advice for reducing ecosystem impacts through informed selection of management tools.

International and national interest in the ecosystem effects of fishing, and calls for an ecosystem-based approach to fisheries management, is spurring integration of these previously disparate efforts (Mooney, 1998; Hall, 1999; NMFS, 1999; NRC, 1999; Gislason *et al.*, 2000). In particular, Alaska marine fisheries management

Table 1. Major national laws governing the management and protection of US marine resources, with a description of main legislative intent.

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NEPA – National Environmental Policy Act of 1969 (as amended)

Environmental protection is provided through a process of outlining the environmental consequences of human activities, to guide decision-makers to take actions that protect, restore, and enhance the environment.

CWA – Clean Water Act of 1972 (as amended)

To restore and maintain the chemical, physical, and biological integrity of US waters through the elimination of point and non-point sources of pollution.

MMPA – Marine Mammal Protection Act of 1972 (as amended)

Protection and conservation of marine mammals through strict limits on both the taking of marine mammals in US waters and the importation of marine mammals and mammal products into the US.

ESA – Endangered Species Act of 1973

Provides for the conservation of species that are in danger of endangerment or extinction throughout all or a significant portion of their range, and the conservation of the ecosystems on which they depend.

MSA – Magnuson-Stevens Fishery Conservation and Management Act of 1976 (as amended)

Conservation and management of fishery resources off the coasts of the US through the establishment of national standards and regional fishery management plans and councils.

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organizations have been developing an ecosystem-based approach for the management of groundfish fisheries (Witherell *et al.*, 2000). This approach is being advanced by scientists and managers in the region, and it brings together disparate groups of scientists previously aligned under specific legislative mandates to contribute to a more formalized system for assessing the ecosystem impacts of fishing. This system consists of annual assessments of prospective impacts, through the examination of a narrow range of policy choices involving changes in allowable catch levels of target species, and broader assessments completed on a longer time frame that consider a wide range of policy options for reducing ecosystem impacts through the use of a variety of management tools. Both types use a variety of ecosystem indicators to determine the magnitude and severity of impacts, and to provide information to alter management accordingly. This strategy means that the ecosystem is considered first, before management actions are taken.

A key characteristic of recent assessments in Alaska is the involvement of a broad range of scientific expertise and the use of NEPA requirements to guide the analysis. Instead of being viewed solely as an administrative burden, the original spirit and intent of NEPA to provide an open, public process to advise decision-makers on alternatives for the protection of the environment is being viewed as an essential framework for implementing ecosystem-based fisheries management. Originators of the NEPA recommended that implementation be integrated with other planning and environmental review procedures, so that all such procedures run concurrently. Thus, this law also provides the means for integrating the disparate requirements and reviews mandated by other US laws governing specific aspects of the marine environment into a common, overarching ecosystem-based assessment framework.

Efforts to develop a comprehensive, ecosystem-based assessment framework for groundfish fisheries in Alaska have been evolving over the past decade. The primary intent of the framework described here is to summarize historical environmental and fishing effects on the shelf and slope regions of the eastern Bering Sea/Aleutian Islands and Gulf of Alaska from an ecosystem perspective, and to provide an evaluation of the possible future effects of climate and fishing on ecosystem structure and function that can be used to guide decision-making by fishery managers.

## Objectives, thresholds, indicators

Ecosystems consist of populations and communities of interacting organisms and their physical environment that form a functional unit and have a characteristic trophic structure and material cycle (i.e. how energy or mass moves among the groups). The framework contains three broad objectives for protecting these ecosystem attributes, along with sub-objectives, significance thresholds, and specific indicators (Table 2). The broad objectives are: (i) to maintain predator/prey relationships, (ii) to maintain energy flow and balance, and (iii) to maintain diversity. These objectives cover the trophic structure that links species, the material cycles of energy flow, and the many types of diversity that characterize marine life. Ecosystems are dynamic, and the criteria for determining the significance of impacts include the natural ranges of variability seen in ecosystem characteristics. The role of both climate and human forcing as agents of ecosystem change are considered in the analysis of present and future fishery management alternatives for reducing impacts on ecosystems. Sub-objectives have been defined under each of these broad categories to define more explicitly the ecosystem characteristics or impact issues of importance in the region.

Significance thresholds for determining associated impacts involve established population-level thresholds, as well as community or ecosystem-level attributes. In the absence of specifically defined standards, the NEPA

Table 2. Objectives, sub-objectives, significance thresholds, and indicators for fishery-induced effects on ecosystem characteristics (MBAL: minimum acceptable biological limits; MSST: minimum stock size threshold).

<b>Objective</b>
<i>Sub-objective</i>
Significance threshold (Indicators)
<b>Maintain predator/prey relationships</b>
<i>Maintain pelagic forage availability</i>
Changes outside natural range or prey variability relative to predator demands (Trends in forage biomass – quantitative)
<i>Reduce spatial and temporal concentration of fishery impact on forage fish</i>
Concentration high enough to impair long-term viability of marine mammals and birds (Degree of spatial/temporal concentration on forage species – qualitative)
<i>Reduce removals of top predators</i>
Catches high enough to cause biomass of a top predator to fall below MBAL (Trophic level of catch) (Sensitive bycatch levels – quantitative or qualitative) (Population status top predators relative to MBAL)
<i>Reduce introduction of non-native species</i>
Exchange of ballast water/hull-fouling organisms high enough to cause viable introduction (Total catch)
<b>Maintain energy flow and balance</b>
<i>Reduce human-induced energy redirection</i>
Long-term changes in system biomass, respiration, production, or energy cycling caused by discarding/offal production practices that are outside the range of natural variability (Trends in discard/offal production – quantitative) (Scavenger population trends relative to discard/offal production – qualitative) (Bottom gear effort – qualitative measure of unobserved gear mortality)
<i>Reduce system impacts attributable to energy removal</i>
Long-term changes in system biomass, respiration, production, or energy cycling caused by fishery removals that are outside the range of natural variability (Trends in retained catch – quantitative)
<b>Maintain diversity</b>
<i>Maintain species diversity</i>
Catches high enough to cause biomass of one or more species to fall below, or recover from, MBAL (Population size relative to MSST or ESA listing thresholds, linked to removals – qualitative) (Bycatch of sensitive [low population turnover rate] species lacking population estimates – quantitative: sharks, birds, structural habitat biota) (Number of ESA listed marine species) (Surface area closed to fishing)

*Maintain functional (trophic, structural habitat) diversity*

Catches high enough to cause a change outside range of natural variability observed

(Guild or size diversity changes linked to fishing removals – qualitative)

(Bottom gear effort – measure of benthic guild disturbance)

(Bycatch of structural habitat biota)

*Maintain genetic diversity*

Catches high enough to cause a loss or change in one or more genetic components of a stock that would cause the stock biomass to fall below MBAL

(Degree of fishing on spawning aggregations or larger fish – qualitative)

(Older-age-group abundance of target groundfish stocks)

standard of “significant adverse impacts” is applied. This takes into account (either qualitatively or quantitatively) the magnitude, extent, duration, frequency, and likelihood of the impact for determining whether a significance threshold has been reached. Community or ecosystem-level attributes are difficult to measure directly, and the range of their natural variability is not well known. Data on population status of some target or non-target species may be insufficient to determine whether they are above or below thresholds. Therefore, indicators of the strength of fishing impacts are used to evaluate the degree to which proposed changes in human activities may be having a significant ecosystem impact relative to the present state. The framework uses established indicators of ecosystem status in response to perturbations (Odum, 1985; Rice and Gislason, 1996; Pauly *et al.*, 1998; Murawski, 2000) and can incorporate new indicators as they are developed.

Total catch and trophic level of the catch provides information about the potential to disrupt predator/prey relationships through introduction of non-native species or fishing down the foodweb through selective removal of predators, respectively. Pelagic forage availability is measured quantitatively by looking at population trends of walleye pollock (*Theragra chalcogramma*) and Atka mackerel (*Pleurogrammus monopterygius*), target species that are the key forage for many species in the area. Bycatch trends of non-target species such as non-commercial forage fish and herring are also used as indicators of possible impacts. The potential for fishing to disrupt the spatial distribution of food to predators tied to land, such as some marine mammals or seabirds, is evaluated qualitatively to determine the degree of spatial and temporal concentration of fishery removals of forage.

Significance thresholds for species diversity impacts are catch removals sufficiently high to cause the population of one or more target or non-target species to fall below minimum biologically acceptable limits: either a minimum stock size threshold (MSST) for a target species, or one that would trigger Endangered Species Act (ESA) listing, or

prevent recovery of an ESA listed species. Significance thresholds for genetic diversity impacts are catch removals sufficiently high to cause a change in one or more genetic components of a target or non-target stock that would cause it to fall below minimum biologically acceptable limits (MBAL). Measures of functional (trophic or structural habitat) diversity, as a key attribute that lends an ecosystem stability (Hanski, 1997), are also included. Although measures of diversity may be subject to bias and may not provide sensitive indicators of fishing effects (Livingston *et al.*, 1999; Jennings and Reynolds, 2000), the framework is used to evaluate the possible impacts of fishing on various diversity measures.

## Evaluation of factors affecting ecosystem status

To evaluate the role of human or climate-induced stressors in influencing the present status of Alaska marine ecosystems, a coordinated effort was needed to obtain information from the scientific community on historical status and trends for various ecosystem components and stressors. In 1994, the North Pacific Fishery Management Council added an Ecosystem Considerations Chapter<sup>1</sup> to the single-species stock assessment document. The chapter was structured to serve as an ecosystem status and trends document, with a standardized content from year to year (Boldt, 2003). The idea was to draw upon a broad range of scientific experts (federal and state fishery management organizations, academia, and other locally based knowledge groups) in the areas of physical and biological oceanography and climate, habitat and effects of fishing, marine pollution, and ecology to evaluate the possible factors influencing change in the various ecosystem components and indicators presented.

In 2002, the information was incorporated into single-species stock assessments with the idea of having a more comprehensive groundfish stock assessment process that considers a variety of ecosystem issues on a fishery-by-fishery basis. The ecosystem status and trends data are now used to perform an evaluation of ecosystem factors that affect each stock and of ecosystem impacts of each fishery (Table 3).

An ecosystem assessment was incorporated into the framework in 2003. That assessment uses the historical status and trend indicators (Table 2) to evaluate the aggregate impact of fishing and climate on the present state of the ecosystem, and a variety of models to evaluate potential future impacts under different scenarios of climate and management. It is hoped that, in this way, medium-term advice on likely shifts in species composition and

Table 3. Ecosystem impact assessment performed for each groundfish stock and fishery in Alaska to evaluate ecosystem effects on the stock, and fishery effects on the ecosystem.

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### Indicators for evaluating ecosystem effects on stock

Prey availability or abundance trends  
 Predator population trends  
 Changes in habitat quality (physical and biological)

### Indicators for evaluating fishery-specific effects

Incidental catch rates of forage species, structural habitat biota, marine mammals and birds, sensitive non-target species  
 Concentration of removals of forage or discrete spawning aggregations of target species in space and time  
 Effects on quantity of large-size fish, age at maturity, or fecundity of target species  
 Effects on non-living benthic structure

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production may be provided to aid in planning mitigation measures. Other goals are to provide annual assessments of future ecosystem impacts of different quota levels, as well as long-term advice (on a periodic basis) on the effectiveness of various management strategies in reducing ecosystem impacts.

## Future ecosystem status: the role of models

The importance of providing ecological forecasts to decision-makers to aid in the selection of policy choices is increasingly recognized (Clark *et al.*, 2001; Carpenter, 2002). Fishery managers need advice on future ecosystem effects of present management choices and how these effects might differ under various scenarios of climate, human population, and economics. The objective in the Alaskan framework is to provide information on historical time trends in all indicators (Table 2), along with their expected future trajectories under various management alternatives. Because multispecies and ecosystem models are still being evaluated (Hollowed *et al.*, 2000), three modelling approaches have been selected to derive multiple predictions for some common indicators of interest rather than relying on a single model (Fulton *et al.*, 2003): (i) a multispecies fishery/technical interactions model that contains traditional single-species, age-structured population forecasts for target species; (ii) an age-structured multispecies predator/prey forecast; and (iii) a full ecosystem biomass dynamics predator/prey forecast.

Model 1 has been used to evaluate fishery management alternatives (NMFS, 2003), by forecasting the dynamics of target groundfish species and incidental catches of other species using the numerous catch constraints placed on Alaskan groundfish fisheries, including strict quota

<sup>1</sup> Available at <http://www.afsc.noaa.gov/refm/docs/2003/APPENDIX%20%20Ecosystem%20Considerations%20Chapter.pdf>.

management for target species, bycatch limits for prohibited species, catch allocations to particular gear types, regions and seasons, and limits on total groundfish catch. This model is comparable to the linear programming approach used by others (Brown *et al.*, 1979; Siegel *et al.*, 1979; Murawski and Finn, 1986) to predict catches of target and non-target species under various management scenarios.

Model 2 is an age-structured multispecies forecast (MSFOR) that uses predator/prey suitability estimates derived from multispecies virtual population analysis (MSVPA) of dominant groundfish species in the eastern Bering Sea (Livingston and Jurado-Molina, 2000; Jurado-Molina and Livingston, 2002). The average suitability coefficients, terminal stock sizes, residual mortalities, weight of prey in predator stomachs, and annual ration of the predator are transferred from MSVPA to MSFOR to carry out the simulation of future dynamics of target species (Gislason, 1991), accounting for changes in predation mortality. Thus, it provides indicators of future change for target species only, and not for the numerous non-target species incidentally caught in these fisheries or consumed by target species.

Model 3 is an Ecopath model (Aydin *et al.*, 2002), which approximates the entire foodweb for evaluating fishing effects. Simulations of historic biomass dynamics in Ecopath/Ecosim (Christensen and Pauly, 1992; Walters *et al.*, 1997) are being evaluated for their ability to replicate observed time trends in species abundance, and for providing indicators of future change that relate more to ecosystem-level properties of energy flow and organization. Unlike the other two models, this one provides projections of future dynamics of non-target species, a desirable attribute when attempting to evaluate ecosystem impacts.

Prediction of future climate effects and regime shifts on Alaskan ecosystems is complex, and it requires better understanding of the probability of certain climate states in the near and longer term, and the effects of this variability on production and distribution of individual species and on foodwebs. Future ecosystem assessments may integrate various climate scenarios into the multispecies and ecosystem forecasting models, based on assumptions about effects of climate on average recruitment of target species. Operationally, deciding whether climate or fishing is the primary driving force in model predictions of change will require contrasting model runs that include varying levels of fishing, relative to assumptions about climate effects. Also, improved retrospective analyses of the relative roles of climate vs. fishing in producing the present ecosystem state will require improvements in models 1 and 2, to explore alternative assumptions in a statistical manner.

## Implementation issues

Legislated mandates (Table 1) provide some direction about thresholds (Table 2) for action (e.g. stop fishing when

MSSTs for target species are reached). However, many of the thresholds listed are not easily quantified. In such cases, the NEPA provides guidance for determining whether an impact is significant. Significance of an impact is considered to depend on both its context relative to the affected region and human society, and on impact intensity or severity. Thresholds have been determined through expert judgement, using scales of ranking relative impact (generally using percentage change in indicators as ranking factors). For example, the indicator used to assess fishery impacts on prey species of marine mammals is the projected rate of fishing mortality for the forage species. A significant adverse impact was determined by experts to occur in instances where the rate was 20% greater than the baseline condition.

Once an indicator is determined to have passed the threshold, a system is needed to determine the appropriate management action. The NEPA requires only that informed decisions be made that disclose the potential impacts, and it also directs managers to avoid or to minimize possible adverse effects, to the extent possible. It does not require that managers choose the most environmentally preferable management alternative.

The traffic light system of Caddy (1999) has been proposed as a way to integrate the results of numerous indicator trends and to provide a structured way of deciding when and how much reduction in catch, etc., is warranted. Essential to this type of system is a pre-negotiated set of actions to be taken when certain thresholds are reached. Such a strategy might be used in the framework for determining annual quota adjustments that take ecosystem considerations into account. At present, there is no structured decision-making process, and adjustments tend to be *ad hoc*. More complicated analyses, such as those involving a comparison of impacts as influenced by different management tools applied over longer time frames, may require use of the models and indicators in a management strategy evaluation, as described by Smith *et al.* (1999).

Several challenges remain in furthering implementation of the framework, including the refinement of the predictive models used so far. In particular, validation of model outputs and explicit incorporation of uncertainty into model predictions have high priority. Improving our understanding of climate links to recruitment is essential for all models, because they rely heavily on assumptions regarding average recruitment. In the absence of a good understanding, a set of standard scenarios regarding climate and recruitment might be developed to drive the models to give decision-makers a range of possible future options to consider. A more formalized decision-making process to incorporate ecosystem considerations realistically may only be expected after some sensitive and meaningful ecosystem indicators have been successfully identified. Finally, it will be important to influence the culture of marine fisheries scientists and managers throughout the US, so that they

embrace the requirements for ecosystem protection that already exist in numerous national laws as a regular part of providing scientific advice and making fishery management decisions, rather than as a bureaucratic exercise. Then we may have truly achieved the goal of implementing ecosystem-based fishery management.

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