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TRANSITION FROM LOW TO HIGH DATA RICHNESS: AN EXPERIMENT IN ECOSYSTEM-BASED FISHERY MANAGEMENT FROM CALIFORNIA

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ABSTRACT

Fisheries can cause major impacts on ecosystems, but the goal of managing them sustainably requires more and different information than we now have. Few fisheries have the legal mandate for ecosystem-based management or to apply precautionary management when information is lacking, so fishermen have little incentive to demand improved information. The California Marine Life Management Act of 1998 requires the maintenance of ecosystem health and diversity in California's complex nearshore ecosystems. We present the key elements, the scientific rationale, and an implementation plan for the transition from information-poor, precautionary management to information-rich, spatially explicit ecosystem-based management in the California nearshore finfish fishery. These elements are included in a fishery management plan adopted by the state in 2002. Marine reserves serve as reference points in repeated-measures before–after control-impact experimental design, in addition to their more familiar conservation benefits. The complexity of scientific monitoring, the statistical power of the monitoring design, and the benefits to consumptive and nonconsumptive uses and values all increase from information-poor to information-rich management. The most significant scientific hurdle comes with incorporation of ecosystem and environmental variability effects.

Resource managers and fishery scientists generally agree that caution must be given higher priority in management of our impacts on wild stocks and on the ecosystems that sustain them. Agreement is also growing that fishery management must go beyond single-species impact management to incorporate ecosystem considerations explicitly. The goal is a sustainable relationship between man and the sea. This approach, in which ecological integrity is given greater importance than short-term benefits to the human enterprise (Stanley, 1995), is called "ecosystem-based management" (EBM). EBM for fisheries has been endorsed by the European Union, the United Nations Food and Agriculture Organization, the National Research Council, the National Marine Fisheries Service, and even some fishery management councils (North Pacific Fishery Management Council, 1999). Data acquisition designed specifically to support EBM is progressing in the Gulf of Alaska/Bering Straits region (Livingston, 1999) and California (the present paper). Now we are down to the details of making EBM work.

The Surplus Production Model and Ecosystem-based Management

With adequate resources, fishery biologists can estimate fish populations and biomass on the basis of landings (fishery-dependent data) and fishery surveys (fishery-independent data). These data are put into population models that calculate the number or biomass of any one species that can be taken without sending its stock into decline. These are called "surplus production" models and are fraught with serious pitfalls (Graham, 1935; Larkin, 1977). By this means, up to 40% of the ocean's production has been deemed "surplus," available for human use. In addition to providing sport and food for humans (either directly or as fertilizer or food for farmed fish), the marine species that we catch also play various roles in supporting each other's populations, as well as functioning as part of an ecosystem that is deemed valuable by noncommercial criteria, ranging from ethical to utilitarian. Fishing a species at its theoretical maximum sustainable yield (MSY), or even its optimum yield (OY) as OY has routinely been interpreted, greatly diminishes that species' function as a predator, prey, or symbiont to other perhaps equally desirable species. These relationships complicate management of multispecies fisheries and multiple fisheries in one system. For example, the sum of the MSYs for all of the species in a fishery cannot be sustainable in the aggregate; it is not possible to maximize yield by this means for many species at once (Brown et al., 1976; May et al., 1979; Link, 2002b). The standard MSY approach also tends to overlook humans' status as versatile predators with very complex behavior (Johnson, 1994). Finally, the MSY approach conveys the notion that fish populations are under direct human control. The inherent fallacy in this "command and control" approach to human interactions with "complex, nonlinear, and poorly understood" natural systems has been clearly pointed out by Holling and Meffe (1996) among others.

Scientific effort can be adjusted to provide the necessary additional information on multispecies considerations, ecosystem effects, and even changing ocean conditions, and the results incorporated into management. Up to now most real-world applications of EBM have concerned by-catch reduction for endangered or endearing nontarget species that fall prey to a particular fishery (e.g., Steller sea lion in the Bering Sea) plus rare consideration of nontarget species and environmental change (e.g., Pacific sardines in the California Current System, Pacific Fishery Management Council, 1998a).

The Marine Life Management Act: A New Paradigm for California Fisheries Management

The situation for fishery management is now distinctly different in the state of California, where by law it must now become ecosystem based. As a single jurisdiction that is now legally friendly to EBM, California provides a good case study of the transition between old and new approaches. California's Marine Life Management Act (MLMA), which became law in 1999, requires that human activities in the ocean be sustainable. The MLMA defines "sustainable" uses as those that secure the fullest range of present and long-term ecological benefits, including maintenance of biological diversity (Weber and Heneman, 2000). This goal is a challenge given California's size, complex nearshore ecology, and multispecies fisheries. Moreover, because the MLMA concerns more than fishery management, it also requires consideration of nonconsumptive uses. The MLMA also required the state to begin managing its fisheries with management plans (FMPs). The second FMP, and the first multispecies plan, mandated by the MLMA was for the complex nearshore finfish fishery.

The Nearshore Fishery Management Plan and the Path to EBM

In 2000, the Secretary of Commerce joined the governors of California, Oregon, and Washington to declare the federally managed West Coast groundfish fishery a disaster. In the fall of 2002, federal managers closed most of the continental shelf portion of this fishery, a situation likely to continue for decades because of the lengthy rebuilding timetables for bocaccio (*Sebastes paucispinus*) and other *Sebastes* species. Target populations of most state-managed fishes and invertebrates were fully or overexploited. These federal closures are expected to cause increased recreational and commercial pressure on the state-managed nearshore finfish species included in the nearshore FMP (NFMP). As a result, the closures provide a strong incentive to improve management in the nearshore.

The "nearshore," ill defined in the state's NFMP, includes the bulk of the ranges of 19 finfish species resident mostly in rock and kelp habitats that support the recreational and commercial nearshore fishery (Table 1). The 19 species, and fishing activities for them, are concentrated in depths less than 40 m and rarely penetrate beyond 80 m. The commercial fishery is primarily a live-fish fishery, pursued with hook-and-line gear and traps, so habitat damage due to fishing is minimal. Fishing is currently the dominant human impact on the NFMP species, although with marked regional variation in character both biologically and socioeconomically. The challenge for the California Department of Fish and Game was to craft an FMP for the 19 species that incorporated the best of classical single-species management while fulfilling MLMA mandates for sustainability, ecosystem conservation, and nonconsumptive uses.

Staged Risk Reduction—Summary of the NFMP Control Rule

The MLMA applies to all components of the nearshore marine ecosystem, not just finfishes, but California did not have the capacity to jump instantly into ecosystem-impact management. A three-stage blueprint was therefore designed to phase in EBM. At its heart, the NFMP is conventional in having a control rule that relates total allowable catch (TAC)—fishing mortality—to population size. Like any other effective fishery management policy, it also defines overfishing and prescribes what to do about it. Beyond this point, however, the control rule for the NFMP is unconventional in emphasizing three underlying principles:

First, certain irreducible uncertainties may never be resolved, so precaution at the outset is essential. The need for precaution can be reduced with improved information, though never eliminated.

Second, single-species management has commonly tended toward inadvertent overexploitation. Ecosystem-based management requires the application of more conservative tools to address this problem and reduce the risk of overexploitation.

Third, better information may ultimately result in higher TACs.

The control rule (drafted by the authors) that was incorporated in the NFMP and adopted by the California Fish and Game Commission in August 2002 is intended to meet three fundamental objectives: (1) to maintain healthy populations of target species, (2) to avoid extreme fishery effects on the ecosystem, and (3) to anticipate the effects of environmental change on the fished populations.

Finally, the control rule proceeds through a progression of three stages that provide a transition from information-poor to information-rich human-impact management: Stage I, data-poor (precaution the primary basis for setting TACs); Stage II, data-moderate (improved single-species or multispecies management and a transition from blind precautionary management to informed risk management); and Stage III, data-rich (ecosystem-based fishery management).

We borrowed some of the terminology above from Restrepo et al. (1998), but our definitions are necessarily different. Restrepo et al. were concerned with a surplus-production model and explicitly did not consider ecosystem relationships or environmental flux.

Table 1. The 19 species of finfishes covered by California's Nearshore Fishery Management Plan.

Species	Common name	Depth range (m)
Primarily northern		
monkeyface prickleback	*Cebidichthys violaceus*	Intertidal–24
greenling, rock	*Hexagrammos lagocephalus*	Intertidal–shallow
greenling, kelp	*Hexagrammos decagrammus*	Intertidal–45
rockfish, china	*Sebastes nebulosus*	9–90
rockfish, black	*Sebastes melanops*	Intertidal–91
rockfish, quillback	*Sebastes maliger*	23–273
Primarily central		
rockfish, black-and-yellow	*Sebastes chrysomelas*	Intertidal–36
rockfish, gopher	*Sebastes carnatus*	9–36
rockfish, blue	*Sebastes mystinus*	Intertidal–91
Primarily southern		
rockfish, kelp	*Sebastes atrovirens*	5–15
treefish	*Sebastes serriceps*	3–45
California sheephead	*Semicossyphus pulcher*	3–55
rockfish, olive	*Sebastes serranoides*	1–145
California scorpionfish	*Scorpaena guttata*	3–182
rockfish, calico	*Sebastes dallii*	18–255
Common statewide		
cabezon	*Scorpaenichthys marmoratus*	Intertidal–76
rockfish, copper	*Sebastes caurinus*	3–182
rockfish, grass	*Sebastes rastrelliger*	Intertidal–6
rockfish, brown	*Sebastes auriculatus*	3–55

The descriptions of the three stages imply a stepwise progression, but implementation will differ in degree and timing for different species and regions. The jump from Stage I to Stage II is dramatic, because the Stage II information threshold allows a fundamental change in the approach to setting TACs. Transition to Stage III, however, will proceed by small steps and cumulatively as new information is incorporated into ecosystem-impact and environmental-change models. The control-rule approach allows the triggers for regulatory action to change as information quality and quantity improve and as the system itself undergoes flux. The control-rule approach looks very much like an MSY/OY control rule in which MSY is reset every year or so on the basis of new information and where TACs truly incorporate catch reductions for relevant ecological factors (as in the Magnuson-Stevens Fishery Conservation and Management Act definition of OY).

The novelty here is the explicit, staged approach to integration of different levels of information about the demographics of target species with different levels of information about ecosystem relationships. The three stages produce formulas for deriving TACs that are appropriate for a given level of awareness about the system. The result is a control rule intended to ensure sustainable catches as defined in the MLMA. Specifically, the result will be a level of catch that allows the maintenance of all of the ecological benefits and biological diversity in the nearshore ecosystem. Control of total mortality in target species will limit fishery-caused changes in ecosystem process indicators (e.g., food-web length).

Precautionary TACs that encompass ecosystem effects are only one of several management instruments in the NFMP intended to help make fisheries sustainable in the holistic sense dictated by the MLMA. The control rule also requires the creation of marine protected areas (MPAs) to ensure basic levels of ecosystem conservation (Murray et al., 1999), as well as the protection of nearshore environments and biota for nonconsumptive uses. MPAs, in this case, mean areas deemed large enough by the state to confer some conservation benefit, where fishing for at least the 19 NFMP species is prohibited. The state has decided that selection of these MPAs will be subsumed in a separate state-mandated process for creating MPAs, including a network of no-take marine reserves. The NFMP anticipates that fishery management benefits of MPAs include buffering against management mistakes, full protection for some fraction of target populations, and possible increased reproductive potential due to the restoration of more natural age structures. MPAs should provide a degree of protection against overfishing. If a population is depressed, MPAs should speed the rebuilding process. MPAs may also increase fishery yields outside their borders over time (Roberts, 1995, 1998; Sladek-Nowlis and Roberts, 1999). Because MPAs allow resident fish to live out their natural life spans, they allow populations to benefit from the naturally evolved life-history strategies against prolonged recruitment failures such as those seen in the 1990s for long-lived species such as rockfishes. This function is especially critical in the California nearshore, where long-lived species comprise a large proportion of the fauna.

Science to Support the NFMP

Both the management and the monitoring protocols for the NFMP were laid out in such a way that the California Department of Fish and Game could move gracefully from the current information-poor, strictly precautionary management to information-rich, ecosystem-based management. The program created to acquire essential fishery information is called "Collaborative Research and Assessment of Nearshore Ecosystems" (CRANE). CRANE is a collaboration among the Department of Fish and Game, the Channel Islands National Marine Sanctuary, academic institutions, and other interested and capable parties. CRANE has begun a nearshore survey program emphasizing SCUBA, remotely operated vehicles, and, eventually, experimental fishing surveys. CRANE was conceived as a large adaptive-management experiment in the California nearshore zone. The experimental design encompasses areas subject to different levels of fishing effort, including fully protected reference reserves, for evaluating management and assessing the long-term health of the nearshore environment.

The CRANE survey protocols include all the most ecologically or economically important taxa, not just the 19 NFMP finfish species. Although the ultimate goal is to understand changes in the nearshore ecosystem, along the way the monitoring program will support management of a variety of fisheries (e.g., finfish, sea urchins, lobster, abalone, kelp). In the pilot surveys initiated in fall 2002, the fishes, invertebrates, and habitat attributes were quantified simultaneously. The inclusion of reference reserves in the NFMP and in the CRANE program is a crucial element of the plan. Reference reserves are intended to be fully protected areas used for comparison with fished areas. They need not be large enough to confer direct conservation benefits.

The difficulty with this approach at present is that few areas in California are large enough or mature enough to serve as reference reserves. There is cause for considerable optimism, however. At the outset, CRANE included several tiny, existing marine protected areas in the design. Soon after, in October 2002, the California Fish and Game Commission designated 10 marine reserves totaling 453 km^2 at the Channel Islands in southern California. Furthermore, the state's Marine Life Protection Act of 1999 mandates development of a plan for a statewide network of marine reserves. Finally, the Fish and Game Commission has decided that a process to modify the boundaries of existing, small reserves to make them suitable as reference reserves can precede the Marine Life Protection Act process, which may take several years. Populations in these reserves have not been assessed, nor have they fully responded to the elimination of fishing pressure. The intended function of these reference reserves in Stage III will entail determination of whether populations within the reserves have reached levels that serve as reasonable indicators of an unfished state under the prevailing environmental conditions.

Because Stage III management will be data driven, its full implementation is probably several years in the future for nearshore finfishes, although the time frame may be shorter for some short-lived species. The elements of Stage III management can still be put gradually in place as information becomes available.

Stage I: Establishing Control Rules under Precautionary Management in a Data-Poor Environment

Stage I, data-poor management uses precaution as the primary basis for setting TACs. Management decisions are based solely on catch history, the primary information available. Information on stock size, life history, ecosystem relationships of the target species, and the effects of environmental change are all minimal or lacking. TACs are set equal to a fraction of the average catch of some series of years (ideally, when evidence indicates that abundance was not declining). This application of risk management provides a reasonable expectation that overfishing will be avoided at the reduced level of catch. In the absence of information to the contrary, the fraction is 50%. This figure is based on the assumption that the stock is below the target biomass but above the overfished threshold. Several authors have been developing new formalizations for precautionary management. The one used in the NFMP is consistent with that described by Restrepo et al. (1998) for precautionary management in a data-poor environment. This approach is already in practice in California. The California Fish and Game Commission adopted this formula in the interim regulations for cabezon (*Scorpaenichthys marmoratus*), California sheephead (*Semicossyphus pulcher*), and greenling (*Hexagrammos* spp.) in December 2000. The Pacific Fisheries Management Council adopted this approach to set OYs for its "minor rockfish" category, which includes the rockfishes and scorpionfish included in the state's NFMP (family Scorpaenidae).

Fishery management often ignores the tendency for species or assemblage ranges to straddle distinct ecological and/or biogeographical regions and the resulting differences in biology, even within single species, across diverse natural selection regimes. Consequently, the NFMP divides the California nearshore into four management regions that the state, with advice from marine scientists and fishermen, has determined make sense both biologically and socioeconomically. The demarcation points for these four regions are at Point Conception, Año Nuevo Point, and Cape Mendocino; all are transition areas between water-movement and thermal regimes. All management measures—TACs, sport/commercial allocation, commercial restricted access, gear restrictions, time and area closures—can vary regionally.

In some cases, the characteristics of the nearshore fishery and catch-reporting limitations necessitate pooling the TAC for a complex of related species. For example, it is not possible to fish for individual rockfish species to the exclusion of others, and identification of catch to species level is sometimes unreliable. For these taxa, the *Sebastes* species in the NFMP, pooled TACs have been defined. To be precautionary, pooled TACs must operate by weakest-link management, in which gear selectivity is low and allowable catches for more abundant species are constrained by allowable catches for cooccurring, less abundant species.

As of this writing, Stage I management applies to all 19 NFMP species. Some species will be eligible for Stage II management before others; cabezon and California sheephead are anticipated to be the first candidates because better catch, life history, and recruitment data exist for those species. A cabezon stock assessment is scheduled for 2003.

Stage I Steps for the Transition to Stage II

Under the arbitrary precaution of Stage I, the only standard for success in meeting the three control rule objectives is not exceeding TACs. Quantitative evaluation is impossible before Stage II. In anticipation of the transition to Stage II management, the quality and quantity of data, necessary for less blind precaution and more informed management, must increase during Stage I. Seven areas deserve special attention:

(1) *Improvements to the fishery-dependent data base*. These include improving accuracy, completeness, and analysis of the catch data and age/size composition of sport and commercial catches and implementing more accurate methods of recording catch location for evaluating data spatially.

(2) *Implementation of fishery-independent surveys*. Traditionally, such surveys involve experimental fishing and ichthyoplankton sampling. To these, the NFMP adds SCUBA and submersible surveys.

(3) *Improved life-history information for tracking ontogenic changes in life stages*. Marine organisms exhibit interesting, and possibly informative, variation in the duration of individual ontogenetic phases, such as larval duration and duration of the pelagic juvenile phase in rockfishes. These are likely to vary with time and environmental conditions.

(4) *Selection of study areas subject to varied fishing effort, including reference reserves, in each region and initiation of comparative studies of those areas in preparation for Stage II and Stage III management*.

(5) *High-resolution mapping of nearshore habitats*.

(6) *Discard-survival studies of the target NFMP species*.

(7) *Incorporation of existing and new ecosystem information into fishery models* (such as food-web studies and physical oceanographic information).

Stage II: Improved Single- and Multispecies Management in a Data-Moderate Environment

Stage II management can be implemented when data streams from the first six sources listed above are incorporated into models used to set TACs. Stage II represents a major reduction in uncertainty over Stage I, and a concomitantly smaller need for strictly precautionary management, a point of immense importance to both the fishing community and regulators. However, precautionary adjustments to TACs—built into the NFMP control rule—are still necessary because information is minimal about ecosystem effects of the fishery and effects of environmental change on the fishery (Roughgarden and Smith, 1996), the latter of particular concern in an upwelling-forced system like the California nearshore. Stage II management incorporates population modeling and other analyses that replace the strictly precautionary approach to TACs in Stage I.

The traditional calculation of MSY deals with quantities like "virgin biomass" and "carrying capacity" that are very difficult to estimate. In practice, a more useful yardstick is an estimate of what a fish stock would look like at any given time if fishing were not a factor. For this reason, the NFMP employs the terms "unfished biomass" ($B_{Unfished}$) and total allowable catch instead of optimum yield. The NFMP defines $B_{Unfished}$ as an estimate of the biomass or stock size that would exist if there had been no fishing in recent history (within several generations). Changes in $B_{Unfished}$ may be reflected as a change in fecundity, stock density, and/or recruits per spawning individual, with the result that stock biomass is reduced or augmented for some time. On the basis of the estimated $B_{Unfished}$, a TAC will be calculated for each stock, including reductions for social, economic, or ecological factors. In cases where the status of the stock is known but $B_{Unfished}$ cannot be directly calculated because of difficulty in determining a spawner/recruit relation, the NFMP default rate of $F_{50\%}$ is the fishing rate that reduces the average recruits per spawner to 50% of the unfished level.

Accurate population estimates require monitoring of year-to-year variation in recruitment success, growth rates, and environmental conditions. Under Stage II (and Stage III), the objective is to recalculate $B_{Unfished}$ as frequently as the varied types of data allow; annual recalculations should eventually be possible and perhaps essential for some species.

When an assessed stock is believed to be below its $0.6B_{Unfished}$ size, TAC would be reduced below the $F_{50\%}$ fishing rate to facilitate stock rebuilding. In the default approach, TAC is reduced below $F_{50\%}$ along a straight line between $0.6B_{Unfished}$ catch (i.e., applying $F_{50\%}$ at $0.6B_{Unfished}$) and zero catch at 20% of the unfished biomass (i.e., $0.2B_{Unfished}$). This same line would be used as the interim Stage II rebuilding plan if a stock falls below its overfished/rebuilding threshold (i.e., $0.30B_{Unfished}$). The point at which the line intersects the horizontal axis implies that zero catch would be allowed and is also used for determining the slope of the TAC line between $0.6B_{Unfished}$ and $0.2B_{Unfished}$. In some circumstances (e.g., multiple-year recruitment failures), even more aggressive reductions in fishing mortality may be necessary.

These standards in the NFMP control rule are more conservative than those used in the federally managed West Coast groundfish fishery. For example, the Pacific Fishery Management Council's policy for determining rockfish catch limits uses a $F_{40\%}$ fishing rate, which is reduced along a straight line between $0.4B_{Unfished}$ catch (i.e., applying $F_{40\%}$ at $0.4B_{Unfished}$) and zero catch at 10% of the unfished biomass (i.e., $0.1B_{Unfished}$) (Pacific Fishery Management Council, 1998b). The rationale for the more conservative approach adopted in the NFMP is that the federal approach is single-species in a multispecies fishery and does not consider either ecosystem effects of the fishery or the effects of variable ocean productivity on the fishery. The NFMP approach better matches the generally low stock productivity that has been evident for many groundfish species since the early 1980s and reduces the risk of severe depletion due to management mistakes.

When reference reserves have been in existence long enough, they will be able to provide an approximation of unfished biomass. Comparison between fished and unfished areas can then be used to calculate a real $B_{Unfished}$. This value for $B_{Unfished}$ is time and context sensitive and therefore much more biologically realistic and useful than the more arbitrary estimate of virgin biomass. The comparison of reference reserves in each management region with areas open to fishing can therefore provide spatially explicit data to establish TACs based on direct fishing impacts on target fish density, age structure, and population viability. When this situation is reached, overfishing may also be defined as a condition in which spawning biomass per recruit is less than 30% of that inside reference reserves. Ultimately, management approaches such as rolling closures could also be considered as a possible means of maximizing TACs outside of MPAs and reference reserves.

Rebuilding times for stocks below their overfished/rebuilding threshold can be influenced by many factors, including the degree to which a stock has declined, the inherent productivity of the stock, generation time for the stock, and the probability of a successful year class in any given period of time. Rebuilding plans provide for recovery to $0.6B_{Unfished}$. The management responses to exceeding or failing to attain a TAC in Stage II management are the same as for Stage I. As Stage II management progresses, one of the most important advances in data will be that it becomes spatially explicit at an increasingly high resolution. In many cases it may be advantageous to manage the nearshore species on the finest spatial scale for which supporting data are available. For example, some invertebrate species, such as red sea urchins, are already managed in one-mile-square fishery-management blocks nested within the 10-mile-square blocks that are the current standard in California. In some circumstances management of areas as small as individual reefs may make biological sense, but such management is unenforceable and extremely labor-intensive from a regulatory standpoint. The ultimate limit on spatial resolution for management will therefore be set in response to explicit conservation needs as constrained by the spatial resolution of research, the precision with which fishermen and enforcement agents can position themselves at sea, and the ability of regulatory processes to respond.

Basic Stage II management corresponds to the current desired practice for federally managed fisheries, and many fisheries around the world, but with the addition of the precautionary TACs described in this section, which allow for uncertainty about ecosystem relationships. Fishery agencies and institutes have produced abundant data to support the equivalent of Stage II management for many species. Unfortunately, these data are simply not used in practice or to good effect for most of them, as evidenced by the widespread collapse of fisheries under such management. The problem is exacerbated in multispecies fisheries, such as the Pacific Coast groundfish fishery and the California nearshore fishery, where managers tend to sum MSYs despite general recognition that trying to maximize yield for multiple species is a recipe for trouble (Brown et al., 1976; May et al., 1979; Link, 2002b)

Precautionary fishery control rules can help reverse this ratchet. Stage I's precautionary restrictions, to work, should be conservative enough to prevent overfishing even during periods of low productivity. Stage II offers the possibility of rewards for sacrifices made in lean times, because restrictions can be relaxed when better times arrive. Fishermen therefore have an incentive for active support of data gathering, which moves the system as quickly as possible to Stage II management.

Stage III: Ecosystem-Based Management in a Data-Rich Environment

The Marine Life Management Act requires that fishery impacts be managed so as to "conserve the health and diversity of marine ecosystems and marine living resources" (Weber and Heneman, 2000). This goal is ambitious given that even first-order ecological relationships are still only poorly understood. The key is attaining the goal in steps, beginning with measures most protective of the natural system. Study of the higher-level effects of fishing on marine communities is a new, vigorous, and still highly contentious science (May et al., 1979; Kaufman and Dayton, 1997; Johannes, 1998; Jackson, 2001; Pauly et al., 2001; Link, 2002a). Until recently, human effects have been distinguished from other factors that influence marine communities retrospectively (see, e.g., Norris et al., 1998), through correlation analyses, and their glorified form as multivariate analyses such as principal-components or factor analysis. Basically, the correlation of fish landings (a data source of dubious reliability and rigor) with data on the natural environment is determined. Whatever portion of the variance is left over is assumed to be due either to human activities or to noise in the model.

Correlative studies of fishery impacts can be enhanced by stratification of study areas across a range of fishing pressures. The monitoring program associated with the NFMP (described briefly, above) was designed with this goal in mind. Such studies correspond to step 4 in the transition to Stage II management, listed above (selection of study areas subject to varied fishing effort, including reference areas, in each region and initiation of comparative studies of those areas). The maturation of reference reserves will make possible a gradual shift from Stage II to Stage III management. With the inclusion of reference reserves—in which no extractive activities are permitted—the shift is made from purely correlative to truly experimental science.

Making the Shift to Stage III Management

In Stage III, the data for management will be expanded beyond the species-specific life-history and population parameters that form the backbone of Stage II, to encompass nontarget species and physical oceanography. As new information becomes available, models complementary from both single-species and ecosystem perspectives can be incorporated into a powerful forecasting protocol, such as that developed by Vasconcellos (2001) for the Brazilian sardine. The threshold for shifting to Stage III management under the NFMP includes two conditions:

(1) The comparison of study areas subject to varied fishing effort, including reference reserves, in each region. These comparisons will provide data on alteration to food-web and other aspects of ecosystem function that are attributable to fishing and may provide additional useful information for establishing TACs that take basic ecosystem conservation into consideration. Examples would include a switch in prey base, change in productivity at one or more trophic levels, and changes in the connectance (see below) of the food web. To address severe ecosystem effects of the fishery (e.g., insufficient forage for predator species, shift in species composition due to change in predator-prey relative abundance, etc.), a determination can be made as to what sort of management measure would be appropriate, e.g., creation of closed areas, size limits, or gear restrictions, depending on the nature of the impact.

(2) Together with physical oceanographic information, the comparison of protected reference areas with areas open to fishing. This approach will provide data that isolate the influence of climate (or other forces extrinsic to the fishery) and may permit reduc-

tion of TACs to protect populations under stress or increases in TACs during periods of high productivity. For example, even for long-lived species, "grand global ocean-atmosphere rhythms" such as the Pacific Decadal Oscillation could produce long cycles of relatively high or low abundance of NFMP species (Bakun, 1996) that can be factored into raising or lowering $B_{Unfished}$ and TACs.

Perhaps the most difficult aspect of Stage III management is the actual setting of TACs. When a TAC is based in a straightforward manner on simple demographic relationships, the number may be hard to believe or enforce, but at least it is easy to calculate. The control rule's default setting for TACs in Stage III is the same as that for Stage II (and the management responses to exceeding or failing to attain a TAC in Stage III are the same as for Stages I and II), but Stage III TACs and other management measures can be either more or less restrictive than those in Stage II, depending on what increased information indicates about trophic relationships, ecosystem effects of the fishery, effects of environmental change on the fishery, and effects of MPAs.

In Stage III, so many data of so many different kinds may be available that a single value for a TAC may have to emerge from a complicated process of consensus and optimization among multiple models and approaches. That process would not really be so bad, however. The numbers going into the reckoning will be more solid than ever, and their uncertainties much lower. Confidence will be much greater about (1) possible ecosystem effects of the fishery and (2) effects of environmental change on the fishery. This level of information, in turn, can reduce the need for strictly precautionary reductions in calculating TACs. The disadvantage is that emphasis will have shifted from uncertainty about the environment to uncertainty about how people will respond to it. Confident, unforgiving knowledge about the environment and fish stocks will place an acute burden on the fishing industry to find functional ways to adapt to the unavoidable realities of environmental flux. It will bring society back to the time when a fisherman's livelihood—not just his or her life—was at the mercy of the sea rather than human miscalculation.

This discussion begs the major question in Stage III implementation: what, other than the number of fish out there, can we use as discrete measures of change in ecosystem structure and function attributable to fishing or environmental effects? Protocols for measuring such changes, and their corresponding set of catch control rules and other management measures, must still be developed. This area is one of the most important for research and development under the NFMP and for EBM generally. Existing theory puts forward several key parameters for initial consideration. One class of parameters—life-history changes—is already incorporated into the control rules described above. Following are additional examples of ecosystem and environmental information that are included in the control rule as examples of what could be incorporated into Stage III management.

Trophic Parameters

Trophic parameters are quantitative measures of predator-prey relationships that define the overall structure, or topology, of a food web (Dunne et al., 2002). They offer a potentially very useful and sensitive reflection of differences in ecosystem function over time and between reference and exploited areas. Trophic parameters can be measured and interpreted accurately by means of stable-isotope and stomach-content analyses provided that these have been conducted at appropriate spatial and temporal scales and are as complete as possible (i.e., consider all possible prey types, rather than following a limited number of prey types up the food chain). An initial list of trophic parameters worth considering in EBM would include:

Effective Trophic Level.—Effective trophic level (ETL) is a number that describes how high in a food web, on average, a particular individual has been feeding. Estimations of trophic level are of course influenced by the degree to which an individual's or species' trophic level can be viewed as a constant. The information from ETL differs from that obtained from stomach contents or a synthesis of diet studies in the literature because, rather than averaging the behavior of a species over many individuals, each viewed at a single point in time (e.g., as in Pauly et al., 2001), ETL is an individual-based measure integrated over a period of several weeks. It is measured directly as the degree to which the tissues of an individual exhibit enrichment in heavy stable nitrogen, relative to other species in the community, and especially as compared to the primary producers that form the base of the food web. When combined with age and growth data, ETL can be used to quantify changes in the life history of an individual, population, or species through ontogeny.

Maximum Food-Chain Length.—Maximum food-chain length is an estimate of the maximum number of trophic links in a community. It can be derived either from the number of trophic levels below the apex predator in a community or from the maximum level of heavy nitrogen enrichment exhibited by the top carnivore in the assemblage. Together ETL and maximum food-chain length offer sensitive measures of "fishing down" in a marine food web that have not been widely exploited.

Connectance.—Connectance is one of several biologically meaningful measures of food-web complexity that can be related to community stability. Connectance is the proportion of all of the theoretically possible connections in a food web that are actually present. It is also a functional measure of the diversity of biological interactions in a community, allowing us to draw inferences about the functional impacts of a change in species diversity.

Several diet and stable-isotope studies of the nearshore California food web are now in progress to determine the practicalities of this approach (Bonacci et al., unpubl. data; Schwartz and Kaufman, unpubl. data). As a test case we have examined the possibility of reliably measuring trophic differences in two very closely related taxa that are barely distinguishable morphologically: the gopher rockfish (*Sebastes carnatus*), and the black-and-yellow rockfish (*S. chrysomelas*). Even though these two forms have been considered to be the same species, they exhibit subtle ecological differences that were painstakingly teased out by Larson (1980). We observed that gopher rockfish at any given size have a slight tendency to feed higher in the food web than black-and-yellow rockfish. Although this tendency is often difficult to determine from stomach contents, the proportion of heavy nitrogen was slightly but significantly higher in the tissues of gopher rockfishes from locations (San Miguel Island and Point Loma) where the two species were caught together (Bonacci et al., unpubl.). The preliminary study also revealed that gopher rockfish appear to feed at slightly different positions in the food web at different points along the California coastline, an intriguing pattern of unknown significance. The relevant issue is that rather small differences (ca. 10%) were statistically detectable. This result bodes well for detecting differences attributable to fishing effects before they become obvious in other ways.

Functional Diversity

Ecologists have found that several measures of community diversity have useful relationships to community properties such as productivity, ecosystem size, and various kinds of stability, including:

Species Richness.—Species richness, the number of species that occur within a given area, can scale in interesting ways with increasing areas of examination.

Evenness.—Evenness is a measure of the shape of the relative abundance curve over all the species in a community. Shifts in evenness can provide an early warning of major changes in relative abundance to come.

Functional Complementarity.—Within any ecological community, more than one species may function in more or less the same ecological role. Such species are considered members of the same functional group, or guild. Though superficially similar and in a broad sense functionally substitutable, guild members tend to vary in other aspects of their biology, such as tolerance to changes in climate, food base, and water quality. A guild consisting of more species might be more stable and therefore increase productivity of a marine community over time, as has been observed in grassland plant communities (Tilman and Downing, 1994). Inversely, a loss of species richness, manifested as a decrease in redundancy, or number of species per guild, could render a community more vulnerable to wild swings in stock sizes and productivity.

For reserves to function as reference reserves as intended in Stage III, populations within the reserves must serve as reasonable indicators of an unfished state under the prevailing environmental conditions. Statistical differences in species' relative abundance patterns can be detected, even though we may not know what difference they make to the fishery or to community function. The key is that, even if we do not understand the changes that are observable, through a design that incorporates reference reserves, some proportion of these changes can at least be directly attributed to human as opposed to other causes. A key goal of the MLMA is to limit change in natural systems caused by human activities such as fishing. The nature of these changes may not be fully understood to be worthy of notice and, perhaps, management response.

Environmental Influences

This stage of implementation for Stage III management also incorporates existing or anticipated effects on the fishery attributable to environmental change. Protocols for measuring such changes, and their corresponding set of catch control rules and other management measures, must still be developed. Existing theory and practice provide key parameters for initial consideration: (1) presence or absence of short-term or long-term environmental change (e.g., a severe El Niño or La Niña, or a shift in the Pacific Decadal Oscillation) that may result in sharply depressed or elevated productivity or in other changes in the fishery, (2) sea-surface temperature as a proxy for the effects of environmental change (e.g., as in management of the Pacific sardine fishery), and (3) shifts in abundance of populations that covary with NFMP species or relevant nontarget species.

To some, our recommended approach to setting TACs may seem unduly conservative, especially as compared to the current standards for the Pacific Fishery Management Council. In fact, we have struck a compromise that lies somewhere between the council's existing standards and the harsh precautionary assumptions of Stage I management. Our recommended approach differs from the council's standards in that it encompasses multispecies, ecosystem, and climatological influences on stock productivities. With additional data we may find that even this stance is not conservative enough unless it incorporates explicit stock rebuilding targets for every species.

Full recognition of human ignorance in the face of the highly dynamic state of fish populations raises fundamental issues about the underlying philosophy by which people exploit the ocean. Even in those management bodies that have begun seriously to address ecosystem considerations in setting TACs (such as the North Pacific Fishery Management Council in Alaska), the exercise nonetheless begins with "looking through the wrong end of the telescope" (Heneman, 2002). The sensible approach is to begin with a low, precautionary TAC and then gradually increase this number as justified by additional data: i.e., the stance taken in California's NFMP. The realized approach is usually the opposite: begin with a big number and whittle it down in deference to emergent risk factors. The resulting TACs are then as high as possible, but at the cost of throwing caution to the wind, in the midst of some very uncertain winds.

So how shall we weigh a fishery management plan to decide whether or not it is truly ecosystem based? To our minds, and as embodied in the NFMP, the key question is whether or not it is precautionary at every step. Has the burden of proof for increased TACs been shifted from a demonstration that stocks are down to a demonstration that stocks are up?

Conclusion

Walters and Hilborn (1978) offered an early exploration of the relationship between information richness and the kinds of models, particularly adaptive models, which might be used in fisheries management. Some of the world's leading fishery nations have expressed a clear intent to move toward ecosystem-based fishery management (Link, 2002b), but nobody seems to have gotten far from the starting gate in implementing EBM. In the area of offshore fisheries, work by NOAA in the Bering Straits/Gulf of Alaska system offers an exemplary case of a rapid ramping up of ecosystem-related information for fishery decision making (Livingston, 1999). At least for the marine nearshore, the NFMP attempts a systematic program for reducing scientific uncertainty in fisheries management that includes management interventions appropriate to each level of information triggered by specific control rules and all in an adaptive framework coupled to a rigorous experimental monitoring design (CRANE). When we drafted the NFMP control rule and joined others in the initial months of planning CRANE, we were unable to find an example in actual practice of management and science protocols for true EBM in any fishery in the world. We feel confident that California's experience with the NFMP and CRANE will have relevance for fisheries elsewhere. The information in information-rich management, however, is often very local, and the adaptation in adaptive management is local as well. It is certainly timely for other jurisdictions to launch their own efforts to make fisheries management smarter and more protective of ocean ecosystems.

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