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Ten Commandments for Ecosystem-Based Fisheries Scientists

ABSTRACT: In an effort to accelerate the ongoing paradigm shift in fisheries science from the traditional single-species mindset toward more ecosystem-based approaches, we offer the following “commandments” as action items for bridging the gap between general principles and specific methodologies.

1. Keep a perspective that is holistic, risk-averse, and adaptive.
2. Question key assumptions, no matter how basic.
3. Maintain old-growth age structure in fish populations.
4. Characterize and maintain the natural spatial structure of fish stocks.
5. Characterize and maintain viable fish habitats.
6. Characterize and maintain ecosystem resilience.
7. Identify and maintain critical food web connections.
8. Account for ecosystem change through time.
9. Account for evolutionary change caused by fishing.
10. Implement an approach that is integrated, interdisciplinary, and inclusive.

Although the shift in worldview embodied in these commandments can occur immediately without additional funding, full implementation of ecosystem-based fisheries science will require an expanded empirical basis as well as novel approaches to modeling. We believe that pursuing these action items is essential for productive marine fisheries to become truly sustainable for present and future generations.

Diez preceptos para científicos pesqueros que aplican el enfoque ecosistémico

RESUMEN: Tratando de acelerar el cambio entre los paradigmas de manejo pesquero de un enfoque convencional que considera la evaluación de una sola especie a otro que toma en cuenta a todo el ecosistema, nosotros proponemos los siguientes preceptos como elementos que contribuyan a tender un puente entre los principios generales y las metodologías específicas de ambas posiciones:

1. Considerar una perspectiva holística, precautoria y adaptativa.
2. Examinar cuestiones clave, no importa que tan básicas sean.
3. Conservar las estructuras poblacionales de edad y crecimiento.
4. Caracterizar y conservar y la distribución espacial de los stocks.
5. Caracterizar y conservar los hábitats viables.
6. Conocer y conservar la resiliencia de los ecosistemas.
7. Identificar y conservar las conexiones críticas del las tramas tróficas.
8. Registrar temporalmente los cambios del ecosistema.
9. Registrar los cambios evolutivos causados por la pesca.
10. Proponer sistemas de manejo integrales, interdisciplinarios e incluyentes.

Si bien el cambio general de perspectiva derivada de estos preceptos puede ocurrir inmediatamente, la implementación total del manejo pesquero a partir de un enfoque ecosistémico requiere ampliar la base empírica y el desarrollo de nuevas herramientas de modelación. Consideramos que el cumplir con los elementos enumerados anteriormente es fundamental para que las pesquerías marinas sean verdaderamente sustentables ales entre los temas e impactos de los torneos y se sugiere que los efectos de los torneos no varían entre las diferentes tipos de pesquería. Comparando estos resultados con un estudio previo se observa que la problemática y los beneficios asociados al desarrollo de los torneos han cambiado de 1989 a la fecha; los temas sociales siguen siendo relevantes, pero los impactos biológicos se consideraron como de poca importancia. Las agencias reconocen que los torneos pueden mejorar el manejo de las pesquerías y el reclutamiento de los pescadores. Para la planeación de los futuros torneos debe considerarse un trabajo más integral.

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Who in blazes are we to have the audacity to issue 10 commandments? Well, we certainly do not believe that we are Yahweh et al. Rather, because you are reading this, we suspect that the title grabbed you, and so our goal regarding this outrageously grandiose heading is fulfilled. In reality, our humble intention is to stimulate much needed discussion regarding the explicit details of ecosystem-based fisheries science as a bonafide new discipline. We perceive a need to bridge the gap between general principles, which are already well-articulated, and specific methodologies for full implementation, which is the present challenge and beyond the scope of this article. Our intention is to help ecosystem-based fisheries science escape the danger of becoming either “quasi-religious” (sensu Larkin 1996:149) or “surreal” (sensu Longhurst 2006:108) by proposing tangible action items. Given our collective backgrounds, we address only the natural sciences, yet emphasize the need for ecosystem-based management to integrate the natural and social sciences (see Commandment 10).

Although a marine “ecosystem” is a human construct that artificially delineates a portion of the ocean, and given that the biosphere comprises highly integrated linkage of all such systems, we are con-

tent using definitions proposed by NOAA (2005:3) in the context of this article: “An ecosystem is a geographically specified system of organisms, including humans, the environment, and the processes that control its dynamics. An ecosystem approach to management is management that is adaptive, specified geographically, takes into account ecosystem knowledge and uncertainties, considers multiple external influences, and strives to balance diverse social objectives.”

The ongoing transition in fisheries management from a traditional single-species focus toward ecosystem-based approaches has many characteristics of a classic Kuhnian “paradigm shift.” According to Kuhn (1962), during the course of a scientific revolution, an established worldview is replaced by another set of fundamental assumptions. Typically, more progressive, open-minded, and often younger practitioners of the new paradigm face substantial resistance from entrenched defenders of the status quo. We personally have witnessed such resistance toward ecosystem-based management by some fisheries scientists, the same profes-

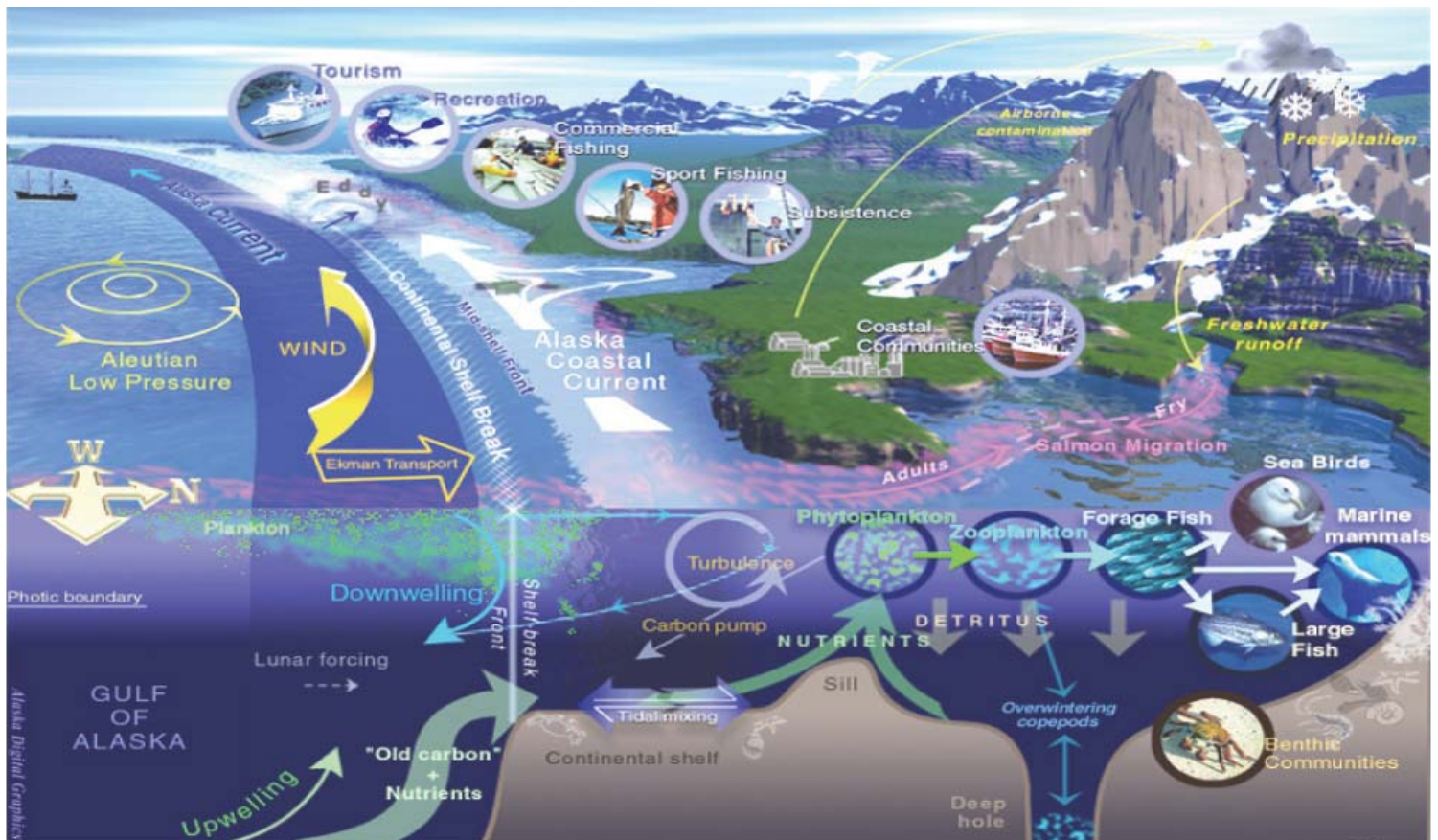
sionals who are the primary purveyors of science for management decisions. However, the paradigm shift in fisheries science is not entirely Kuhnian because the ongoing transition toward ecosystem-based approaches has been more evolutionary than revolutionary, and no one to our knowledge is advocating the complete abandonment of traditional fisheries biology.

Despite some resistance toward ecosystem-based approaches, single-species fisheries science and management is increasingly seen as necessary yet insufficient, and often ineffective for maintaining catches that are both productive and sustainable (“sustainable” in both the modern and post-modern sense of Quinn and Collie 2005, but see Longhurst 2006). This problem is especially evident where bycatch is substantial, where bottom gear impacts seafloor habitats, where fisheries exploit multiple species simultaneously, and when various assumptions of traditional single-species approaches are violated (Browman and Stergiou 2004 and included papers). There is ample evidence that many marine fishery stocks are not managed sustainably, even those subjected to rigorous scientific

scrutiny (Hilborn et al. 2003). Worldwide, an estimated 25% of major stocks are over-exploited, depleted, or recovering from depletion, 52% are fully exploited, and 23% are under or moderately exploited (FAO 2006; see also Mullon et al. 2005). Some practitioners are gravely concerned that only about a quarter of the stocks are clearly healthy (e.g., Jennings 2004), whereas others are content that only a quarter of the stocks are depleted or otherwise over-exploited (e.g., Mace 2004). Regardless of whether one sees the glass as three-quarters empty or three-quarters full, and despite the fact that traditional fisheries biology has been adequate in some systems (Hilborn 2005), more effective approaches to fisheries science seem prudent.

Although ecosystem-based fishery concepts have existed for many years (e.g., Sette 1943; Iles 1980), and have been implemented in some regions for some time (e.g., Murawski et al. 2000; Withereil et al. 2000), critics of traditional management have only recently pressed for a more holistic scientific approach that incorporates the ecosystem context of fisheries into management policy (e.g.,

Commandment 1. The Gulf of Alaska from a holistic ecosystem perspective (NOAA Fisheries Service).



Botsford et al. 1997; Pikitch et al. 2004; USCOP 2004; Field and Francis 2006). To date, most publications on ecosystem-based management have focused on broad principles (e.g., Ecosystem Principles Advisory Panel 1999; NRC 1999; Gislason et al. 2000; Coleman and Travis 2002; Link 2002a; Barange 2003; Francis 2003; Rose and Cowan 2003; Browman and Stergiou 2004, 2005; Walters and Coleman 2004; Guerry 2005; McLeod et al. 2005).

Beyond useful compendia of ecosystem-based management guidelines (e.g., Larkin 1996; Link 2002b; Fowler 2003; Walters and Martell 2004; Garcia and Cochrane 2005; NRC 2006), there has been no definitive exploration of explicit action items for a full transition to what we call “ecosystem-based fisheries science” (EBFS). We believe that EBFS should not replace traditional fisheries biology per se, but rather that conventional single-species approaches should be incorporated into the broader and ecologically more realistic discipline of EBFS. In an effort to clarify the essential components of EBFS and to address the important question posed by Frid et al. (2006) regarding advances in natural science required for ecosystem-based management, we offer the following 10 commandments to both the revolutionaries and the reactionaries in this ongoing paradigm shift. Although these action items are general in nature, most examples are drawn from the California Current Ecosystem, with which most of us have the greatest experience.

COMMANDMENT 1:

Keep a perspective that is holistic, risk-averse, and adaptive.

Out of context, the best minds do the worst damage.

—WES JACKSON (BERRY 2005:45)

This fundamental commandment provides the necessary worldview and general context for all that follows. For us, EBFS is more an issue of context and mindset than of method (and thus does not require vast quantities of additional data and funding). Berry (2005:42) says this regarding context in modern agriculture:

It is no longer possible to deny that context exists and is an issue. If you can keep the context narrow enough (and the accounting period short enough), then the industrial criteria

of labor saving and high productivity seem to work well. But the old rules of ecological coherence and of community life have remained in effect. The costs of ignoring them have accumulated, until now the boundaries of our reductive and mechanical explanations have collapsed.

Walters and Kitchell (2001) point out that over the past half century, context has changed in marine fisheries as well. They argue that there have been three important steps in the evolution of the theory of fishing. The first two focused on abundance of individual single-species stocks and the direct effects of exploitation on stock productivity, respectively. The third step—focus on ecological interactions—has become necessary with recent severe stock depletions and their unexpected or unknown ecosystem consequences, rendering some single-species techniques either unreliable or unsatisfactory when considered in isolation (e.g., Longhurst 1998; Pauly et al. 1998; Bundy 2001; Jackson et al. 2001). As a result, fishery resource managers are confronted with increasingly complex issues—issues characteristically involving tradeoffs and interactions within and between nature and society.

With this in mind, we believe that Field and Francis (2006:552) provide a useful basis for characterizing EBFS and, in particular, the role of the biological sciences in its implementation:

A common theme is that such an ecosystem approach involves a more holistic view of managing resources in the context of their environment than presently exists. For marine fisheries management, this must include taking into greater consideration the constantly changing climate-driven physical and biological interactions in the ecosystem, the trophic relationships between fished and unfished elements of the food web, the adaptation potential of life history diversity, and the role of humans as both predators and competitors. Recognizing that all management decisions have impacts on the ecosystem being exploited, an ecosystem-based approach to management seeks to better inform these decisions with knowledge of ecosystem structure, processes and functions.

Recently there has been a serious attempt to join the concept of sustainability with the growing scientific understanding that both human and natural systems are complex and adaptive (Holling 2001). Holling and Meffe (1995) made the point that science and policy are inextricably linked when it comes to natural resource issues. What they call “command and control” policy—reduce system variability and make the system more predictable—is based on a “first-stream” scientific view of natural and social systems that concentrates on stability near an equilibrium steady-state. Clearly, the concept of maximum sustainable yield (MSY) falls into this realm. An alternative basis for natural resource policy, what Holling and Meffe call “golden rule” policy—retain or restore critical types and ranges of natural and social variation, and facilitate existing processes and variability—is based on a “second-stream” scientific view of natural and social systems that concentrates on conditions far from any equilibrium. In this case, instabilities can flip a system into another regime of behavior (see Commandments 2, 6, 7, and 8). Developed by Holling and colleagues, these concepts have formed the basis for the integrated concept of “social-ecological systems” (Berkes et al. 2003), and a new field of sustainability science that seeks to understand the fundamental character of interactions between nature and society (Kates et al. 2001; Hughes et al. 2005).

Once fisheries are viewed from such a holistic perspective, then ecosystem-based fisheries science necessarily becomes both risk-averse and adaptive. The biosphere is so complex that we will never have sufficient information to understand ecosystems completely. At the same time, those who dismiss the ecosystem approach as being too data-hungry miss the point. Fishery science will always be severely data-limited and uncertainty will always be high (Walters and Martell 2004). As such, the onus is on fishery scientists to encourage implementation of risk-averse management approaches that set fishing quotas, gear restrictions, and fishing zones in ways that are relatively conservative compared to traditional approaches.

There are two major incarnations of risk-averse decision making, also characterized as the so-called precautionary principle. First, quoting the United Nations Food and Agricultural Organization’s “Code of Conduct for Responsible

Fisheries” (FAO 1995:5): “The absence of adequate scientific information should not be used as a reason for postponing or failing to take measures to conserve target species, associated or dependent species, and non-target species and their environment.” Second, Dayton (1998) describes reversal of the burden of proof, involving a shift in perspective from risk-prone type I error (e.g., increasing exploitation rates until it is demonstrated that those rates have negative effects on a stock) to risk-averse type II error (e.g., not increasing exploitation rates until it has been demonstrated that negative effects are unlikely). Fundamentally, this shift requires nothing more than sound judgment, derived from a holistic appreciation that fisheries systems are complex beyond our immediate grasp. Approaches for implementing the precautionary approach are detailed in the following commandments (see also González-Laxe 2005).

Hand-in-hand with a precautionary approach is the adaptive approach, which calls for learning by doing in the face of incomplete knowledge. As originally proposed by Holling (1978) and refined by Lee (1993), adaptive management treats economic uses of nature as experiments, so that we may learn efficiently from experience. As Lee (1993:9) says, “Linking science and human purpose, adaptive management serves as a compass for us to use in searching for a sustainable future.” Of particular importance to this discussion, adaptive management is ecosystem-based rather than based solely on jurisdictional criteria, and operates on a time scale that is biologically driven. In the context of adaptive management, ecosystem-based fisheries scientists should encourage implementation of management policies that test hypotheses regarding sustainable fisheries in a cycle of informed trial-and-error (Walters and Hilborn 1976; Walters 1986). Modeling plays a central role in this approach, both in generating hypotheses and synthesizing information (Latour et al. 2003; Walters and Martell 2004). Lee (1993) gives an excellent example of an attempt at adaptive management regarding salmon enhancement in British Columbia.

COMMANDMENT 2:
Question key assumptions,
no matter how basic.

Here lies the concept, MSY.

It advocated yields too high.

—PETER LARKIN (1977:10)

This is a critical commandment for any kind of science, but is particularly true for science which is advisory to fishery management decisions. For example, the most common and sophisticated single-species stock assessment models often assume that: (1) recruitment is solely a function of spawning biomass; (2) natural mortality is constant over the time frame of stock assessment; (3) unexploited biomass is constant; (4) if exploitation ceases, the stock biomass will rebuild to that unexploited level due to endogenous density-dependent mechanisms; and (5) for any given level of fishing effort, stock biomass will approach an equilibrium at which it will remain in perpetuity. Now the question is not whether these assumptions are actually true, but whether making these assumptions affects the integrity of the stock assessment. Consider documented violations of each assumption:

1. Recruitment of many marine fish stocks appears to depend as much on stock structure (e.g., spatial distribution, age structure) as on cumulative stock biomass (Berkeley et al. 2004b).
2. Natural mortality can be highly variable in time and space (Sogard 1997), and constant values used in stock-assessment models often have little or no empirical basis (Vetter 1988). Walters (2000) argues that whole-ecosystem processes (e.g., food web dynamics) can have profound effects on individual stock processes, such as natural mortality and the nature of recruitment.
3. If one takes the best estimate of highly variable recruitment from a recent stock assessment of Pacific hake (*Merluccius productus*) and simply runs an unexploited version of the stock assessment model over that trajectory, estimated unexploited stock biomass will vary considerably. One might then ask what the concept of constant unexploited biomass (B_0) means in this case. Additionally, increasing evidence indicates that density dependence in at least demersal (seafloor-associated) marine fishes is largely caused exogenously by predation rather than endogenously by competition (Hixon and Jones 2005). Accordingly, a more modern view of MSY and its associated biomass (B_{MSY}) is as a dynamic equilibrium incorporat-

ing natural variability in recruitment and survivorship, and potentially incorporating biological interactions if they can be quantified (Mace 2001).

4. The collapse of fisheries for northern cod (Bundy 2001; Haedrich and Hamilton 2000, Longhurst 1998) and West Coast rockfish (Ralston 1998; Gunderson 1984; Levin et al. 2006) clearly show the incapacities of marine ecosystems to “rewind” from overfishing. When marine ecosystems are contorted enough by exogenous factors, thresholds are passed and the rules of organization change. Not only are new stability domains created, but also reversibility (i.e., stock rebuilding) is no longer a meaningful assumption.
5. The cases of Pacific hake (above) and Bristol Bay sockeye salmon (*Oncorhynchus nerka*; Hilborn et al. 2003) suggest that stocks may have no long term equilibrium behavior.

Once again, any scientific assessment requires making assumptions about the way nature works. The important point is to be explicit about those assumptions and question them within the context of the particular issue being addressed.

Walters et al. (2005) have used ecosystem models to show that widespread application of the contemporary (MSY-proxy) single-species management approach could lead to dramatic impacts on ecosystem structure, particularly where such approaches are applied to forage species. The lesson is that fisheries scientists should exercise caution in recommending MSY policy based on single-species assessments that ignore the ecosystem roles of exploited species. There are at least two perspectives on coping with this issue, both of which are held by different authors of this article. One is to view MSY as an evolving and viable paradigm that has not always been implemented properly in the past, but is nonetheless essential in fisheries science (Mace 2001, 2004). The other is to replace MSY with a more holistic “ecologically sustainable yield” (ESY) (Zabel et al. 2003). The concept of ESY could include a variety of indicators (Froese 2004), including

1. Percentage of mature fish in the catch, with the target approaching 100%;
2. Percent of fish near optimum length in the catch, with the target approaching 100%; and

3. Percentage of “big, old, fat female” spawners in the catch (see Berkeley et al. 2004b), with the target approaching 0%.

COMMANDMENT 3:
Maintain old-growth age structure
in fish populations.

Logic surely demands that a fishery for a species having intermittent recruitment must somehow eschew the common practice of truncating the age structure.

—ALAN LONGHURST (2002:6)

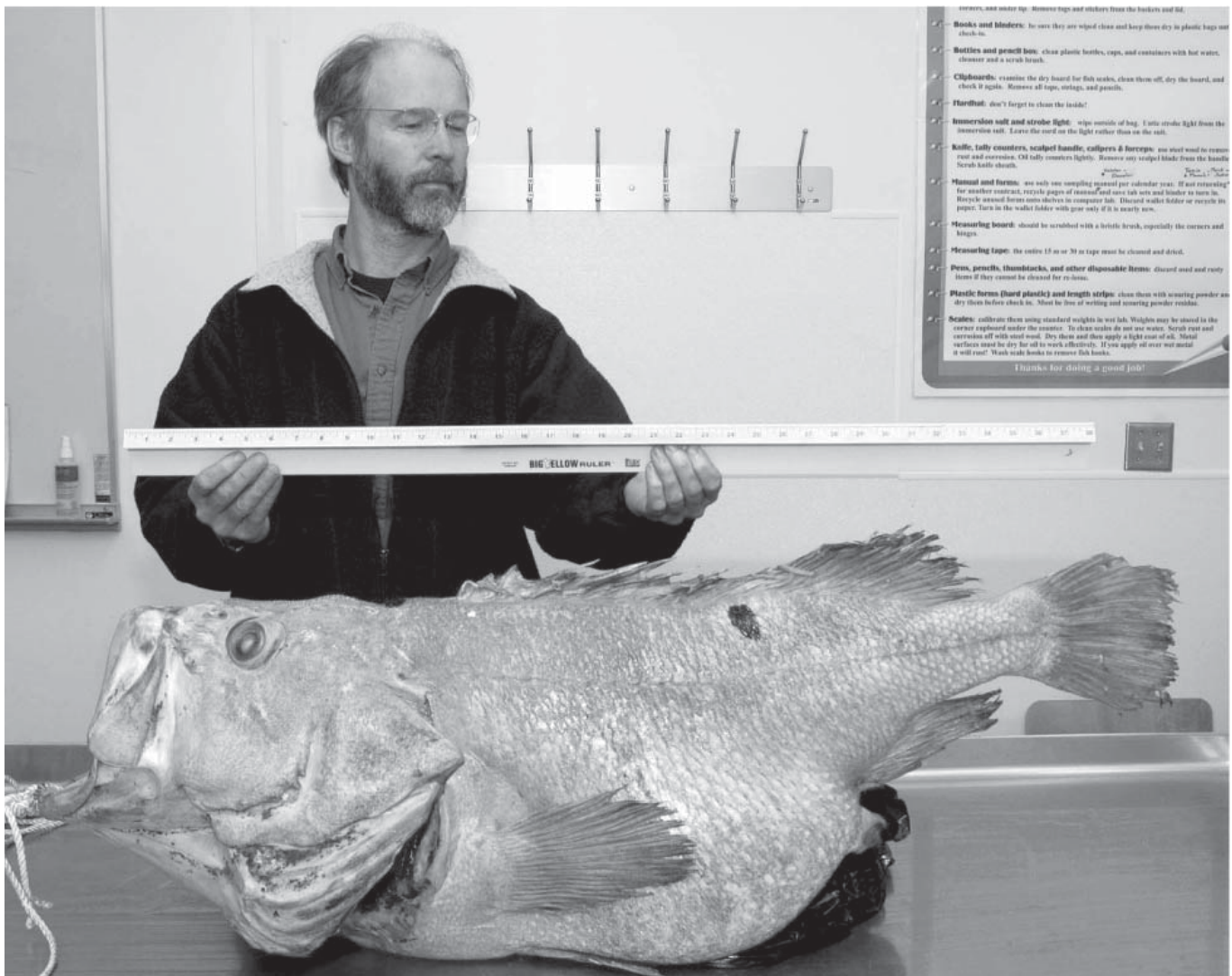
Recent (and even not so recent) studies belie three implicit assumptions of traditional fisheries biology regarding spawning females of relatively long-lived species.

The first assumption is that all eggs are identical, and in particular, that eggs from younger smaller females and older larger females are equivalent (Beverton and Holt 1957). This notion has persisted despite early evidence that larger females produce larger eggs (Nikolsky 1953). Recent experiments on Pacific rockfish (genus *Sebastes*) have demonstrated that older females produce eggs with larger oil droplets, resulting in larvae that both grow faster and survive starvation better than larvae from younger females (Berkeley et al. 2004a). Such maternal effects are evident in a variety of fish species (reviews by Chambers and Leggett 1996; Heath and Blouw 1998; Berkeley et al. 2004b; Berkeley 2006; Longhurst 2006).

The second assumption of traditional fisheries biology is that all mature females

are equivalent in terms of spawning behavior. They often are not. In a broad range of marine fishes, older females spawn earlier and may have more protracted spawning seasons than younger females (Berkeley and Houde 1978; Pederson 1984; Lambert 1987; Berkeley et al. 2004b). In environments where larval food production and larval drift vary either seasonally or in unpredictable ways, fish that spawn at the wrong time or place will not contribute to the new cohort because their larvae will perish. Off Oregon, older female black rockfish (*Sebastes melanops*) spawn earlier than younger females (Bobko and Berkeley 2004), and in some years are responsible for producing most of the new cohort despite the fact that older females comprise a small fraction of the spawning stock (Bobko 2002). Similar patterns are

Commandment 3. Big (44 in), old (ca. 100 y), fat (60 lb.), fecund female shortraker rockfish (*Sebastes borealis*) taken off Alaska (Karna McKinney, Alaska Fisheries Science Center, NOAA Fisheries Service).



evident in Icelandic cod (*Gadus morhua*; Marteinsdottir and Thorarisson 1998) and North Sea haddock (*Melanogrammus aeglefinus*; Wright and Gibb 2005).

The third assumption is that long-lived individuals per se are not essential for an exploited stock to persist. In reality, the evolution of long life spans with repeated spawning (iteroparity) is now recognized as a bet-hedging response to variable environments where larval survival and successful recruitment may be uncommon (Leaman and Beamish 1984; Longhurst 2002, 2006; Hsieh et al. 2006). Long-lived spawners thus provide a “storage effect” whereby a stock will persist as long as enough adults outlive periods unfavorable to successful spawning and recruitment (Warner and Chesson 1985). This pattern is expected to be particularly important at the margins of species ranges, where successful recruitment is often rare (MacCall 1996). Additionally, age-related differences in the time and location of spawning (Berkeley and Houde 1978; Lambert 1987; Hutchings and Myers 1993) may spread larval production in a way that accounts for temporal and spatial variability in larval environments. Indeed, there is genetic evidence that Hedgecock’s (1994a,b) “sweepstakes hypothesis” occurs in West Coast rockfishes (review by Berkeley et al. 2004b; see also Field and Ralston 2005). Available data indicate that each new cohort is the product of a small fraction of all spawners, and that this small group of successful spawners changes both spatially and temporally due to unpredictable variation in larval environments.

The fact that traditional fishery biology often subsumes these considerations indicates that the age and size structure of a stock are likely as important as the magnitude of its spawning biomass in providing sustainable catches (Berkeley et al. 2004b; Beamish et al. 2006). The obvious conclusion is the need to minimize what has conventionally been seen as an expected and harmless side-effect of fishing to maximize density-dependent surplus production: age and size truncation (the loss of older age classes and larger size classes). Such alteration of population structure is prevalent among many fishery species (e.g., for the West Coast, see Harvey et al. 2006; Levin et al. 2006) and is now seen as leading to “longevity overfishing” (Beamish et al. 2006; Hsieh et al. 2006).

Old-growth age structure can be maintained by three approaches

(Berkeley et al. 2004b):

1. Lowering catch rates substantially, which can be economically infeasible;
2. Implementing slot limits (release of both small and large individuals), which is often impossible due to capture mortality (e.g., via swimbladder expansion); and
3. Implementing marine protected areas (MPAs) to ensure that at least part of the stock can reach old age and large size.

Berkeley (2006) has modeled these scenarios and concluded that, for species similar to rockfishes, utilizing MPAs may provide the greatest fishery yields. At the very least, ecosystem-based fisheries scientists should monitor age and size structure, and incorporate these considerations into stock assessments.

COMMANDMENT 4:
***Characterize and maintain
the natural spatial structure of fish
stocks.***

*Broad spatial distribution of
spawning and recruitment is at least
as important as spawning biomass in
maintaining long-term sustainable
population levels.*

—STEVEN BERKELEY ET AL. (2004B:23)

Traditional fisheries biology was founded on the assumption of unit stocks: regionally interbreeding populations that are reproductively closed (Cushing 1968; Pitcher and Hart 1982). In modern parlance, a stock is actually a “metapopulation” comprising local populations linked by larval dispersal (Kritzer and Sale 2004), rather than the older and often false assumption of a larger, spatially discrete and reproductively isolated population (reviews by Frank and Leggett 1994; Field and Ralston 2005). Recent genetic and otolith microchemical studies indicate that marine stocks have complex spatial structures at much smaller scales than previously assumed (reviews by Laikre et al. 2005; Gunderson and Vetter 2006). For example, most of some 60 species of rockfish (*Sebastes*) are assessed as single stocks along the entire Washington-Oregon-California coast of the United States. Yet, recent genetic analyses show substantial geographical discontinuities that indicate multiple, isolated stocks along this coast-

line (Rocha-Olivares and Vetter 1999; Buonaccorsi et al. 2002, 2004, 2005; Cope 2004; Miller and Shanks 2004; Gomez-Uchida and Banks 2005; Hawkins et al. 2005; Miller et al. 2005).

The important implication of these findings is that a decline in fish abundance in one region may not be replenished quickly or inevitably from another region. Thus, averaging stock assessments among regions may result in localized overfishing. Management fallout from this scenario is that the fishing community in one region may be unfairly penalized for overfishing that occurs in another, ecologically distinct region.

How can this dilemma be avoided? In short, the artificial spatial scale of stock assessment and management must better align with the natural spatial scale of target populations. Each managed species should be screened for stock subdivision using now well-developed and reasonably-priced genetic and otolith approaches. We anticipate that ecological regions will emerge where stock boundaries of particular groups of species are coincident. Until such analyses are completed, and as the first approximation in an adaptive process, initial subdivisions could be based on well-documented biogeographic boundaries, such as the series of large capes along the U.S. West Coast. Such ecologically-based regions should initially define the spatial units of stock assessment and management, rather than the arbitrary political regions presently used. Eventually, new data will allow delineation of actual metapopulation boundaries.

If present management regions, such as the entire U.S. West Coast, are subdivided into so many ecologically-based regions that multiple stock assessments as traditionally implemented become prohibitively expensive, then more robust and less data intensive approaches should be implemented to assure stock sustainability and ecosystem integrity (see Froese 2004). These approaches include less aggressive catch quotas, as well as use of novel tools to ensure stock viability, such as marine protected areas (NRC 2001; Ward et al. 2001; Shipley 2004; Sobel and Dahlgren 2004). In any case, continuing to rely on traditional stock assessments that either ignore or artificially delineate the true spatial structure of fish populations is clearly a recipe for disaster.

COMMANDMENT 5:
*Characterize and maintain
viable fish habitats.*

*No habitat, no fish—
it's as simple as that.*

—ANONYMOUS

Within the biogeographical region inhabited by a particular stock, the types of fish habitats and their spatial distributions must also be incorporated into fisheries science if sustainability is to be ensured (Benaka 1999; Coleman and Travis 2000). Seafloor mapping and fish habitat characterization over broad spatial scales is now a reality (Barnes and Thomas 2005 and included papers). Until Essential Fish Habitat (EFH) and Habitat Areas of Particular Concern (HAPC) were incorporated as part of fisheries management law in the United States, there was little focus on habitat by traditional fisheries biology. An ecosystem-based approach includes identification of nursery habitats, spawning sites, and other areas required to maintain stock integrity, and protection of those areas from bottom-gear impacts and other deleterious activities (NRC 2001, 2002). Importantly, much seafloor habitat is biogenic, created by corals, kelps, seagrasses, and other structure-forming organisms, so protection of fisheries habitat is truly equivalent to conserving the biodiversity of seafloors (see Kaiser et al. 2002, 2006). Additionally, stock assessments of demersal species should take into account the fact that the seafloor is heterogeneous, thereby increasing the accuracy of assessments via integration of spatially explicit population sampling with seafloor habitat mapping (Nasby-Lucas et al. 2002; NRC 2004). In short, ecosystem-based fisheries science is inherently place-based at multiple spatial scales.

COMMANDMENT 6:
*Characterize and maintain
ecosystem resilience.*

*Even though the scientists on a team
may be world-class experts in their
respective component fields, they are
all likely to be amateurs when it comes
to the system as a whole.*

—CRAIG NICHOLSON ET AL. (2002:383)

The science of both ecological and social systems has undergone a major conceptual change in the past few de-

CADES—the recognition that nature is seldom linear (the rules of organization can change) and often unpredictable (Berkes et al. 2003). The concept of “resilience” is a useful scoping device for integrating ecosystem and social system complexity. This concept originated in ecology and has been applied and studied primarily in the context of non-human systems. However, there have recently been attempts to apply the concept in the broader context of social-ecological systems (Levin et al. 1998; Berkes et al. 2003). Taking the narrower line and focusing on natural ecosystems, “resilience” is defined as “the extent to which ecosystems can absorb recurrent natural and human perturbations and continue to regenerate without slowly degrading or unexpectedly flipping into alternate states” (Hughes et al. 2005:380). Walker et al. (2004) describe four crucial components of resilience (see also Gunderson 2000):

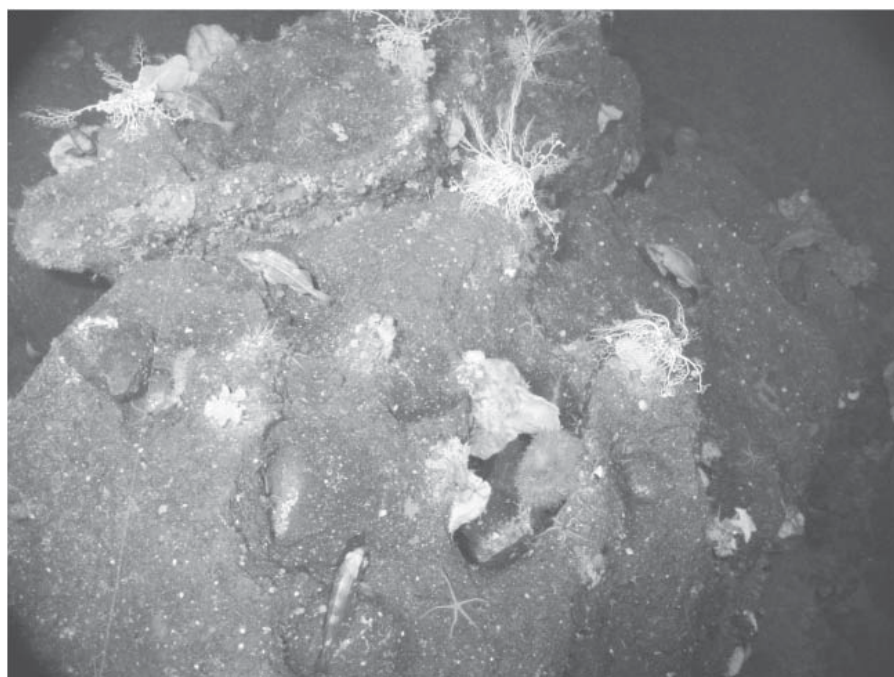
1. **Latitude:** the maximum amount a system can be changed before losing its ability to recover;
2. **Resistance:** the ease or difficulty of changing the system;
3. **Precariousness:** how close the current state of the system is to a limit or threshold; and
4. **Panarchy:** dependence of the focal sys-

tem on processes occurring and scales above and below (influence of cross-scale interactions).

The first three components define the capacity of an ecosystem to maintain its current rules of organization. Since food webs comprise the fundamental organizing relationships in ecosystems (Paine 1980), these first three components really refer to the nature of the stability domain of the existing food web—how broad is it, how resistant is it to change, and how close is the current food web to reorganizing. Gaichas (2006) and Little et al. (personal communication School of Aquatic and Fishery Sciences, University of Washington, Seattle, Washington) attempt to quantify these first three components with regard to the Gulf of Alaska and Northern California Current coastal marine ecosystems, respectively.

The final component of resilience, panarchy, refers to the cross-scale effects that can occur in both space and time. Climate change is a perfect example of a major marine ecosystem perturbation that is occurring at very different temporal and spatial scales than those that previously dominated the structure and function of most marine fishery ecosystems, and yet has a huge potential impact on ecosystem resilience (see Commandment 8). A sec-

Commandment 5. Bank rockfish (*Sebastes rufus*) and basket stars live at 200-m depth on a rocky seafloor at Cherry Bank off California (Northwest Fisheries Science Center, NOAA Fisheries Service).



ond example of panarchy is metapopulation structure manifested as a complex network of source and sink populations with vast spatial reach (Frank and Leggett 1994). Field and Ralston (2005) describe an example of this phenomenon regarding rockfish in the California Current system.

And so, within the context of an ecosystem as a complex adaptive system (Levin 1998), there are two looming questions that must eventually be addressed by ecosystem-based fisheries scientists:

1. How is ecosystem resilience created and maintained in exploited systems?
2. How can this understanding be translated into fishery management policy?

Evolving ecosystem indicators will provide useful tools for monitoring resilience (reviews by Cury and Christensen 2005; Jennings 2005). In any case, the emerging paradigm is one in which marine biodiversity per se at the genetic, population, and ecosystem level is valued by fisheries science as an essential requisite for the resilience of fisheries (Hughes et al. 2005). This recognition underscores the importance of monitoring bycatch and other collateral loss of sea life during fishing activities and minimizing that loss via gear modifications and marine protected areas (Crowder and Murawski 1998; Lewison et al. 2004). It also indicates the value of marine reserves for enhancing resilience by ensuring that at least portions of ecosystems remain relatively intact (NRC 2001).

COMMANDMENT 7:

Identify and maintain critical food-web connections.

To keep every cog and wheel is the first precaution of intelligent tinkering.

—ALDO LEOPOLD (1953:146)

The structure of an ecosystem is defined by relationships, and food webs create the fundamental organizing relationships in ecosystems (Paine 1980), especially in the context of fisheries (Mangel and Levin 2005). From this point of view, one of the most important tasks of EBFS is to understand food web relationships, and subsequently use them to form a context for setting fishery management policy. Mathematical modeling is an imperfect but useful tool for exploring the consequences of various fishery management policies. And if we want to explore complex interactions

and tradeoffs, we are almost forced to use some kind of mathematical model. Walters and Martell (2004:xix) put it this way:

[Fisheries] management is a process of making choices. There is no way to make choices without making at least some predictions about the comparative outcomes of the choices, and these predictions cannot be made without some sort of "model" for how the world works.

And thus, like it or not, to the extent that food-web processes affect ecosystem resilience and fishery productivity, they need to be better understood and incorporated into stock-assessment and management models. Of course, models have their limits in terms of their abilities to represent complex adaptive dynamics.

The words of Levin (1998:433) certainly ring true in this regard: "All ecosystems are complex adaptive systems, governed by similar thermodynamic principles and local selection." Yes, the laws of thermodynamics are universal and do apply. And it is those laws that serve as a basis for the way we model ecosystems. However, the ocean environment is highly variable. The heat of the sun, spin of the Earth, and structure of the ocean basins create an ever-changing mosaic of marine habitats—a mosaic that, over deep time, has guided the evolution and organization of life in so many different directions. On top of that, ecosystems are non-linear—their rules of interaction change as the system evolves.

And so, what evidence do we have that, in fact, food web processes affect ecosystem resilience and fishery production? And what actions can we take to begin to further understand these patterns and mediate management concerns?

1. **Northern cod collapse.** A model of the Newfoundland-Labrador ecosystem (Bundy 2001) suggested that although overfishing drove massive declines in northern cod abundance, cod recovery was likely hindered by top-down food web processes. This seems to be a concrete example of the existence of ecological feedbacks such as cultivation-dependensation (Walters and Kitchell 2001). In addition, the model suggested that declines in cod and several other heavily fished species may have resulted in increases in commercially

valuable invertebrates. This example suggests that the entire single-species concept of overfishing and recovery needs to be readdressed in an ecosystem context. This conclusion overlaps with Commandment 2 by questioning key assumptions of conventional fisheries biology and the whole concept of recovery from overfishing.

2. **Alaska ecosystem reorganization.** Springer et al. (2003) present a convincing argument that the sequential collapse of four northeastern Pacific marine mammal species (northern fur seal, harbor seal, Steller sea lion, and sea otter) in recent decades was caused by increased predation (top-down forcing) which resulted from altered food-web dynamics brought about by the post-World War II decimation of the great whales of the region. They postulate that the extremely rapid reduction of whale biomass profoundly altered the workings of the ecosystem, in terms of both predation by baleen whales on zooplankton and forage fish, and predation by killer whales on great whales. A combination of population-matrix and bioenergetic models was used to support the robustness of their inference. Their conclusion is that commercial whaling in the North Pacific set-off one of the longest (half-century) and most complex ecological chain reactions ever described. This example suggests that exploiting species with strong connections to forage organisms could trigger severe and long-term ecosystem shifts. Additionally, it points out the potential top-down effects of large-scale and rapid removals. Both these lessons indicate that ecosystem-based fisheries scientists would do well to recommend avoidance of such activities.
3. **Fishing-induced trophic cascade on Scotian Shelf.** Frank et al. (2005) documented long-term dramatic shifts in the Scotian Shelf ecosystem caused by the overfishing of northern cod and other large predatory fishes (see also Scheffer et al. 2005). The demise of these top predators caused increases in the abundance of their prey (including small fishes and shrimp), which in turn resulted in declines of their prey (large-bodied zooplankton), which in turn caused increases in the abundance of their prey (phytoplankton), which ultimately resulted in declines in nitrate utilized by the phytoplankton, a classic

trophic cascade. As in previous examples, this case suggests the importance of an ecosystem perspective in developing the concept of overfishing (see Murawski 2000; Little et al. personal communication).

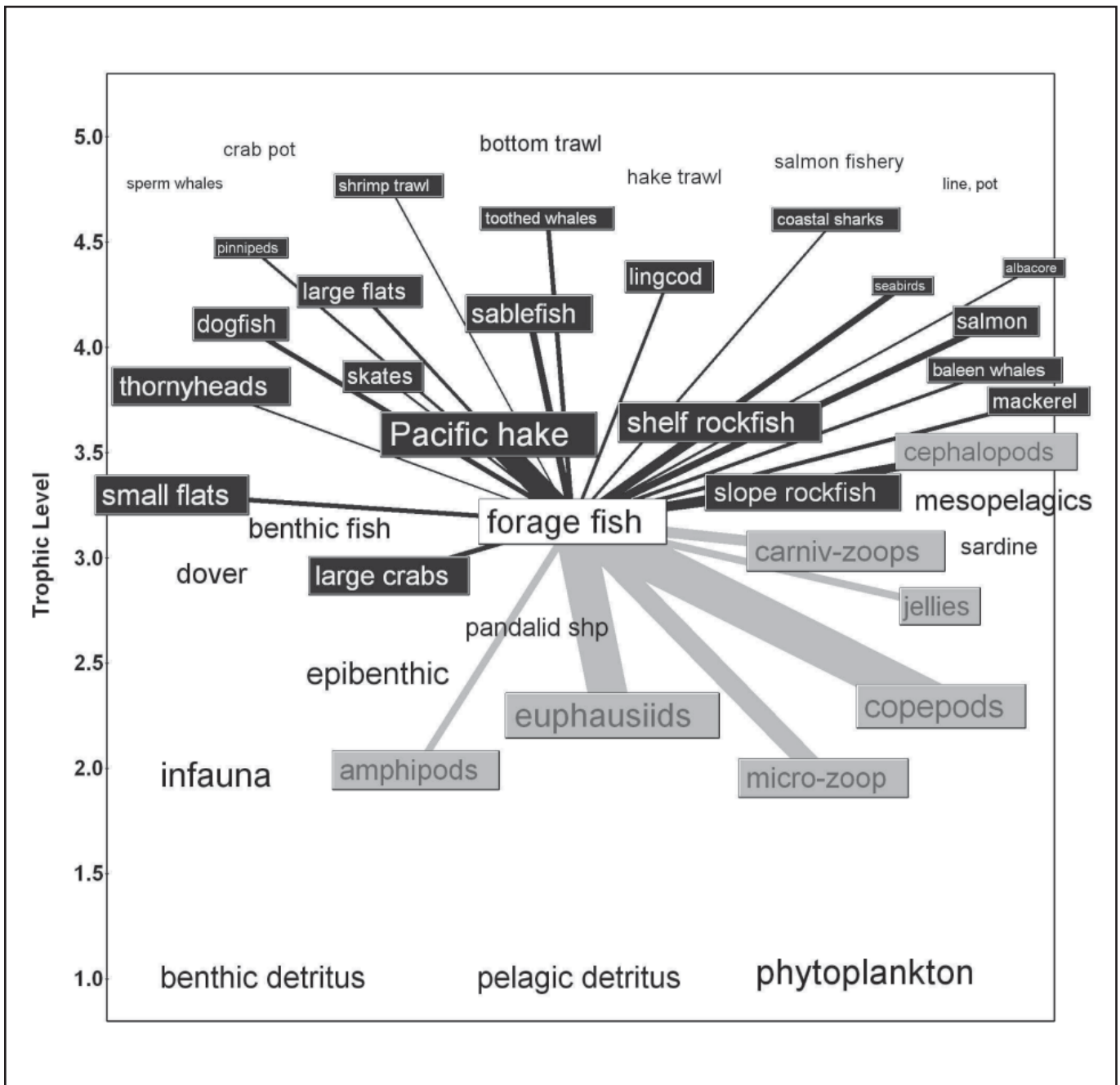
4. **Northern California Current ecosystem and climate.** Field et al. (2006) showed that climate can affect ecosystem productivity and dynamics both

from the bottom-up (through short- and long-term variability in primary and secondary production) as well as from the top-down (through variability in the abundance and spatial distribution of key predators). Incorporating both top-down and bottom-up effects of climate forcing into an Ecosim model for the Northern California Current significantly improved the performance

of the model over a 40+ year historical time series. This pattern certainly shows the controlling influence that climate has on a major predator like Pacific hake (*Merluccius productus*). Clearly, fisheries scientists recommending harvest policy on such species should keep this example in mind.

Echoing the ramifications of Com-

Commandment 7. The central and crucial role of various forage fish (mostly clupeids and osmerids) in the northern California Current food web during the 1990s. Black boxes are predators of these forage fish and gray boxes are their prey, including very small cephalopods. Boxes are positioned by mean trophic level and sized by log-scaled standing-crop biomass. Trophic lines are scaled by biomass flow from prey to predator (John Field and Kerim Aydin).



mandment 6, such case studies underscore the importance of maintaining the integrity and biodiversity of marine ecosystems, not only obviously important top predators and forage species, but also the entire the food web on which fishery species depend. In this sense, it is imperative to keep in mind that target populations not only may be regulated and stabilized by their predators and competitors (review by Hixon and Jones 2005), but also may in turn affect the populations and biodiversity of their prey (review by Hixon 1986).

COMMANDMENT 8:
Account for ecosystem change through time.

Nothing is permanent but change.

—HERACLITUS

The issue of time presents itself to fishery scientists in at least two ways. First, it challenges the conventional scientific method in terms of our inability to predict the behavior of complex adaptive systems. And second, it stretches the traditional time domain of management in terms of the effects of the physical climate on ecosystem structure and dynamics. Consider each of these issues in turn:

Scientific method. Clearly ecosystem structure unfolds in time and this happens at a vast number of scales. Carpenter (2002) points out that the range of turnover times in ecosystems spans at least 12 orders of magnitude, from the split-second generations of bacteria to the millennial generations of redwoods. In order to operationalize the concept of the ecosystem in the context of resource management, we must allow our thinking to range from evolutionary time (Levin 1998) to sudden interannual shifts in ecosystem organization (Hughes 1994).

Folke et al. (2004) point out the importance of slow changing variables in structuring ecosystem resilience. Examples include long-term shifts in marine ecosystems induced by exploitation (see Commandment 7). Carpenter (2002:2070) describes “the long now” as a way of connecting the past, present, and future of ecosystems. What he strives for is a way to look forward in a way informed by the past:

The ecology of the long now helps us understand how present ecosystem states came to be, how present decisions impact future ecosystems,

and how systems of people and nature might be perpetuated.

Of particular importance is the idea that prediction has very limited use when dealing with ecosystems, because in order to predict for a given time horizon, one must treat slow variables as parameters (constants). And with the exception of very limited time horizons:

The future dynamics of ecosystems are contingent on drivers that are outside the domain of ecology, such as climate change, human demography, or globalization of trade. The probability distribution of ecological predictions depends in part on the distributions of such drivers, but future driver distributions may be unknown or unknowable. Therefore the uncertainty of the ecological prediction cannot be calculated.

And so, how do we examine the future under such constraints on prediction? Carpenter (2002) proposes scenarios—narratives of plausible futures consistent with ecological understanding and their estimated probabilities based on current knowledge. Perhaps, most importantly, is the point that “scenarios encourage action whereas uncertainties sometimes lead to doubt, inaction, and further analysis” (Carpenter 2002:2080). Scenarios provide a context for the future by stimulating broad thinking. Bundy (2001) used a model of the Newfoundland-Labrador ecosystem and fishery to explore scenarios for observed ecosystem responses after cessation of fishing in the early 1990s (e.g., failure of cod to recover, increases in snow crab and shrimp fisheries). Little et al. (pers. comm.) used a similar model of the Northern California Current ecosystem and fishery to develop scenarios for both short-term and long-term interactions and feedbacks between fleet and ecosystem structures.

Physical climate. Climate variability clearly has a huge impact on the structure and dynamics of marine ecosystems. Focusing on the California Current coastal marine ecosystem as an example, the effects of climate on the biota of the ecosystem have long been known (e.g., Hubbs 1948; Chelton et al. 1982). Currently the El Niño/Southern Oscillation (ENSO) is widely recognized to be the dominant mode of interannual variability in the

equatorial Pacific, with impacts throughout the rest of the Pacific basin and globe (Mann and Lazier 2006). In addition to interannual variability in ocean conditions, the North Pacific seems to exhibit substantial interdecadal variability (Francis et al. 1998). Mantua et al. (1997) first described what is now commonly referred to as the Pacific (inter) Decadal Oscillation (PDO) which is defined technically as the leading principal component of North Pacific (N of 20° N) sea surface temperature between 1900-1993. Numerous studies have shown links between these two climate processes and biological production in the California Current (e.g., McGowan et al. 1998, Peterson and Schwing 2003, Peterson and Keister 2003 for zooplankton; Hare et al. 1999, Logerwell et al. 2003 for salmon; Field and Ralston 2005 for rockfish recruitment; Field et al. 2006, Little et al. personal communication for the Northern California Current Ecosystem).

Processes we have come to think of as cyclic are really evolutionary when examined at the appropriate time scale. Using proxy records from trees and corals, Gedalof et al. (2002) indicate that the PDO does not appear to have been a robust feature of North Pacific climate variability over the past two centuries. Whereas it had a strong interdecadal signature during the twentieth century (Mantua et al. 1997), it had a much reduced influence during the nineteenth century. Recent studies have questioned whether the PDO continues to be the dominant mode of interdecadal variability in North Pacific climate (Bond et al. 2003; Goericke et al. 2005).

Beyond recognized cyclical variation, the world oceans are now changing directionally into unknown territory due to global climate change, including increasing ocean acidity (reviews by Orr et al. 2005; Roessig et al. 2004; Harley et al. 2006). Despite denial in nonscientific circles, it is now obvious that the oceans are warming (Levitus et al. 2000; Hansen et al. 2005) and the scientific consensus regarding this fact is equally clear (Oreskes 2004; IPCC 2007). A major effect of ocean warming is ongoing poleward shifts in the geographic distributions of fishery species (Perry et al. 2005), as well as species of plankton (Hays et al. 2005), benthos (Barry et al. 1995), and marine diseases (Harvell et al. 1999). Models additionally predict that upwelling patterns, and thus the distribution and abundance of productive fisheries, could shift dramatically (Bakun 1990; Diffe-

baugh et al. 2004). Indeed, spatial patterns of primary production in the North Atlantic (Richardson and Schoeman 2004) and secondary production in the Southern Ocean (Atkinson et al. 2004) are already changing detectably. Additionally, the frequency of cyclical events, such as El Niño conditions, is predicted to increase (Timmermann et al. 1999). In the Pacific, Paya (2005) and Field (personal communication, NOAA Fisheries Service Southwest Fisheries Science Center, Santa Cruz, California) report a recent poleward range expansion of jumbo squid (*Dosidicus gigas*) into waters off Chile and California, respectively, with potentially profound effects on food webs (e.g., consumption of hake in both systems). Paya (2005) estimates that squid predation has decimated the Chilean hake biomass from 1.2 million to 300,000 metric tons in 2 years.

Such ongoing and predicted shifts indicate the need for ecosystem-based fishery scientists to monitor at least the boundaries and characteristics of stocks through time, and in any case, to implement both precautionary and adaptive approaches to address unpredictable directional change in fishery systems. In any case, what is true today may very well not be so tomorrow.

The degree to which long-term climate change is affecting the world's oceans and their ecosystems relative to other forms of variability is currently a major concern, and the consequent interactions among monotonic (global warming), interdecadal (PDO), and interannual (ENSO) climate variability are difficult to disentangle. The bottom line is that climate variability and change have major impacts on coastal marine ecosystems and their fisheries, and so any ecosystem-based fishery science must attempt to take these phenomena into account despite ever-growing uncertainty. The first step would be to reject any notion that we have the capacity to fine-tune allowable biological catches to the razor edge of MSY (Schrank 2007). Rather, the risk-averse approach to MSY is to set targets with sufficient margins of error to reflect variations in life history and recruitment of target species, ocean productivity, and errors in estimation and implementation. Perhaps MSY would be more realistically characterized as a time-dependent variable (MSY_t). Additionally, marine reserves could serve as reference sites to help disentangle the local effects of fishing from the global effects of human activities (NRC 2001).

COMMANDMENT 9:
Account for evolutionary change caused by fishing.

Yet ultimately the success for fishery management may be judged not by the catch achieved in any given year or decade, but by whether it was sustained across future generations.

—DAVID CONOVER (2000:306)

Traditional fisheries biology has not fully recognized the potential of fishing mortality to cause directional selection in fish populations (reviews by Frank and Leggett 1994; Conover 2000; Hutchings 2000; Law 2000; Stokes and Law 2000; Walters 2000; Law and Stokes 2005; Longhurst 2006). A truly ecosystem-based fisheries scientist takes a Darwinian perspective of how fishing affects fish populations, acknowledging that most fisheries are selective by their very nature, and therefore comprise large-scale uncontrolled manipulations of life-history evolution via artificial selection (Rijnsdorp 1993). More generally, we believe that ecosystem-based management—that broader context now being forced on us by history and the law of consequences—is essentially the incorporation of more holistic evolutionary and ecological principles into natural resource management.

Selective fishing-induced mortality affects previously unfished populations by, first, reducing absolute fitness within the population (i.e., decreasing the proportional frequency of genotypes between generations), and second, changing the relative fitness of genotypes that code for different life histories within the population (Conover 2000). There are two specific issues regarding documentation of these effects (Stokes and Law 2000): (1) whether there is genetic variation for traits selected by fishing, and (2) how strong the selection caused by fishing is. Available evidence suggests that heritabilities of traits affected by fishing are large enough to lead to observable evolution over mere decades of fishing. There is also ample evidence that large phenotypic changes have occurred in major fish stocks due to differentially targeting larger and older size and age classes (i.e., size and age truncation), including reduction in length and age at maturation and overall reduction in size-at-age (reviews by Stokes and Law 2000; Law and Stokes 2005). More directly, Conover and Munch (2002) demonstrated

experimentally that selective fishing can cause evolutionary change, and Olsen et al. (2004) showed that such genetic effects occurred during the decline and collapse of the northern cod fishery.

Because fisheries-induced genetic changes in stocks are not easily reversed (de Roos et al. 2006), precautionary catch quotas and other efforts to sustain old-growth age structure, including life-history reference points in stock assessments, are important tools to avoid unwanted artificial selection. Additionally, theory suggests that marine reserves can protect against strong fisheries-based selection for earlier maturation (Baskett et al. 2005).

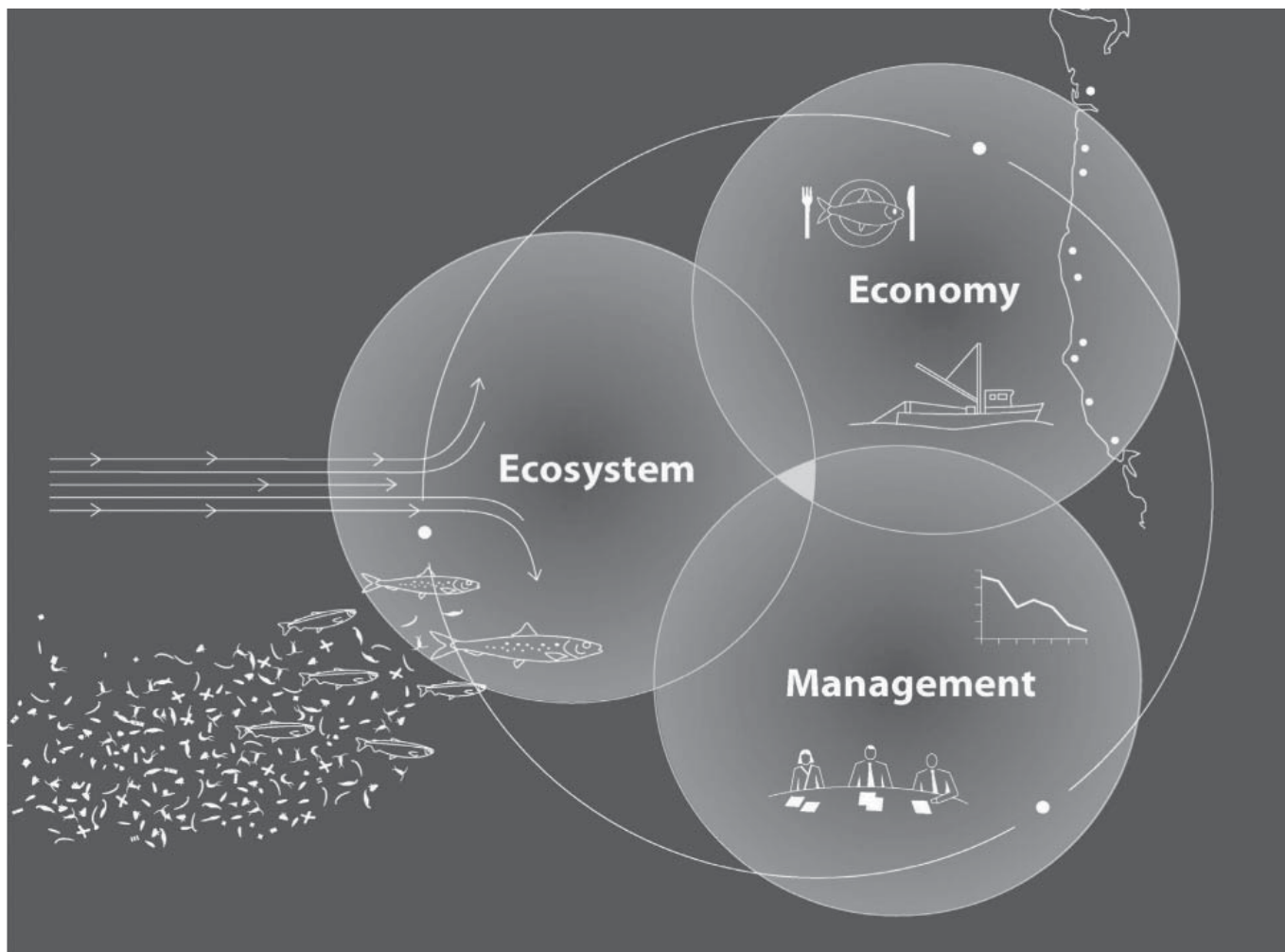
COMMANDMENT 10:
Implement an approach that is integrated, interdisciplinary, and inclusive.

When we try to pick out anything by itself, we find it hitched to everything else in the universe.

—JOHN MUIR (1911:110)

The kinds of issues raised by moving to a more holistic ecosystem-based approach to fishery science simply cannot be addressed adequately by a single disciplinary perspective. These issues require an integrated view to bridge perspectives and disciplines both within and among the natural and social sciences, integrating and synthesizing knowledge from disparate disciplines into an emerging field of “integrated assessment” (Nicolson et al. 2002). Add to this synthesis the fact that fishery science is only useful to the extent that it can help facilitate resource management decisions, and the reach of ecosystem-based fishery science broadens even more. Effective implementation of ecosystem approaches to fisheries management must necessarily embrace the full range of stakeholders and all concerned citizens.

In considering integrated assessment, two important points arise. First, integrated system models are often very useful tools for interdisciplinary researchers in that they:



1. Help codify knowledge from different disciplines into a unified and coherent framework,
2. Encourage integrated and clear thinking about causal relationships,
3. Allow researchers, managers and stakeholders to explore plausible scenarios, and
4. Identify crucial information gaps (Nicolson et al. 2002).

Second, in concert with Holling (1993) and Holling and Meffe (1996), we propose that EBFS should focus on “second stream” approaches to science (focus on interdisciplinary, holistic relationships between nature and society) which encourage management approaches (e.g., the “golden rule” of facilitating existing processes and variability) that are proactive rather than reactive.

Finally, one of the corollaries to all of these commandments is that ecosystem-based approaches require ecosystem-based

data. Not only will information gaps need to be filled by additional scientific research and monitoring, but also ecosystem-based fisheries scientists would do well to better include and integrate the vast experiential knowledge of fishermen. Although such knowledge is informal, qualitative, and provincial, the accumulated information held by the fishing community is immense and certainly an important source of supplemental data.

THE FUTURE AWAITS

We acknowledge that these 10 “commandments” raise substantial questions regarding the details of implementation. We nonetheless argue that the ongoing paradigm shift toward ecosystem-based fisheries science must necessarily involve these action items to effectively guide fisheries management toward long-term and productive sustainability. Success will depend on creativity and ingenuity to devise

specific methods to bridge the gap between general principles and full implementation. We emphasize that this paradigm shift does not comprise an abandonment of traditional fisheries biology, but rather a holistic extension of conventional approaches that grapples with the complexity of social-ecological systems in the face of incomplete knowledge.

Although the shift in worldview embodied in these commandments can occur immediately, the full implementation of ecosystem-based fisheries science will require an expanded empirical basis as well as novel approaches to modeling. This expanded knowledge base must include mechanistic ecological studies in the field, not only ocean observing systems (NRC 2003). Ultimately, we believe that ecosystem-based fisheries science must be fully implemented as soon as possible to avoid—or at least to delay—critical declines in seafood for an ever-expanding human population. ☺

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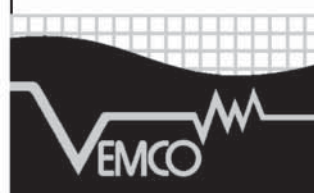


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