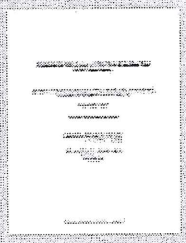

Evaluating the Effectiveness of Fish Stock Rebuilding Plans in the United States

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Committee on Evaluating the Effectiveness of Stock Rebuilding Plans of the 2008 Fishery Conservation and Management Reauthorization Act; Ocean Studies Board; Division on Earth and Life Studies; National Research Council

SUMMARY

In the United States (U.S.), the Fishery Conservation and Management Act of 1976, now known as the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA), was the first major legislation to regulate federal fisheries in the U.S. Fishery Conservation Zone (later designated as the U.S. exclusive economic zone). Although the MSFCMA contained language to "prevent overfishing", the emphasis was on developing the domestic fishery. Major declines in the productivity of several important fisheries led Congress to amend the MSFCMA in 1996, with the Sustainable Fisheries Act, which more clearly defined overfishing and required rebuilding of overfished stocks within a specified time limit. The re-authorization of the MSFCMA passed by Congress in 2006 included additional mandates for conserving and rebuilding fish stocks and strengthening the role of scientific advice in fisheries management.

The depleted status of many fish stocks continues to be a challenge for fishery managers and the fisheries that depend on these stocks. Approximately 20% of the fisheries that have been assessed are considered overfished according to the September 2012 stock status Report to Congress prepared by the U.S. National Oceanic and Atmospheric Administration (NOAA). Overfished refers to a stock that is below the minimum stock size threshold, commonly set to half the stock size at which maximum sustainable yield (MSY) is achieved. Under the provisions of the MSFCMA, rebuilding plans for overfished stocks, covering both commercial and recreational fisheries, should take no more than 10 years, except when certain provisions apply. To meet these provisions, rebuilding plans have required substantial reductions in catch and effort for many fisheries, raising concerns about the consequent social and economic impacts to the fishing communities and the industry. Fishing restrictions have not only affected stocks under rebuilding plans, but have also impacted the utilization of stocks that are not overfished but are part of mixed-stock fisheries. In 2010, U.S. Senator Olympia Snowe and U.S. Representative Barney Frank requested that the NOAA Administrator fund a study by the National Academy of Sciences' National Research Council (NRC) regarding the MSFCMA's rebuilding requirements.

The committee reviewed the technical specifications that underlie the current set of federally-implemented rebuilding plans, the outcomes of those plans in terms of trends in fishing mortality and stock size, and changes in stock status with respect to fishery management reference points.

A total of 85 stocks or stock complexes were declared overfished under the provisions of the MSFCMA. Rebuilding plans were implemented for 79 stocks, of which 25 were classified as

rebuilt[1] and 5 more stocks rebuilt before a plan was implemented. Based on the review of information for a subset of stocks that are assessed by analytical methods, the committee found that fishing mortality of stocks placed under rebuilding plans has generally been reduced and stock biomass has generally increased following reductions in fishing mortality. Although some stocks have rebuilt, others are still below rebuilding targets, and some continue to experience overfishing. Given the inherent uncertainties in both specifying a threshold for rebuilding and in determining whether a stock has dropped below that threshold, the current policy dependence on thresholds results in discontinuities in management when there is a change in stock status associated with updated stock assessments. While the Committee attributes some of the variable or mixed performance of rebuilding plans to scientific uncertainty, this should not be interpreted as a criticism of the science. It often reflects a mismatch between policy makers' expectations for scientific precision and the inherent limits of science because of data limitations and the complex dynamics of ecosystems.

The mixed outcomes of rebuilding plans have added to concerns about the significant social and economic costs associated with the implementation of time-constrained rebuilding plans. To address these rebuilding challenges, the committee highlights the following key findings for consideration by scientists, managers, and policy makers:

1) Harvest control rules that promptly, but gradually reduce fishing mortality as estimated stock size falls below B_{MSY} could result in a lower likelihood of a stock becoming overfished and provide an approach for rebuilding if necessary;
2) Fishing mortality reference points seem to be more robust to uncertainty than biomass reference points both in the context of rebuilding and more generally;
3) Rebuilding plans that focus more on meeting selected fishing mortality targets than on exact schedules for attaining biomass targets may be more robust to assessment uncertainties, natural variability and ecosystem considerations, and have lower social and economic impact.
   a. The rate at which a fish stock rebuilds depends on ecological and other environmental conditions such as climate change, in addition to the fishing-induced mortality,
   b. A rebuilding strategy that maintains reduced fishing mortality for an extended period (e.g., longer than the mean generation time) would rebuild the stock's age structure and be less dependent on environmental conditions than one that requires rebuilding to pre-specified biomass targets, and
   c. When rebuilding is slower than expected, keeping fishing mortality at a constant level below F_{MSY} may forgo less yield and have fewer social and economic impacts than a rule that requires ever more severe controls to meet a predetermined schedule for reaching a biomass target.
4) In the case of data-poor stocks for which analytical assessments are not available and catch limits are therefore difficult to establish, empirical rebuilding strategies that rely on input controls to reduce fishing mortality may be more effective and defensible than strategies based on annual catch limits and B_{MSY} targets.
5) Retrospective reviews of the socioeconomic impacts of rebuilding plans are rare, in part due to data availability. Such reviews would help in refining rebuilding plans and objectives and ameliorating for the consequences of such actions.

[1] As of 30 September 2012.

These key findings are described in more detail below. The remainder of this summary is organized around the seven tasks that the committee was directed to address.

TASK 1

Evaluate methods and criteria used (1) to set target fishing mortality and biomass levels for rebuilding overfished stocks, and (2) to determine the probability that a particular stock will rebuild by a certain date. Consider the quantity and quality of information available for defining maximum sustainable yield (MSY)-based reference points or proxies for such reference points. Compare these methods and criteria to those used in major fishery management settings outside the U.S.

The committee reviewed the evolution of the MSFCMA from its origins in 1976, its subsequent amendments that introduced rebuilding requirements and accountability measures, and the guidelines for rebuilding U.S. fish stocks. Fisheries management has evolved substantially since 1977 when the U.S. extended its jurisdiction to 200 miles, in the direction of being more prescriptive and precautionary in terms of preventing overfishing and rebuilding overfished fisheries. This evolution has been positive in making clear the objectives, resulting in fewer fisheries are currently subject to overfishing. However, the trade-offs between precaution, ecosystem impacts, and net benefits from fisheries have not been fully evaluated.

One of the central tenets of fisheries management is the concept of MSY, which represents the maximum, sustainable, long-term average yield that can be taken from a fish stock. The MSFMCA bases the success or failure of fisheries management on the MSY concept and its associated population biomass (B_{MSY}) and fishing mortality rate (F_{MSY}), which are used as reference levels against which to compare how stock status and harvest rate change over time.

MSY is not fixed but may be influenced by a variety of factors encompassing fishing practices, ecological interactions and environmental conditions. In addition, management reference points based on MSY have a level of uncertainty that depends on the amount and quality of information available. Estimates of B_{MSY} may be imprecise even for stocks that are relatively "data-rich," because of the complex and dynamic nature of ecosystems. The MSFCMA is virtually silent on the implications of uncertainty and variability of MSY. Guidelines for implementing the Act are primarily oriented to situations in which estimates of MSY reference points are reasonably precise and stable. Although the MSY approach has been successful for some fisheries, in other situations, management based on MSY falls short in addressing ecosystem complexity and variability, and in accounting for uncertainty in the estimates of stock size and reference points.

The requirement to end overfishing for all stocks in mixed-stock fisheries has protected less productive species but has led to loss of yield for healthy stocks in the same complex. The "Mixed-Stock Exception" in the MSFCMA provides an option for reducing the impact of rebuilding on the harvest of healthy stocks. However, it has not been invoked in these cases, in part due to the narrow range of situations to which it applies under the MSFCMA and also because of the complexity of the issue it is meant to address. The operational feasibility of the mixed-stock exception could be modified to expand the range of situations to which it can be

applied, subject to assurances that the less productive species are not driven to unacceptably low abundance.

Rebuilding Plans are designed using quantitative models to project likely future trends in stock size in response to alternative harvest control rules. This approach works best for data- and knowledge-rich fisheries, which are generally those stocks with a long history of exploitation and high economic value, and which contribute the bulk of the U.S. landings. The main focus of this review was on the stocks for which quantitative assessments and estimates of MSY reference points are available. For many stocks, however, data and understanding are so limited that stock projections cannot be conducted, and stock-by-stock application of MSY-based control rules is unrealistic. NOAA reports to Congress indicate that over half of the stocks or stock complexes identified have either not been assessed or their status as overfished or experiencing overfishing is unknown.

In general, fishing mortality reference points appear more robust to scientific uncertainty than biomass reference points. Fishing mortality reference points are often more reliably estimated at lower stock sizes than biomass reference points, whose estimates rely more strongly on density-dependent processes that generally manifest only at higher stock sizes. Furthermore, proxy values for fishing mortality reference points can often be derived from other information sources, such as life history parameters of growth and natural mortality, which do not require estimates of future recruitment levels.

When data and understanding are too limited to design a rebuilding plan with a pre-determined time limit for rebuilding, it may be practical to implement harvest control measures (either by adjusting catch limits or effort controls) that at a minimum would be expected to increase stock size. In the case of data-poor stocks for which analytical assessments are not available, and therefore catch limits are difficult to establish, empirical rebuilding strategies that rely on input controls to reduce fishing mortality may be more effective and defensible than strategies based on annual catch limits and B_{MSY} targets as prescribed by the National Standard 1 Guidelines (NS1G).

TASK 2

Assess the effects of uncertainty in current stock abundance, population dynamics, and variability in recruitment in setting rebuilding targets. Identify criteria for adjusting rebuilding targets and schedules based on new information and updated stock assessments.

Scientific management advice is subject to several sources of uncertainty, including variability and bias in the data, sensitivity to model assumptions, implementation uncertainty (reflecting management effectiveness and fisher responses), and unpredictable natural events. These sources act simultaneously, resulting in substantial uncertainty surrounding reference points, the determination of stock status, and projected outcomes of management regulations**.** As required by law, rebuilding plans have target years for recovery to B_{MSY}, but the rate at which stocks rebuild is probabilistic such that some stocks will rebuild before the target year while others will rebuild after the target year or not rebuild until environmental conditions improve, even if the rebuilding plan is implemented as intended, fishing mortalities are close to the targets, and targets are based on robust stock assessments.

The MSFCMA requires review of progress of rebuilding plans at least every second year. However, reviews do not always include updated, quantitative stock assessments. The frequency of assessments varies widely, both within and among regions, from stocks that have never been assessed to stocks that are assessed annually. More frequent assessments might lead to more frequent, but less extreme, changes in rebuilding plans and closer adherence to fishing mortality targets.

Due to the uncertainty in stock assessments, the perceived status of fish stocks in any particular year can change substantially as more data become available and as assessment methods change over time. According to the most recent assessments available, there is a substantial probability of (i) classifying stocks as overfished and requiring rebuilding plans when later assessments indicate that the stocks were not below the minimum stock-size threshold, and (ii) classifying stocks as rebuilt when the updated assessments indicate that the stocks were never overfished. By inference, the inverse may also occur so that overfished stocks may be misclassified as not overfished. How many and which stocks these are cannot be determined from the data available.

The MSFMCA, as operationalized by the NS1G, requires an end to overfishing and provides minimum standards for stock rebuilding, namely that stocks designated as overfished must rebuild to B_{MSY} within a maximum time period. Although effective in increasing the probability that rebuilding occurs quickly once a stock has fallen below the minimum stock-size threshold, preventative management actions taken prior to falling below the threshold could obviate the need for a rebuilding plan. Harvest control rules that promptly, but gradually, reduce fishing mortality as estimated stock size falls below B_{MSY} could result in a lower likelihood of a stock becoming overfished as well as providing an approach for rebuilding if necessary.

Such rules may reduce the need for more stringent reductions that would be required if the stock fell below the minimum stock-size threshold. Delaying reductions in fishing mortality until the stock falls below the threshold creates a discontinuity: – managers are then required to make immediate and substantial decreases in fishing mortality based on what may be only small changes in estimates of stock size from a previous assessment. Furthermore, the mandate that rebuilding targets be met with a certain minimum probability, along with the requirement to utilize the most current stock assessments, may lead to marked changes in rebuilding plans based on new data or models as they become available. These adjustments can also create economic and social impacts, potentially either positive (e.g., increases in allowable catch due to rapid rebuilding) or negative (e.g., decreases in allowable catch when rebuilding is slower than expected). Although these adjustments may reflect the best available science, the perceived credibility of the science among stakeholders may be reduced when rebuilding plans are changed markedly.

Population projections used in rebuilding analyses have much higher uncertainties than historical estimates of population sizes. Because of the uncertainty surrounding projections, the emphasis placed on achieving a biomass threshold in a defined time frame may require severe reductions in target fishing mortality (well below F_{MSY}) when rebuilding is slower than expected. In situations where recruitment is below expectations (e.g., due to unfavorable environmental conditions), a control rule aimed at maintaining fishing mortality at some constant level below F_{MSY} may forgo less yield, especially in mixed-stock situations, and have fewer social and economic impacts than one that forces ever more severe controls to try to keep rebuilding on schedule.

The standard approach used in most regions for adjusting catch limits involves the use of a single "best" estimate of current or projected stock size. Often, several alternative models or configurations of a standard stock-assessment model are first applied and the "best" of these is selected using formal criteria or expert judgment. An alternative to this best-assessment approach is to describe the consequences of alternative decision rules under each of the models considered plausible. A general framework known as Management Strategy Evaluation (MSE) has been used internationally and by some RFMCs to evaluate alternative harvest control rules that specify in advance how catch limits will be adjusted in response to new data as they become available. Different candidate rules are tested across a broad range of simulated scenarios (e.g., different levels of stock productivity, different environmental regimes), a process that allows decision-makers to select a decision rule based on robust performance under various scenarios.

TASK 3

Provide an overview of the success of rebuilding plans under the MSA and compare to success of approaches used outside the U.S. Using a few representative rebuilding plans, identify factors (such as fishing mortality rate, life histories, uncertainty in stock assessments, and others) that affect the timeframe over which a stock is rebuilt.

The committee reviewed the 85 stocks or stock complexes that were declared to be overfished or approaching an overfished state between 1997 and 2011. Rebuilding plans were implemented for 79 of these 85 stocks, based on target fishing mortalities generally lower than 75% F_{MSY} and substantially lower than this in some regions; rebuilding time frames chosen in those regions are much shorter than the maximum specified by the NS1G.

The committee focused on a subset of 55 stocks assessed using quantitative methods. The most recent assessments indicate that fishing mortality was reduced below F_{MSY} (i.e., overfishing was halted) in 23 of the 36 stocks that were subject to overfishing at the time of overfished designation. According to these assessments, 20 of the 55 stocks analyzed were not overfished, and 10 were actually above B_{MSY} at the time of overfished designation. Of the 35 stocks that were below the minimum stock size threshold:

- 43% of the stocks are no longer overfished; 10 have rebuilt and 5 are rebuilding.
- Of the remaining 20 stocks estimated to still be overfished, 11 had fishing mortalities well below F_{MSY} in the last year included in the assessment and are therefore expected to rebuild if low fishing mortalities are sustained.

Stocks that rebuilt or whose biomass increased appreciably were, in almost all cases, experiencing fishing mortalities below F_{MSY}.

Some stocks (9 of the 35) continue to be subject to overfishing even though fishing targets were set at or below 75% F_{MSY} to allow rebuilding within the maximum time frame. The failure of rebuilding plans to achieve the intended reductions in fishing mortality reflects implementation problems due to ineffective input controls and lack of accountability measures, difficulties in reducing fishing mortality of species caught as bycatch in other fisheries, or errors in the estimates of stock size that led to catch limits that were too high. In particular, retrospective biases in the assessments revealed apparent overestimations of stock size that contributed to continued overfishing.

The U.S. approach to rebuilding overfished stocks is comparable to that used by several developed countries (such as Australia, Canada and New Zealand) and the results are similar (in terms of the fraction of overfished stocks). The European Union has a higher proportion of stocks that are subject to overfishing than the U.S., although the proportion has decreased sharply in recent years.

TASK 4

Consider the effects of climate and environmental conditions, habitat loss and degradation, ecological effects of fishing on the food chain, and ecological interactions among multiple species, and identify ways to adjust rebuilding plans to take these factors into account.

Ecosystem variables related to climate, habitat, and food-web interactions can influence population dynamics, yielding a broader spectrum of possible outcomes than is typically considered in single-species rebuilding projections. Stock biomass forecasts and projections can vary in response to alternative plausible assumptions (models) and parameter values used in simulations, because the underlying population dynamics are nonlinear. Reference points, such as B_{MSY}, that are used throughout fisheries management, are based on single-species production functions that do not generally account for the influences of environmental and ecological interactions. The committee notes that reference points based on single-species assessments are likely to shift over time as a consequence of climate change and the complex and dynamic nature of ecosystems.

Fishing truncates the age structure of a population, especially when fisheries selectively harvest larger fish. Removing the more productive individuals from a population may amplify the effects of environmentally-driven recruitment variability. Rebuilding plans that restore the demographic structure of the overfished population are more likely to improve recruitment and increase the likelihood of success of the rebuilding effort than plans that restore spawning stock biomass without also restoring demographic structure. In nature, growth, maturity, and natural mortality are influenced by interactions with other species that may be competitors, predators, or prey. Fisheries management involves tradeoffs among harvested species that interact, even if these tradeoffs are not explicitly considered in management decisions. Our understanding of how ecosystems function is improving, in some cases enough to contribute to the models used in fisheries management. For example, stock assessments can be linked with multispecies models. Ecosystem considerations, among other reasons, argue for more emphasis on rebuilding plans that maintain reduced fishing mortality for an extended period (e.g., longer than the mean generation time). This strategy rebuilds age structure and is more robust to natural variability than a focus on biomass targets, which may be more or less attainable depending on environmental conditions.

TASK 5

Assess the types of information needed and current understanding of the economic and social impacts of rebuilding programs, particularly on fishing communities. Identify the economic, social, and ecological tradeoffs of rebuilding a fishery associated with shorter or longer

rebuilding times. Evaluate available methods for integrating these social, economic and ecological factors when designing and evaluating rebuilding plans.

The relationship between economic and social factors and rebuilding programs that extend over multiple years is complex and dynamic, although the state of knowledge and understanding about these interactions is improving. Causal relationships among rebuilding and socio-economic outcomes are difficult to disentangle, due to the general quantity and quality of data and resources available to fishery managers and scientists, behavioral responses of those being impacted by the changes, and the multitude of confounding factors. It can also be difficult to establish counterfactual conditions that capture what the status of a stock might have been in the absence of rebuilding or under alternative rebuilding plans. The estimated impacts of a rebuilding plan are conditional on these (assumed or estimated) counterfactuals. Hence, the ability to predict and measure rigorously the *ex post* economic and social impacts and tradeoffs is limited.

Socioeconomic analyses and research are used to inform the evaluation of alternative rebuilding plans, but the role of the formal analyses in the decision process is less clear, as these decisions are made in a highly charged political setting. Furthermore, compliance with MSFCMA requires that economic and social considerations for rebuilding plans are contingent on biological mandates being met. Rebuilding plans that do not meet these mandates cannot be adopted, even if doing so would improve projected socioeconomic outcomes.

Fish stock rebuilding plans are designed to achieve rapid rebuilding of biomass and spawning stocks consistent with the biological characteristics of the resource. However, the requirement to rebuild within 10 years, if biologically possible, eliminates certain management options from consideration that could lead to greater social and economic benefits while still supporting stock recovery in the long run. Several alternative management strategies that could be considered in this context have been implemented successfully in venues outside the U.S. (e.g., New Zealand).

At the same time, socioeconomic considerations do influence the management of overfished stocks through the public participation process (e.g., public testimony to Councils regarding the magnitude of socioeconomic impacts). Stakeholder participation and concerns regarding the impacts of rebuilding plans can also result in *ad hoc* mitigation measures (e.g., disaster relief assistance) that operate outside of the fishery management process. The implications of these measures on other fisheries, and on the long-run social and economic viability of coastal communities are not fully known.

TASK 6

Summarize how the social, economic and ecological impacts of rebuilding plans are affected by the structure of fisheries management measures, e.g., limited entry, catch shares systems, and closed areas.

In the U.S., many commercial and recreational fisheries are managed by allocating a portion of a species' total allowable catch to different fishing sectors (e.g., defined by gear type, recreational versus commercial, and size of fishing vessel) and linking this allocation with

additional controls, for example on fishing locations, seasons, technology, size and sex restrictions, and trip or bag limits. The incentives and constraints created by this (and any other) regulatory strategy affect the economics of fishing, the structure of fishing communities, and the choices available to fishermen. These common regulatory constraints, which are often tightened if stocks become depleted, reduce the ability of fishermen to adapt their fishing behaviors (e.g., changing where, how and for what species they fish) in response to the new harvest limits that accompany rebuilding plans. Although constraints and incentives may vary across regulatory strategies (e.g., catch shares, limited entry, regulated open-access), all approaches limit the capacity of fishermen to adapt practices in some manner. As a result, fishermen are less able to mitigate costs associated with rebuilding plans.

Another factor limiting the adaptive potential of fishermen is the highly specialized fleets that evolved in response to the sector-by-sector allocation process institutionalized by the RFMCs. While specialization can have economic gains, it also reduces the potential for behavioral responses, such as switching fishing gears to improve quality (and obtain higher prices for the fish) or switching between species in response to a rebuilding plan. Specialization of the fishing sector also has ripple effects in the fish processing and fishing-related industries and can result in local communities having less diversity in the local economy to mitigate short-run economic impacts.

In summary, the nature of fisheries management can lead to situations that exacerbate the economic and social impacts of meeting rebuilding targets by institutionalizing the specialization of the fishing industry (including fishing fleets, processing, and related support businesses). These constraints reduce the ability of the fishermen and communities to absorb some of the costs associated with curtailing catches and have potential impacts on the resilience of fishing communities.

TASK 7

Identify the biological, ecological, social and economic knowledge gaps that impede the implementation and effectiveness of rebuilding programs, and determine what additional data and analyses are needed to address those gaps.

Gaps in knowledge exist at many different points due to limitations in data and assessment methods, shortage of human resources and expertise, and analytical capabilities to integrate biological, economic and social data. Some of the knowledge gaps could be filled with additional data collection and analysis. Other knowledge gaps will likely remain unfilled because of finite resources and limits to the predictability of coupled human-natural systems (for example, the influence of climate change on fisheries). This type of gap requires robust strategies for managing with uncertainty, as mentioned below.

When data are insufficient to perform analytical stock assessments and estimate biomass and fishing mortality reference points with sufficient confidence to design and apply MSY-based control rules, alternative paradigms should be considered and evaluated. Strategies that combine spatial controls and habitat-based approaches with empirical rules to adjust harvest measures in response to demographic indicators or other proxies of stock status, as well as ecosystem-level

indicators, could be designed to try and ensure that fishing rates are reasonable and precautionary and that rebuilding is progressing.

The success of any formal approach for developing robust control rules requires clearly-specified management objectives, so that quantitative performance measures and tradeoffs (e.g., between risks and yield) can be evaluated. While analyses generally consider uncertainties that affect population or ecosystem projections and future catch rates, most do not consider the full suite of risks in these complex and dynamic systems. Currently, the treatment of uncertainty is not integrated across the ecological, economic, and social dimensions of rebuilding, and the cumulative risk tradeoffs are not well understood. Consequently, it is not clear whether the necessary precaution (or too much precaution) is being applied.

In terms of assessing actual outcomes of rebuilding plans, the Committee focused its review on biological metrics, consistent with current legal mandates. These are available through regular stock assessments conducted for ongoing management. By contrast, information is not readily available to evaluate the broader impacts of rebuilding plans. Retrospective reviews of the socioeconomic impacts of rebuilding plans are rare, at least partially due to data availability. These socioeconomic impacts include changes in the structure of commercial fishing sector, economic returns, recreational values, fish processing industry, and culture of fishing communities. Methods exist and innovations are emerging in economic and social science approaches to characterize the breadth of economic and social impacts of rebuilding plans and factors in a coupled natural-human system that contribute to the success of these plans, although they have not yet been broadly applied, tested and refined to meet these information needs.

CONCLUSIONS

The current implementation of the MSFMCA relies on a prescriptive approach that has resulted in demonstrated successes in identifying and rebuilding overfished stocks. Fishing mortality has generally been reduced, and stock biomass has generally increased, for stocks that were placed under a rebuilding plan. Where they have been estimated, the long-term net economic benefits of rebuilding appear to be generally positive. Stocks that rebuilt or whose biomass increased appreciably were, in almost all cases reviewed, experiencing fishing mortalities below F_{MSY}, and often lower than 75% of F_{MSY}. More extreme reductions in target fishing mortalities have been implemented in situations in which rebuilding progress was slower than anticipated when the rebuilding plan was adopted, or the target year for rebuilding was approaching. In some cases rebuilding plans have failed to reduce fishing mortality as much as intended, either due to overestimation of stock sizes or implementation issues, and rebuilding has been slow or has not occurred.

The legal and prescriptive nature of rebuilding mandates forces difficult decisions to be made, ensures a relatively high level of accountability, and can help prevent protracted debate over whether and how stocks should be rebuilt. Setting rebuilding times is useful for specifying target fishing mortality rates for rebuilding and for avoiding delays in initiating rebuilding plans, which would otherwise require more severe management responses. However, the focus on trying to achieve a rebuilding target by a given time places unrealistic demands on the science, and forces reliance on forecasts and estimates of biomass-based reference points, which may be very uncertain. Emphasis on meeting fishing mortality targets rather than on exact schedules for

attaining biomass targets may result in strategies that are more robust to assessment uncertainties, natural variability and ecosystem considerations, and less prone to rapid changes in management measures, which have social and economic impacts that may be more severe than more gradual changes. The choice between a rapid or gradual response involves tradeoffs between economic and social impacts and ecological/resource risks, which should be evaluated. The current approach is designed for the nations' most valuable, high-volume stocks, but over half of the nation's stocks have not been assessed and their status is unknown, rendering application of MSY-based control rules unrealistic. Alternate paradigms should be considered for these data-poor stocks.

The Committee offers comments on major issues of rebuilding with a long-term view at further improving the efficiency of the current approach to stock rebuilding. These issues directly or indirectly relate to the overarching issue of what is the appropriate balance between prescription and flexibility in stock rebuilding. Many of our comments could serve as suggestions for research and application to future revisions of National Standard Guidelines to improve the overall performance of stock rebuilding programs and thereby enhance the benefits derived from fisheries in the future.

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ARTICLE

An Evaluation of Harvest Control Rules for Data-Poor Fisheries

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Abstract
For federally managed fisheries in the USA, National Standard 1 requires that an acceptable biological catch be set for all fisheries and that this catch avoid overfishing. Achieving this goal for data-poor stocks, for which stock assessments are not possible, is particularly challenging. A number of harvest control rules have very recently been developed to set sustainable catches in data-poor fisheries, but the ability of most of these rules to avoid overfishing has not been tested. We conducted a management strategy evaluation to assess several control rules proposed for data-poor situations. We examined three general life histories ("slow," "medium," and "fast") and three exploitation histories (under-, fully, and overexploited) to identify control rules that balance the competing objectives of avoiding overfishing and maintaining high levels of harvest. Many of the control rules require information on species life history and relative abundance, so we explored a scenario in which unbiased knowledge was used in the control rule and one in which highly inflated estimates of stock biomass were used. Our analyses showed that no single control rule performed well across all scenarios, with those that performed well in the unbiased scenario performing poorly in the biased scenarios and vice versa. Only the most conservative data-poor control rules limited the probability of overfishing across most of the life history and exploitation scenarios explored, but these rules typically required very conservative catches under the unbiased scenarios.

In many fisheries, management actions are based on estimates of stock biomass and management targets (biological reference points [BRPs]) produced from stock assessment models. Such models typically require long time series of catch and relative abundance by age and often life history information, and stocks for which there is such information are considered "data rich." For many stocks, however, this information is lacking, preventing the use of a data-driven assessment model. Such stocks are considered "data poor," and they pose a challenge to fisheries managers.

In the USA, fisheries managers are now confronting this challenge due to the Magnuson–Stevens Fishery Conservation and Management Reauthorization Act (MSFCMRA). The act requires that the Statistical and Scientific Committees of each of the eight regional fisheries management councils recommend acceptable biological catch (ABC) levels for all stocks under a fisheries management plan. National Standard 1 of the MSFCMRA further requires that the ABC prevent overfishing (i.e., when the fishing mortality rate exceeds that which produces the maximum sustainable yield, or F_{MSY}), while still attempting to achieve optimum yield for the fishery. To prevent overfishing, the ABC must have a probability of overfishing (P_{OF}) that does not exceed 50%. Scientific uncertainty must also be considered in the selection of an ABC, with the goal of achieving a specific, acceptable probability of overfishing. Importantly, the ABCs constrain the council's annual catch limits, which may not exceed the ABC.

For data-rich stocks, approaches have been developed for selecting a catch level that is expected to achieve a specified probability of overfishing, or P^* (Shertzer et al. 2008). Although

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arising from the vertical density gradient and the sloping interface

$$\alpha g \int_0^{\delta} (\rho - \rho_\delta) dz \qquad (1)$$

is balanced by the turbulent shear stress at the interface. With density ρ and layer height δ taken from the CTD profile and basal slope α calculated from depth differences between Drill A and B, the buoyancy force is estimated at 0.043 Pa. This compares favorably to the average shear stress measured by the flux package, ρu_*^2= 0.076 Pa (Fig. 4B), indicating that the observed boundary layer flow is forced by the melt-generated buoyancy acting along the sloping base of the shelf.

These in situ measurements of the underside of the PIG ice shelf reveal strong but spatially non-uniform ice/ocean interaction, in which ocean boundary layers are strongly coupled to basal melting: They are buoyantly forced by melt water and are constrained by the resulting melt channel morphology. The pRES melt rate estimates document the cross-channel variability in melt rate that results from the channelized flow, whereas the longer-term flux package estimates demonstrate that melt rates and boundary layer properties were fairly steady over the month of observations, which is consistent with the idea that the forcing is due to the relatively slowly evolving buoyancy field within the ocean cavity. If these direct melt rates within the channel are annualized, they range between 14.2 and 24.5 m year^{-1}. However, we expect that melt rates will be affected by seasonal or other long–time-scale variability associated with the oceanic forcing. We also expect along-shelf spatial variability in cross-shelf melt patterns, as supported by recent altimetry analyses (*13*) that infer preferential melting of keels toward the terminus. The continuity of the channels seen in satellite imagery and the airborne radar survey, in conjunction with the vigorous melt rates here described, indicate that basal melting is active from the grounding line to at least the mid-shelf location of the observations. In addition to our observations, a recent idealized numerical simulation of an ice shelf base and ocean boundary layer has suggested that channelization is of fundamental importance, because a channelized base actually melts much less vigorously than a nonchannelized one (*14*). The remarkable ice/ocean coupling evident in our observations points to the need to represent channelized ice/ocean interaction in models of PIG and similar outlet glaciers in global climate simulations of sea-level change.

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Supplementary Materials

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Marine Taxa Track Local Climate Velocities

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Organisms are expected to adapt or move in response to climate change, but observed distribution shifts span a wide range of directions and rates. Explanations often emphasize biological distinctions among species, but general mechanisms have been elusive. We tested an alternative hypothesis: that differences in climate velocity—the rate and direction that climate shifts across the landscape—can explain observed species shifts. We compiled a database of coastal surveys around North America from 1968 to 2011, sampling 128 million individuals across 360 marine taxa. Climate velocity explained the magnitude and direction of shifts in latitude and depth much more effectively than did species characteristics. Our results demonstrate that marine species shift at different rates and directions because they closely track the complex mosaic of local climate velocities.

Global warming during the past century has had many biological effects, including changes in phenology and poleward shifts in species distributions (*1–3*). However, species have not responded uniformly, and shifts in their distributions have occurred at widely different rates and in different directions (*1–10*). In both marine and terrestrial assemblages, up to 60% of species are not shifting as expected; i.e., to higher latitudes, higher elevations, or greater depths (*1–10*). A range of hypotheses has been proposed to explain this observed variation, including the effects of habitats (*11*), species interactions (*11*, *12*), sensitivity to environmental gradients (*13*), response times (*10*), colonization abilities (*14*), and physiological or evolutionary adaptations (*15*). In essence, many of the leading hypotheses have emphasized biological differences among species (*8–10*, *14*).

An alternative and possibly more general hypothesis posits that local differences in climate velocity (*16*, *17*) can explain heterogeneity in species shifts. Climate velocity is the rate and direction that isotherms shift through space, and it combines both temporal and spatial rates of temperature change (*16*, *17*). Previous authors have hypothesized that species may follow

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climate velocities (*16–19*), but a direct test has not been attempted (*2, 13, 18*). An examination of broad taxonomic groups found faster shifts in regions of higher climate velocities but did not examine variation among species or shifts toward lower latitudes (*2*). These issues are particularly important in the ocean, where climate velocities are up to seven times higher than on land (*16, 18*).

To understand how marine species respond to climate velocity, we compiled four decades of scientific surveys of fish and invertebrates from the continental shelves of North America across nine regions spanning ~3.3 million km^2 and 60,394 bottom-trawl samples from 1968 to 2011 (fig. S1 and table S1). These surveys captured 128 million organisms from 580 populations of 360 species or species groups; we refer to these collectively as "taxa."

We measured range shifts by tracking the location of range centroids (*20*). Taxa showed considerable variation in the direction and rate of shifts, both within regions (Fig. 1, B to D) and between regions (Fig. 1A and figs. S2 to S4). Individual species shifted north (for example, American lobster in the northeast), south (big skate on the west coast), or remained approximately stable (Pacific cod in Alaska, Fig. 1). Defining an assemblage as the set of sampled taxa within a geographic region, four assemblages shifted poleward (Fig. 1, A, B, and D), whereas five shifted south (Fig. 1, A and C, and fig. S2). For example, assemblages from the west coast and the Gulf of Alaska shifted south at >11 km/decade during a cooling period that is thought to reflect multidecadal climate variability (*21*).

At the assemblage level, regional temperature changes explained differences in observed shifts, although modified by geographic constraints. Assemblage shifts were positively but weakly related to bottom temperature trends ($r^2 = 0.27$, $P = 0.15$, $n = 9$ regions; Fig. 2A). However, the Gulf of Mexico assemblage (Fig. 1C) was an outlier in this relationship and the only warming region with an east-west coastline that prevented poleward shifts. Instead, this assemblage shifted deeper (Fig. 2D). After this region was omitted, bottom temperature explained more than half of the variation in assemblage shifts ($r^2 = 0.60$, $P = 0.023$, $n = 8$ regions). Surface temperature trends were not correlated to latitudinal shifts ($P = 0.75$, $r^2 = 0.02$; without the Gulf of Mexico, $P = 0.53$, $r^2 = 0.08$). However, assemblages that experienced increasing surface temperatures tended to shift deeper, away from warming waters ($r^2 = 0.80$, $P = 0.0028$, $n = 8$ regions; Fig. 2D and fig. S5). Depth shifts were not related to bottom temperature changes ($r^2 = 0.12$, $P = 0.36$). These relationships concern whole assemblages, not individual taxa. Individual shifts were weakly correlated to changes in average regional temperature (latitude versus bottom temperature without the Gulf of Mexico: $P = 0.0013$, $r^2 = 0.022$, $n = 474$ taxa; depth versus surface temperature: $P < 0.0001$, $r^2 = 0.05$, $n = 497$ taxa).

Although regional patterns can be informative, they do not reveal the extent to which individual taxa follow local variation in climate velocities. Climate velocities are often calculated for grid cells (*16, 17*), but taxon distributions are irregular and a taxon-specific version of climate velocity is needed that averages velocities across species' ranges. We therefore used survey data

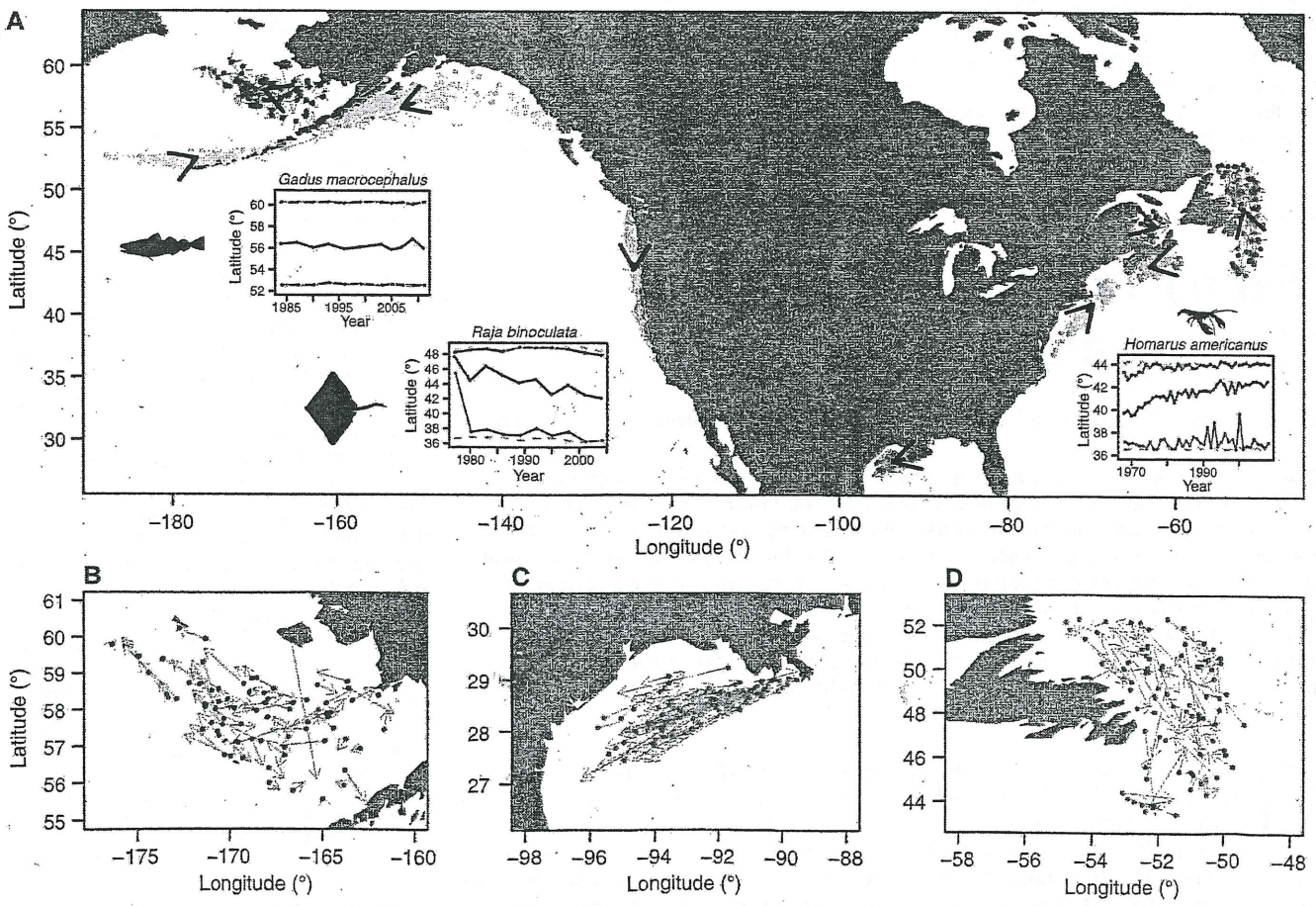

Fig. 1. Shifts in the distribution of marine taxa. (**A**) Vectors show the average shift in latitude and longitude for each taxon (colors) and the mean shift in each region (black). Insets show the mean (black), maximum (blue), and minimum (red) latitude of detection for Pacific cod (*Gadus macrocephalus*) in the Gulf of Alaska, big skate (*Raja binoculata*) on the U.S. West Coast, and American lobster (*Homarus americanus*) in the Northeast. Gray dashed lines in insets indicate the range of surveyed latitudes. Detailed views are also shown of (**B**) the Eastern Bering Sea, (**C**) the Gulf of Mexico, and (**D**) Newfoundland.

to calculate the temperature range inhabited by each taxon and measured taxon-specific climate velocity as the rate and direction that these temperatures shifted across the landscape (*20*). We found considerable spatial variation in climate velocities (Fig. 3). The taxa also showed considerable heterogeneity: 46% shifted south and 58% shifted shallower (Figs. 1 and 3 and figs. S5 and S6).

Such heterogeneity among taxa, however, was not random. Instead, differences in climate velocity explained much of the variation in the rate and direction of latitudinal range shifts ($r^2 = 0.38$, $P < 0.0001$, $n = 325$ taxa; Fig. 3A). The relationship remained significant if random effects for region were included ($P < 0.0001$) or if we used bootstrap resampling to generate a null distribution of correlations ($P = 0.019$) (*20*). Across all taxa, 74% shifted latitude in the same direction as climate velocity, and 70% shifted depth in the same direction. This explanatory power was equally high for "non-intuitive" shifts that deviate from the poleward-and-deeper pattern: 73% of shifts to lower latitudes and 75% of shifts toward shallower water were explained by climate velocity.

To estimate whether taxa were shifting faster or slower than climate velocity, we measured the bias [in degrees north (°N) per year] as well as relative bias between taxon-specific velocities and observations (*20*). However, we found that taxa on average do not lag (bias: $P = 0.13$, mean = 0.003 °N/year; relative bias: $P = 0.39$, mean = 4.68).

Climate velocity can also be projected across depth, and we found evidence that climate velocities can explain variation in the rate and direction that taxa shifted shallower or deeper ($r^2 = 0.13$, $P < 0.0001$, $n = 325$ taxa; Fig. 3B and fig. S7). Depth biases were not significantly different from zero (bias: $P = 0.60$, mean = −0.040 m/year; relative bias: $P = 0.49$, mean = 3.8), again indicating little to no lag in species response to changing climate.

There was little evidence that other factors could explain variation in the speed and direction of taxon shifts. For example, adding survey and species characteristics to a multiple regression model only increased the explained variance in species shifts for all taxa from 38% (model with climate velocity as the only explanatory variable) to 42% (full model with all variables), or from 36 to 45% for fish (Table 1 and table S5). Survey and species characteristics, however, may be more likely to influence the speed (absolute value of °N/year) rather than the combined speed and direction of observed shifts. Higher relative variable importance (RVI) for survey extent and duration, as well as for climate velocity (table S4), suggested that the most rapidly shifting species might not appear in our analysis because they left the survey area. There was also limited evidence that invertebrates, commercially fished taxa, pelagic taxa, taxa with declining biomass, fish with small ranges, fish higher in the food chain, and large fish shifted faster (tables S4 and S5). Such species characteristics, however, explained at most 1.3% of the variation in speed across all taxa (3.3% across all fish), as compared to 18% for climate velocity (or 20% across all fish). We conclude that variation in the environment is a much more powerful predictor of taxon shifts than variation in life history.

A previous study also found that species traits had little power to explain distribution shifts, but it did not examine climate velocities (*14*). Likewise, climate heterogeneity has been connected to the direction but not magnitude of shifts in birds and fish (*3*, *5*, *7*, *13*). Recognizing and quantifying heterogeneity in climate velocities across multiple scales may substantially improve our ability to explain ecological changes and project into the future. Our findings suggest that bioclimate envelope methods are valuable (*19*) but can be improved by the use of fine-scale climate data.

Beyond climate velocity, other influences on species shifts probably include species interactions (*12*), fisheries harvest, habitat, and species' abilities to disperse and adapt (*14*, *15*). Release from a poleward-shifting predator, for example,

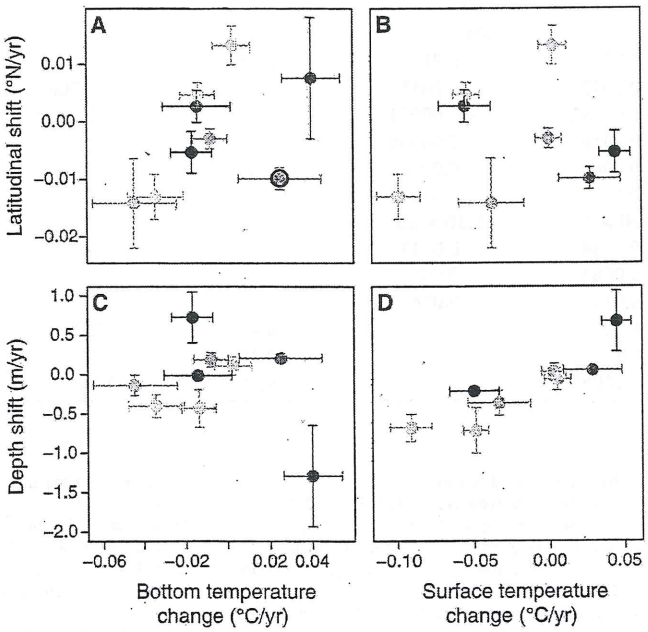

Fig. 2. Relationships between sea temperature change and assemblage shifts. (**A**) Latitude shifts versus bottom temperature (the black circle marks the Gulf of Mexico), (**B**) latitude shifts versus surface temperature, (**C**) depth shifts and bottom temperature, and (**D**) depth shifts and surface temperature. Positive depth shifts are toward deeper water. Error bars show standard errors, and colors match the taxon vectors in Fig. 1.

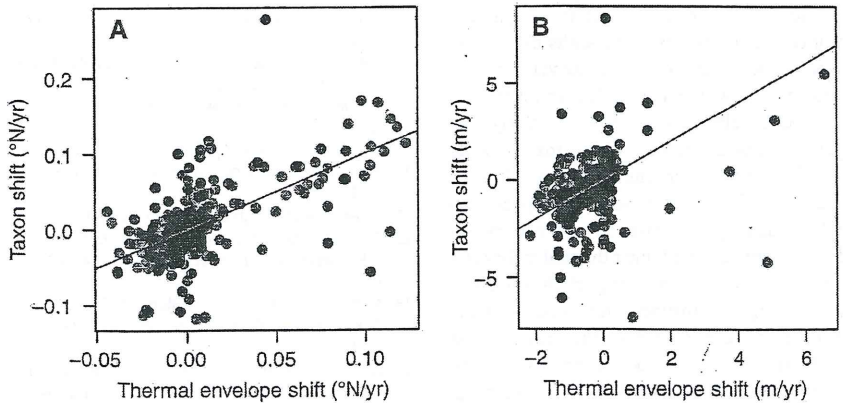

Fig. 3. Climate velocity and taxon shifts. The relationship between taxon-specific climate velocities and observed shifts in taxon range centroids is shown for (**A**) shifts in latitude and (**B**) shifts in depth. The 1:1 line is shown in red.

Table 1. Models explaining the direction and speed (°N/year) of latitudinal shifts in taxon distributions. Models were fit to data either for all taxa (top section, $n = 325$ taxa) or for fish alone (bottom section, $n = 199$ taxa). RVI ranks all explanatory variables from high to low importance. The model coefficients associated with each variable are shown for the most parsimonious model with the lowest Akaike information criterion (AIC) value (best model); a model with all factors retained (full model); a multimodel average (model average); and models with only climate velocity, only survey characteristics (survey char.), or only species characteristics (species char.) retained as explanatory variables. The ΔAIC indicates the difference in model parsimony as explained by AIC relative to the best model; a ΔAIC value <10 indicates higher support for a model. Values of r^2 and Akaike weight for each model are also shown. RVI and Akaike weights were calculated across all possible models (128 for all taxa, 1024 for fish alone).

Variable	RVI	Best model	Full model	Model average	Climate velocity	Survey char.	Species char.
				All taxa			
Climate velocity	1	0.92	0.87	0.9	0.96		
Survey extent	0.505		0.00093	0.00044		0.005	
Survey duration	0.3		0.00015	1.80×10^{-5}		0.0012	
Fish/invert.	0.796	0.011	0.0098	0.0084			0.02
Unfished/fished	0.848	−0.0087	−0.0085	−0.0079			−0.0099
Pelagic/demersal	0.776	0.016	0.014	0.012			0.024
Biomass trend	0.45		0.0048	0.0023			0.0056
ΔAIC		0	2.52		11.1	127	145
r^2		0.41	0.42		0.38	0.12	0.081
Akaike weight		0.11	0.03		0.00041	3.50×10^{-29}	2.90×10^{-33}
				Fish			
Climate velocity	1	0.76	0.77	0.78	0.93		
Survey extent	0.838	0.0023	0.0017	0.0018		0.0063	
Survey duration	0.42		−0.00041	−0.00021		0.00074	
Growth rate	0.3		−0.0016	−0.00066			−0.0091
Unfished/fished	0.41		−0.0068	−0.0028			−0.0025
Pelagic/demersal	0.947	0.028	0.023	0.025			0.041
Range size	0.286		3.70×10^{-5}	1.30×10^{-5}			0.00013
Biomass trend	0.344		0.0034	0.0013			0.0046
Trophic level	0.356		−0.0061	−0.0022			−0.005
Maximum length	0.956	0.014	0.014	0.014			0.013
ΔAIC		0	8.63		20.4	72.1	95.9
r^2		0.44	0.45		0.36	0.18	0.13
Akaike weight		0.071	0.00095		2.60×10^{-6}	1.50×10^{-17}	1.10×10^{-22}

could drive a prey's range centroid toward lower latitudes. However, even such shifts would be subject to the physiological constraints imposed by thermal conditions.

We find that marine taxa follow climate velocities with surprising accuracy, a pattern that holds largely irrespective of individual life histories. Hence, it appears that much of the seemingly individualistic variation in the magnitude and direction of species range shifts can be explained by local variation in climate velocity. Our results contrast with evidence that terrestrial species lag behind climate velocity (*4*, *10*) [though see (*5*)] and suggest that marine species may be better able to keep pace with climate change. Marine species may shift more rapidly than species on land because they face fewer barriers to dispersal and more completely fill their thermal niches (*6*). However, the observed rapid range shifts will fundamentally reorganize marine communities. Climate-induced movements of highly commercial species have already sparked cross-border fisheries conflicts, and they can confound traditional management approaches (*8*). Forecasts of climate velocity may provide an important tool to anticipate the scale and magnitude of these impacts now and into the future.

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Supplementary Materials

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Materials and Methods
Figs. S1 to S6
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