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Considering ecosystem-based fisheries management in the California Current

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Abstract

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. For marine fisheries in the California Current, along the West Coast of North America, such an approach must take 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. This paper reviews fisheries-based ecosystem tools, insights, and management concepts, and presents a transitional means of implementing an ecosystem-based approach to managing US fisheries in the California Current based on current scientific knowledge and interpretation of existing law.
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Keywords: Ecosystem management; Fisheries management; California Current

1. Introduction

In the California Current ecosystem, a great many fish populations and the human communities that depend upon them are in a state of crisis as a result of a combination of factors. Many long-lived and slow growing groundfish stocks have been severely depleted, and obligatory rebuilding plans suggest that some could take decades to centuries to recover to target levels. The condition of several stocks is so poor that the Pacific Fishery Management Council (PFMC) found it necessary in 2003 to close a vast majority of the continental shelf to most fishing gears as an emergency measure; such actions have been criticized at "weak-stock management" by virtue of the foregone yield of healthy stocks in order to protect overfished species [1]. Salmon crises have been ongoing in the Pacific Northwest for decades, driven by a complex combination of factors, although recent changes in ocean conditions have boosted salmon production in some regions to record levels. The California sardine has recovered nearly half a century after its spectacular collapse, yet could enter into a period of low productivity if ocean conditions change, as past climate patterns suggest they might. Still other fisheries, such as those for Dungeness crab and pandalid shrimp, have demonstrated considerable short- and long-term fluctuations in abundance and productivity yet appear to be sustainably managed with relatively minimal regulatory measures.

While there has been a wealth of new initiatives to protect habitat, minimize bycatch and otherwise rationalize fisheries, there is increasingly a perceived need for the development of a more proactive approach to managing fisheries resources in an ecosystem context. Although efforts to develop an ecosystem focus in

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fisheries are far from new [2,3], the drive to do so has increased in recent years as perceptions of fisheries have evolved from limitless frontiers to systems with limits and thresholds [4–6]. Most marine ecosystems, and particularly upwelling ecosystems such as the California Current, are relatively open systems characterized by fluctuations in physical conditions and productivity over multiple time scales [7–9]. Food webs in these systems tend to be structured around species that exhibit boom–bust cycles over decadal time scales [10,11], and top trophic levels of such ecosystems are often dominated by highly migratory species such as salmon, tunas, shearwaters, fur seals and baleen whales, whose dynamics may be partially or wholly driven by processes in entirely different ecosystems.

2. What is ecosystem-based management?

As Larkin [12] recognized, "ecosystem-based management means different things to different people, but the underlying concept is as old as the hills." 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 [5,6,13–16]. 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.

Ecosystem management has had a longer history in terrestrial resource management, where two general philosophies have been developed. Callicott et al. [17] describe these as the compositionalist and functionalist views, also at times referred to as the biocentric and anthropocentric views [18]. Although they exemplify the extremes of a continuum, a comparison of the two is useful when considering the interactions between competing objectives, mandates and scientific perspectives ("ecologies") in marine resource management. In general, the compositionalist view emphasizes the application of ecological science and knowledge, viewing the world "through the lens of evolutionary ecology," towards the goal of protecting diversity and integrity over the long term. From this perspective, humans are separate from nature, and anthropogenic needs are largely secondary. This is the view developed by Grumbine [19] when he detailed goals for sustaining ecological integrity. These goals included maintaining viable populations of native species, representing (within protected areas) all native ecosystem types across their natural range of variation, maintaining evolutionary and ecological processes, managing over time periods long enough to maintain evolutionary potential, and accommodating human use within these constraints. Grumbine recognized that these goals were in striking contrast to traditional, extraction driven resource management objectives. Consequently, the compositionalist philosophy may be more acceptable for wildlife refuges, wilderness areas, and similarly managed lands that include areas of high biodiversity, endemism or unusual community assemblages.

By contrast, a strict interpretation of the functionalist perspective is of a process-oriented, thermodynamic approach, with a foundation on the energy-transfer-based view of ecological function [17]. This functionalist view is focused on obtaining as much production from landscapes as possible, in order to achieve a high production to biomass efficiency [20]. This view is clearly more consistent with the current paradigm of contemporary fisheries management, which is premised on the assumption that populations (and subsequently the ecosystems in which they exist) are healthy if they are maintained close to the levels that provide the maximum amount of surplus production, or maximum sustainable yield (MSY). As such, the functionalist perspective is dependent on the assumption of equilibrium resilience, such that ecosystems and populations are capable of restoring themselves to (or close to) past equilibrium states given the opportunity to do so [21]. The fundamental belief of this perspective is the assumption that management can control multiple interacting population trajectories with enough precision to shift populations (and implicitly, ecosystems) into a mode that is as functionally beneficial to society as possible.

Beyond these two historically terrestrial perspectives, a third general philosophy that might guide ecosystem-based fisheries management (EBFM) is the social–ecological perspective. Based on his historical analysis of fisheries development in California, McEvoy [22] presented a model of a fisheries system as a combination of three elements: the physical and biological environment (ecosystem), a group of people working (economy), and a system of social control within which the work takes place (management). A conceptual schematic of McEvoy's model is presented in Fig. 1. McEvoy's key assertion is that management must equally weigh the many social and economic relationships within the fishery and how, in turn, they both influence and are influenced by marine ecosystem processes and dynamics. In this perspective, it is the human interactions with the environment that should be of particular concern to decision makers. Thus, McEvoy's model is a classic example of a social–ecological system [23], as

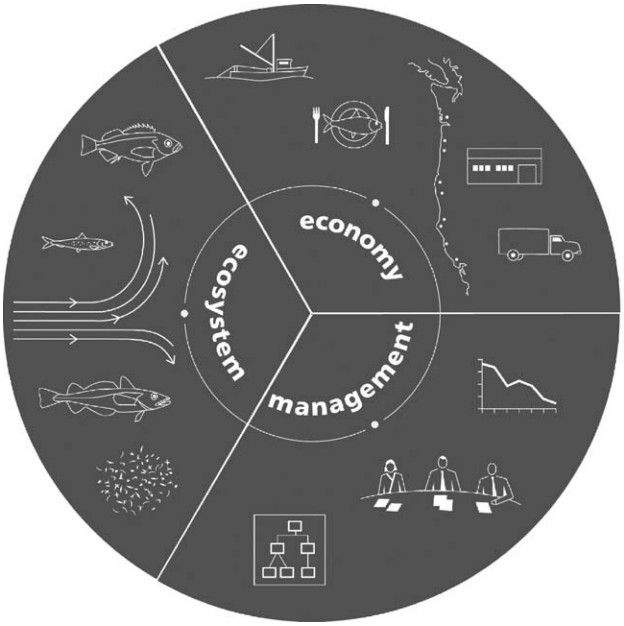

Fig. 1. Schematic of the key elements of a fisheries system; ecology (the physical and biological elements of the ecosystem), economy (fisheries and communities) and governance (the management system). Based on McEvoy [22].

representing an integrated concept of humans in nature, in which the essence of a sustainable fishery is the health of the interactions between the ecosystem, economy and management. Within the socio-ecological perspective, the role of EBFM is to provide decision makers with tools to recognize and respond to the potential consequences to the ecosystem that may result from the activities undertaken by fishermen and sanctioned by management bodies, given the recognition that there is risk of negative outcomes to both the ecosystem and the economy if poorly informed decisions are made.

3. Sustainable fisheries, ecosystem management, and the law

Ecosystem management, or ecosystem-based fishery management, means different things to different people largely as a result of the three philosophies discussed above, which simultaneously conflict with, yet complement, one another. In the discussions leading up the passage of the 1996 Sustainable Fisheries Act (SFA) amendments to the Magnuson Stevens Fishery Conservation and Management Act (MSFCMA), there was increasing recognition of the potential for an ecosystem-based approach to improve fisheries management. Although the Congress did not explicitly adopt an ecosystem-based approach,[1] the SFA did require the National Marine Fisheries Service (NMFS) to convene a panel of experts to "expand the application of ecosystem principles in fishery conservation and management activities" (16 USC 1882, §406). This panel's primary recommendation was that the eight regional Fishery Management Councils develop Fisheries Ecosystem Plans (FEPs) for the ecosystem or ecosystems under their jurisdiction [5]. The FEP would act as an "umbrella document" containing detailed information on the structure and function of the ecosystem under consideration, and increase the awareness of managers and stakeholders on the effects that their decisions have on the ecosystem. Although the current system of fisheries management plans (FMPs) would remain the basic management tool in the near term, they would be amended to ensure compatibility with the ecosystem principles, goals and policies of the FEP. Since the completion of their report, the NMFS approach has continued to center around single-species assessments, but has increasingly supported ecosystem-based research and modeling efforts. The most recent National Oceanic and Atmospheric Administration (NOAA) Strategic Plan explicitly refers to a primary agency mission to "protect, restore and manage the use of coastal and ocean resources through ecosystem-based management," however, this plan also recognizes that management in the near term will continue to be on a species and site-specific basis [24].

The extent to which existing legislation, in particular the National Environmental Policy Act (NEPA) of 1972 (42 USC 4321), may or may not be interpreted as requiring that ecosystem considerations be evaluated in making management decisions is somewhat unclear. The Act requires an environmental impact statement (EIS), on the potential impacts of proposed federal actions that might affect the environment (across a reasonable range of impacts), detailing not only adverse impacts that could not be avoided if the proposal were implemented, but also reasonable and prudent alternatives to such actions. Fishery management councils have traditionally been required to develop a programmatic EIS (PEIS) for FMPs prior to their approval (PEIS are typically required for connected or closely related actions, such as the broad-scale management of multiple fisheries components). While there is no clear regulatory requirement to revisit past PEISs, questions regarding the longevity of these documents have arisen as the lifespan of past PEISs lengthens [25,26].

Currently, the only fishery management council to revisit their programmatic EIS is the North Pacific

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[1] The SFA included no mention of ecosystem considerations in the National Standards or in fishery management plan (FMP) requirements, however, some authority is inferred in the definitions section of the Act where optimum yield is defined as "the amount of fish which will provide the greatest overall benefit to the Nation, particularly with respect to food production and recreational opportunities, and taking into account the protection of marine ecosystems" (16 USC. 1802, §3).

Table 1
Comparison of the focal elements of a fisheries ecosystem plan as envisioned by the Ecosystem Principals Panel (left) and the ecosystem elements considered under the NEPA programmatic review of NPFMC groundfish fishery management plans

Ecosystem Principles Advisory Panel	NPFMC Interpretation of NEPA
• Delineate and characterize ecosystems • Develop a conceptual model of the food web • Develop indices of ecosystem health	• Stability of the food web and (ecological) community structure • Seabird and marine mammal interactions
• Describe habitat needs and how they are considered in conservation and management measures	• Consider impacts on marine habitat, including benthic essential fish habitat
• Calculate total removals (including incidental mortality), and show how they relate to biomass, production, optimum yields, and trophic structure	• Sustainability of target stocks (prevent overfishing) • Bycatch (discards) and incidental catches
• Assess the ecological, human, and institutional elements of the ecosystem	• Sustainability of fisheries and communities • Alaska native participation in fishery management and traditional ways of life • Value of marine resources (both commercial and non-commercial)
• Assess how uncertainty is characterized and how buffers are included in conservation and management actions • Describe available monitoring data	• Data quality, monitoring, research and enforcement requirements

Fishery Management Council [27]. The principal objective of their Programmatic Supplemental Environmental Impact Statement (PSEIS) is to serve as the central environmental document for the groundfish fishery, and provide a "big picture" evaluation of both the impacts of fisheries and fisheries management objectives for North Pacific marine ecosystems. The PSEIS includes consideration of alternative fisheries management policies, and while all of the alternatives were designed to be compatible with other existing laws, they were also intended to bookend a reasonable range of what might be considered strictly compositionalist and functionalist harvest strategies and objectives. For example, the proposed alternatives ranged from fishing all stocks aggressively in order to maximize biological and economic yield from the resource (arguably a functionalist approach), to adopting a highly precautionary approach in which the burden of proof is shifted to resource users to demonstrate negligible impacts of fisheries to the ecosystem (arguably a compositionalist approach). The preferred alternative was the status quo: characterized as adaptive to new information and reactive to environmental issues, and based on the assumption that fishing at levels approaching, but not exceeding proxies for MSY, is compatible with ecosystem health and sustainability. The alternatives are accompanied by a suite of likely or expected impacts associated with their adoption, and there is also considerable overlap between the impacts evaluated in the PSEIS and those envisioned to be the principal elements of an FEP, as seen in Table 1.

Although past applications of the law indicate that neither NEPA nor the MSFCMA explicitly mandate an ecosystem approach, the language in both laws suggests that ecosystem considerations should be evaluated in making policy decisions within the context of the current fishery management system. As Livingston et al. [28] suggest, the original spirit of NEPA to provide an open and public process for advising decision makers is integral to any successful implementation of an ecosystem-based approach to fisheries management. Despite the fact that it has been viewed as primarily an administrative burden, NEPA remains one of the most powerful environmental laws in the nation as a result of legal requirements for analysis, disclosure, and transparency. Consequently, NEPA offers a means to scientifically evaluate the cumulative impacts of fisheries on marine ecosystems (Table 1).

It seems clear that the legislative authority exists to change the fundamental nature of how fisheries resources are managed, with the goal of sustaining both the resources and the interactions between the resources and the resource users. Given the opportunity, if fishery management councils were to embrace an ecosystem-based approach in principle, but were limited in the rate at which such an approach could be prescribed as policy, where might they start? For fisheries in the California Current, managed by the PFMC, we suggest that three elements would be key, these being:

- Increasing exposure to the management and user communities of short- and long-term climate and ocean status, trends and scenarios for the California Current.

- Consideration of trophic interactions among fished and unfished species and associated impacts on ecosystem structure and dynamics.
- The increasing application of new management approaches, including spatial management measures to protect life history characteristics and biodiversity.

Ideally these elements would complement, rather than replace, existing management efforts relative to single-species conservation objectives. While they admittedly add to the plethora of ongoing activities and developments currently being undertaken by the NMFS and the Council, they should rightly be considered critical elements of any future success at meeting NOAA and NMFS' current objectives. The following sections elaborate on these recommendations, followed by a potential blueprint for implementing ecosystem-based management on both short and long time scales.

3.1. Climate considerations

The effects of climate on the biota of the California Current ecosystem have been recognized for some time. Hubbs [29] believed so strongly in the correlation between water temperature and fish distributions that he felt "justified in drawing inferences, from the known data on fish distribution, regarding ocean temperatures of the past." In particular, Hubbs had already drawn distinctions between eras that seemed to be associated with the establishment of warm-water populations over long time periods, which may be associated with Pacific Decadal Oscillation (PDO) scale variability [30,31], and the occasional warm years that brought irregular tropical or subtropical fish much further north along the coast in response to interannual (El Niño) warm events [11,32,33]. Over decadal time scales, climate-driven changes in ocean conditions have long been attributed to both long-term variability in reproductive success and survival in sardine, anchovy and other coastal species that, in turn, appear to be responsible for some of the most spectacular boom and bust fisheries seen in the world's oceans [34–36]. Interestingly, there may be trophic interactions associated with these presumably climate-driven shifts as well, as MacCall [11] noted that peak abundances of predators such as mackerel and bonito seemed to follow their prey, anchovies and sardines, such that two given species never seemed to be abundant at the same time (Fig. 2). A similar sequence seems to occur in the Kuroshio Current off of Japan [37], as well as in large-scale currents off Peru and Chile [38]. This might suggest a trophic response to climate-induced changes in coastal pelagic species productivity on a basin scale.

In recognition of the role of climate in driving this productivity, the California sardine fishery is currently managed under an innovative harvest control rule based on the 3-year running average of the Scripps Pier sea surface temperature. The harvest rule allows for high harvest rates during favorable environmental conditions, and lower rates during periods of low productivity (harvest rates also reach zero when the biomass is at low levels regardless of climate conditions). Although there is no clear mechanism or process defining the strong relationship between SST and sardine productivity [39,40], this example demonstrates that provisional linkages and correlations can be successfully applied to generate management models within the bounds of the existing fisheries management regime. As such, the control rule is consistent with the implementation guidelines for the SFA, which include allowances for shifting biological reference points where evidence exists that the productivity of stocks has changed. Perhaps more importantly, this demonstrates that management is both willing and able to implement regulatory measures that recognize the impacts of climate on population productivity.

Pacific hake are also characterized by climate-induced variability in both production and distribution. Adults migrate from their winter spawning grounds off southern California to their summer feeding grounds off the Pacific Northwest coast, where they are the targets of the largest (by volume) fishery on the US West Coast. A much greater proportion of the hake biomass extends north of the US/Canada border during warm years than cold years, a distributional shift that has historically complicated management of this shared resource between the US and Canada [41–43]. These dramatic distributional shifts are matched by equally spectacular changes in abundance when recruitment conditions are good. In the early 1980s, two strong recruitment events (in 1980 and 1984) caused the stock biomass to nearly triple, from approximately 2 to 6 million metric tons (Fig. 3), and accounted for roughly 60% of the over 3 million tons of hake landed between 1983 and 1997 [based on 44]. Although an oceanographic mechanism explaining the success of these year classes (and the relative failures of others) has proven elusive [45,46], it is clear that such tremendous shifts in distribution and abundance have major impacts on the rest of the ecosystem. Pacific hake have been implicated as predators of juvenile salmon [47], inflict substantial predation pressure on commercially important pandalid shrimp and are voracious predators of krill, herring and other forage fish that are the primary prey of salmon, rockfish and other groundfish species [48–50].

Climate and oceanographic information is increasingly available in highly detailed, descriptive and meaningful forms to researchers and managers alike [51–53], including an annual review of the physical and biological state of the California Current ecosystem itself [54,55]. Biological indicators of productivity include time series of zooplankton abundance [9,56],

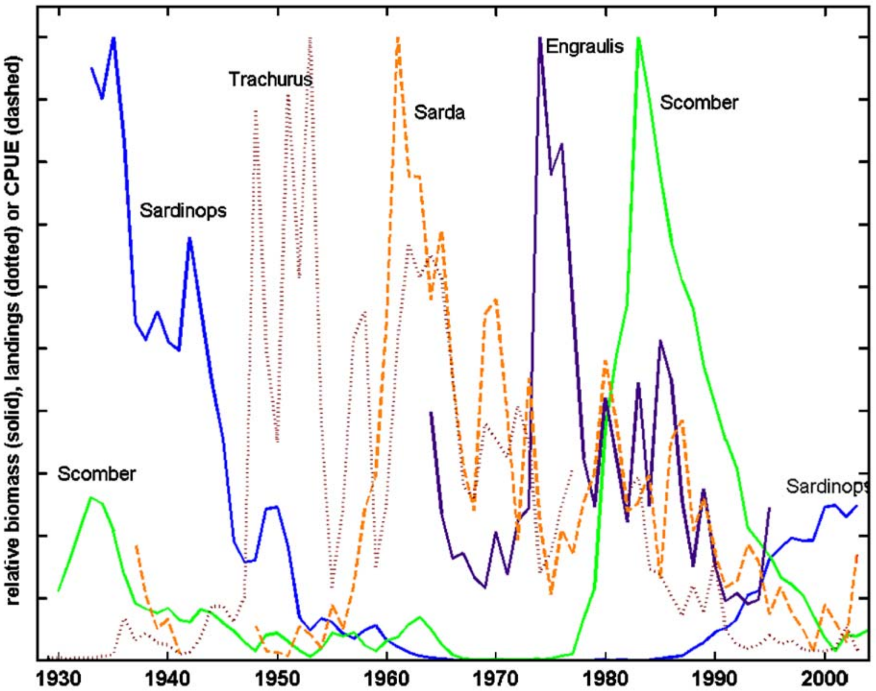

Fig. 2. Sequential nature of the relative abundance of coastal pelagic species in the California Current ecosystem, based on stock assessments (solid lines) and indices of relative abundance or landings (dotted lines). Species shown are Pacific mackerel (*Scomber japonicus*), Pacific sardine (*Sardinops sagax*), jack mackerel (*Trachurus symetricus*), bonito (*Sarda chiliensis*) and northern anchovy (*Engraulis mordax*). Updated from MacCall [11].

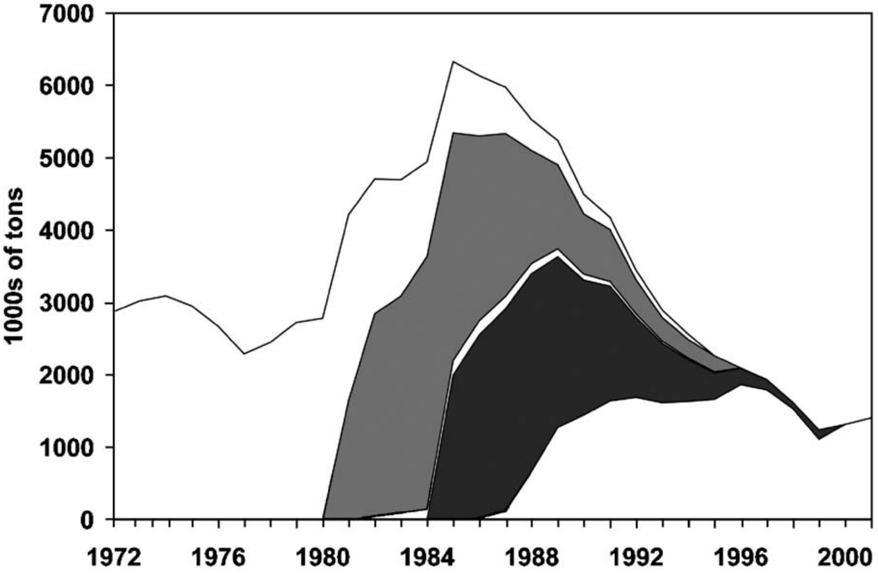

Fig. 3. Relative contributions of the 1980 (light gray) and 1984 (dark gray) year classes to the total estimated biomass of Pacific hake (*Merluccius productus*) population in the California Current System. Data from Helser et al. [44].

estimates of rockfish year class strength [57], and models of salmon survival based on physical and biological ocean indices [56,58]. A study group organized by North Pacific Marine Science Organization (PICES) in response to a formal request by the US government recently concluded that the time is long overdue for the formal inclusion of climate and ecosystem information into the management consciousness and decision-making framework [36]. The PICES group recommended four key actions for incorporating climate considerations into fishery management activities, which included acceptance of the regime concept for marine ecosystems, the development and maintenance of improved observation and monitoring efforts, the continued application of climate indices and research linking climate indices to predictable components of the climate system, and the evaluation of future regime scenarios in stock assessments to assess the vulnerabilities of fisheries and ecosystems under different management strategies and climate conditions [36].

As these elements of climate considerations are developed, a transitional approach to incorporating climate considerations into management would be to periodically brief the PFMC and the Council community with reports on climate and ocean observations, forecasts and scenarios for the California Current. This could include designating a regional fisheries oceanographer, whose primary responsibility would be to synthesize climate information into usable and understandable formats, orchestrate the development of a climate and ecosystem status and trends document, and act as a conduit between the climate research and the fisheries management communities. A blueprint for defining the role of regional fisheries oceanographers could be taken from the existing framework for the role of state climatologists, whose obligations include summarizing and disseminating weather and climate information to user communities, demonstrating the value of climate information, performing impact assessments, and conducting climate research and projections.[2] Currently, the users of such climate information include a wide array of business leaders and local government workers, including those involved with water management, agriculture, forestry, public utilities, and emergency response, for which short-term (seasonal to annual) forecasts have the potential to reduce or increase revenues by billions of dollars [59,60].

Given widespread recognition of the broad and large-scale impacts of climate on fish and fisheries, it seems rational that the consideration of climate information by the Council community could significantly improve the context in which management decisions are made. For example, an improved understanding of the relationship between salmon success and climate might suggest that greater precaution be taken under the expectation of an El Niño event, or a particular phase of the PDO. A regional fisheries oceanographer would also provide a channel for transmitting climate information and forecasts both to and from fishermen and fisheries-dependent communities, an important role given that a majority of California fishermen believe that climate is the most important factor in determining the productivity of many fish and shellfish populations [61]. Similarly, Dalton [62] found substantial direct impacts of climate on fishing effort, ex-vessel prices and future expectations of production and availability in Monterey Bay fisheries. This work showed that regulations that allowed fishermen to allocate their effort freely in response to climate and price variability would maximize the value of future climate information, and emphasized the importance of improving the understanding of complex physical, biological and economic feedbacks between fisheries and the ecosystem. Consideration of how managers might facilitate the response of resource users, without increasing the jeopardy of resources, would be one way to operationalize McEvoy's [22] key target for sustainability, as the long-term health of the interaction between nature, the economy and the legal system. Given the precedent set by the adoption of the sardine harvest policy, the increasing understanding of processes and mechanisms that drive variability in this ecosystem, and recognition of the importance of regime-scale variability on resource productivity, it seems clear that there is a growing need for the PFMC and other councils to more formally consider climate factors in management.

3.2. Ecosystem models and trophic considerations

As emphasized in the previous section, energetic and highly variable oceanographic processes shape the physical environment and drive production throughout the California Current food web over a range of time scales. Additionally, over the past 200 years, massive removals of whales, pinnipeds, salmon, coastal pelagics, groundfish, invertebrates and hake have taken place throughout the California Current (Fig. 4), often driving many populations to extremely low levels of abundance. It would be difficult to presume that such removals have not fundamentally disturbed energy pathways, and altered the basic structure and function of the ecological community. We now know that many of the living resources in the California Current are not capable of providing a steady and predictable surplus to humans year after year, and removals have often severely exceeded the productive capacity of many stocks. Yet, populations of whales, pinnipeds, sardines and other species have often made dramatic recoveries from past overexploitation, often under strong management constraints, providing us with opportunities to better appreciate the resilience of stocks, species and communities in this dynamic ecosystem.

Where trophic interactions among exploited species are documented or suspected, ecosystem modeling can provide a template to evaluate both the magnitude and consequences of removals of either predators or prey in the system of interest [63,64]. For instance, Walters et al. [65] have used ecosystem models to demonstrate that widespread application of contemporary (MSY proxy) single-species management approaches could lead to

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[2] The role and affiliations of State climatologists are described by the American Association of State Climatologists (AASC) website (http://lwf.ncdc.noaa.gov/oa/climate/aasc.html#ABOUT).

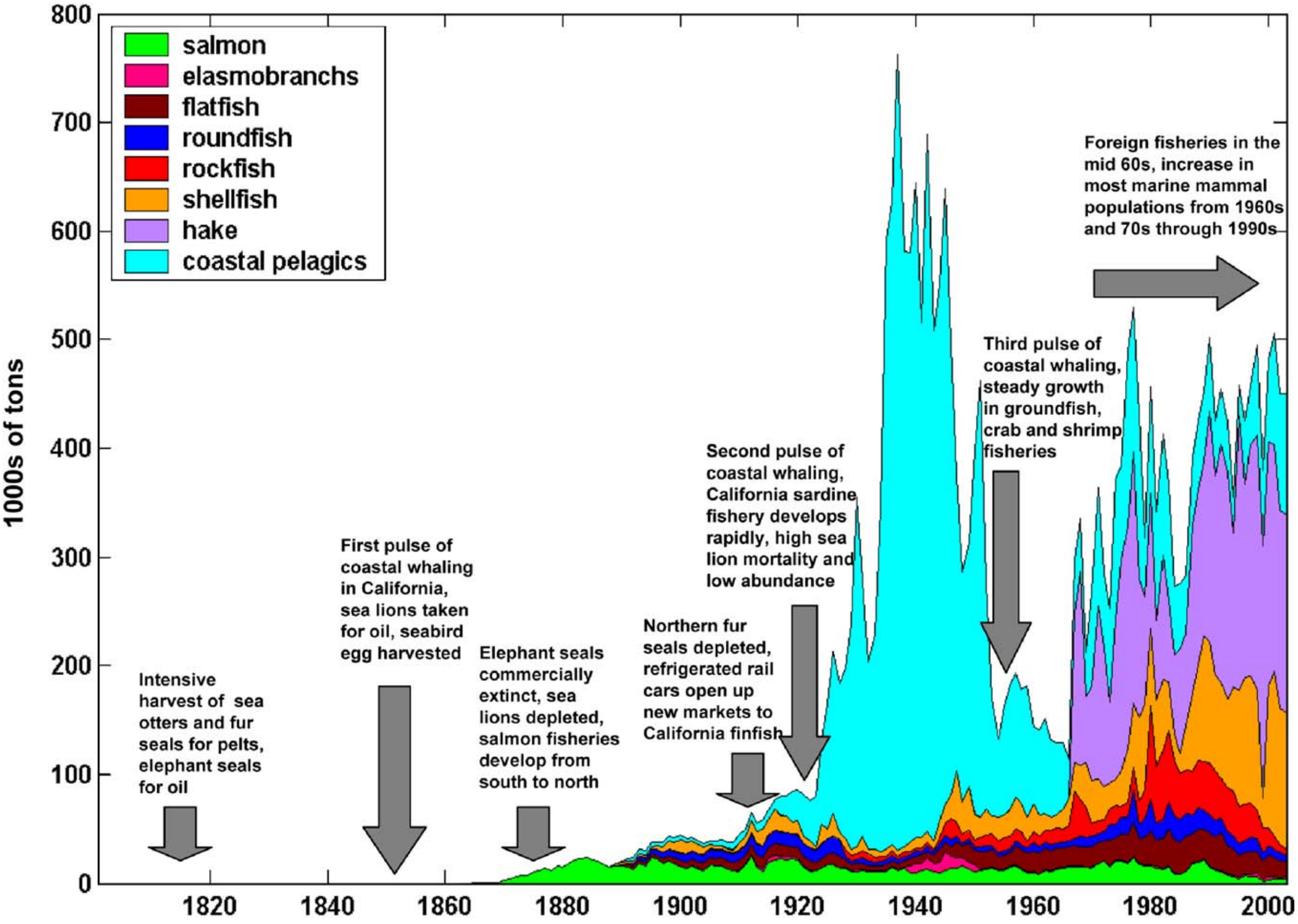

Fig. 4. Major removals, developments and fisheries catches throughout the US portion of the California Current Ecosystem over the past 2 centuries.

dramatic impacts on ecosystem structure, particularly where such approaches are applied to forage species. Their results add considerable weight to the perceived need to consider forage species as resources whose value is derived from their role as prey to commercially and recreationally important stocks. Petitions made to the PFMC to manage krill (euphausiids) as a forage species, and place either a temporary or permanent ban on krill harvests in recognition of their importance as a key prey item, would thus be consistent with an ecosystem perspective towards fisheries management in the California Current.[3] The significance of euphausiids as one of the most important vehicles for the movement of energy through this ecosystem is reflected in Fig. 5, which illustrates the key role that euphausiids play as forage for commercially important species such as hake, rockfish and salmon. Table 2 provides a summary of the more significant species or taxon in the aggregated functional groups shown in Fig. 5, as well as the scientific names of species commonly referred to throughout the text.

In another example, a model of the Newfoundland-Labrador ecosystem suggested that although overfishing drove massive declines in cod abundance, cod recovery was likely hindered by the increase in natural mortality rates associated with a nearly constant per capita consumption of cod by an increasing population of harp seals [66]. Although this model did not replicate all of the trends estimated by single-species models, it did suggest that the decline in cod and several other heavily fished species might have also resulted in the increase of shrimp and other large crustaceans, an outcome supported by empirical studies [67]. While these results alone may not provide sufficiently rigorous evidence to guide policy, they are informative for policy makers, especially where consistent with more empirical evidence of ecosystem changes. Other modeling efforts have also met with some success at replicating the behavior of key commercial fish populations over long time periods

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[3] Correspondence between the Southwest Fisheries Regional Center, the Southwest Fisheries Science Center and the PFMC in 2004 and 2005 has resulted in a commitment to incorporate krill into the Coastal Pelagic Species Fisheries Management Plan, and to consider alternatives for krill management that would include a moratorium on directed fisheries for krill (http://www.pcouncil.org/bb/2005/0305/ag_g2.pdf).

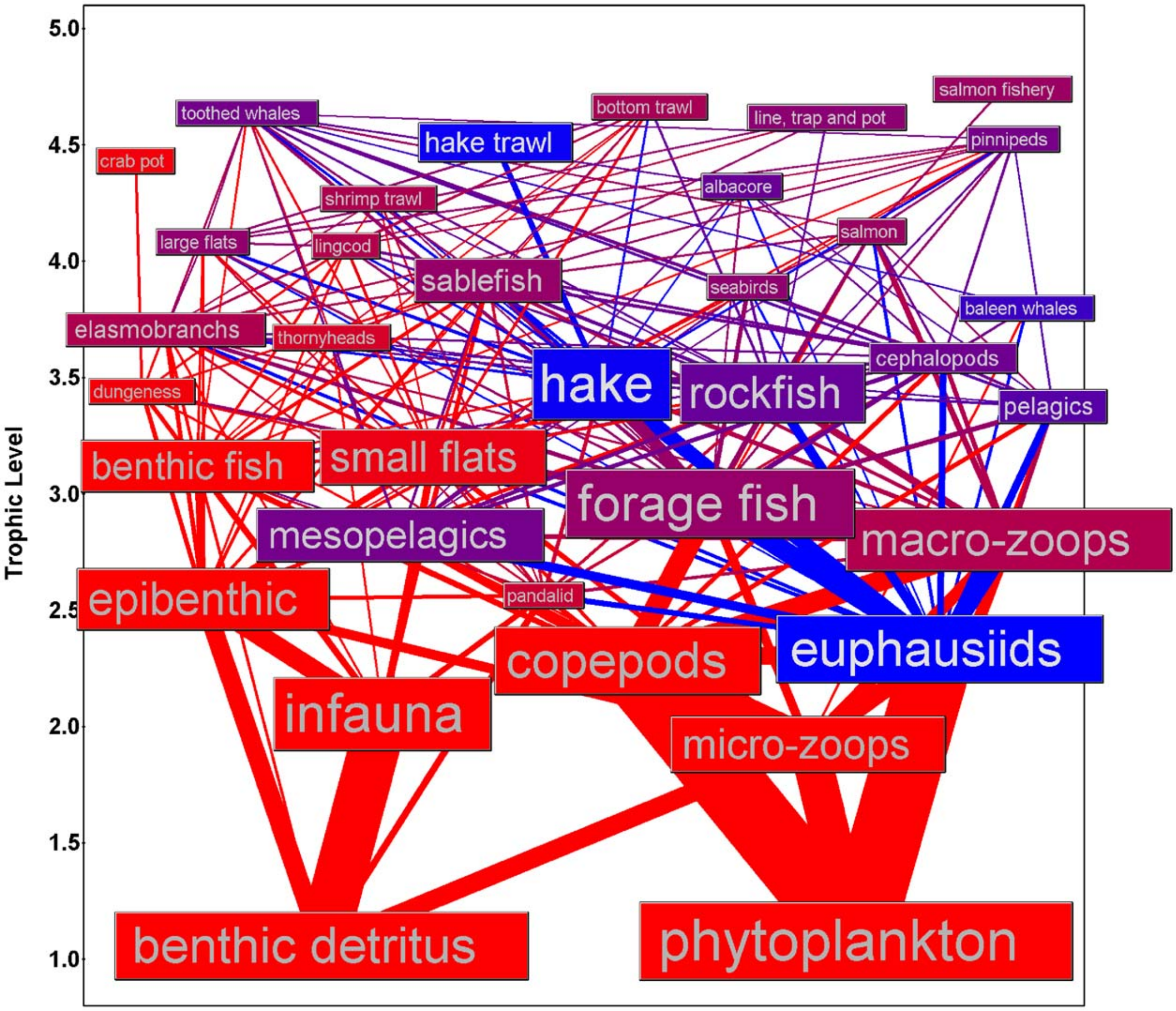

Fig. 5. Dispersal of energy from euphausiids with respect to other energy sources in the Northern California Current. The estimated trophic level is along the *y*-axis, and colors representing the alternative energy pathways such that energy derived from euphausiid production is blue and energy from other sources is red. The size of the boxes and the width of the bars connecting various boxes are scaled to the log of the standing biomass and biomass flow, respectively.

using fishing pressure and climate as forcing factors of ecosystem dynamics, including the Central North Pacific, Eastern Tropical Pacific, and Northern California Current ecosystems [68–70]. For the Northern California Current, observed trends for most groundfish can be fairly well replicated with a multi-species model, suggesting fairly weak trophic interactions among adult life history stages of most fishes relative to the impacts of fishing [70]. Stronger interactions were observed in forage species such as shrimp, salmon, and small flatfish, where there is greater population turnover and high predation, coupled with substantial changes in many of their key predators over the period modeled. Perhaps most importantly, model performance improved when climate was introduced as a driving force, given the a priori assumption that climate forcing is a critical factor in determining productivity and dynamics in this ecosystem.

In all of these examples, quantitative modeling of trophic interactions has the potential to lead to changes in harvest or management strategies in the near term, and at a minimum represents a valuable contribution to a more holistic understanding of ecological connections and interactions. Conveying to decision makers the significance of ecological processes may be just as important as monitoring and conducting process-oriented research into the causes and consequences of the same. Many criticisms of ecosystem modeling approaches are based less on the model structure, than on the misuse and misunderstanding of the model limitations [64,71,72], a characteristic shared with single-species models [73]. The far more important feature of ecosystem models is that if based on reasonable knowledge, and presented with an appropriate degree of skepticism, such models can serve as a stimulus for initiating dialogues with regard to both past population

Table 2
Summary of the more significant species or taxon in aggregated functional groups, and scientific names of commonly referred to species from the text and figures

Phytoplankton	Functional group of all photosynthetic primary producers, diatoms generally dominate
Infauna	Functional group of polychaetes, bivalves, small crustaceans, and some echinoderms
Epibenthic	Functional group including benthic crustaceans (decapods, isopods, amphipods), echinoderms (holothuroids, asteroids, ophiuroids), gastropods and other organisms
Micro-zoop	Functional group of small heterotrophic zooplankton, primarily protozoans such as gymnodiniods, dinoflagellates, ciliates, and nanoflagellates
Copepods	All developmental stages of species in the subclass Copepoda
Euphausiids	All developmental stages of species in the order Euphaussiacea
Macro-zoops	Functional group including pasiphaid, seregestid and other pelagic shrimps, chaetognaths, pelagic polychaetes, pelagic amphipods, and gelatinous zooplankton
Cephalopods	Functional group of cephalopods, such as *Loligo*, *Gonatus*, and *Octopus* species
Forage fish	Functional group of principally clupeids and osmerids, including northern anchovy, Pacific herring, sandlance, eulachon, surf smelt, and whitebait smelt
Mesopelagics	Functional group of many meso- and bathypelagic species, including northern lampfish, California headlightfish, blue lanternfish and longfin dragonfish
Benthic fish	Functional group including grenadiers (*macrouridae*), eelpouts (*Zoarcidae*), snailfish (*Cyclopteridae*), poachers (*Agonidae*), and sculpins (*Cottidae*)
Small flatfish	Functional group including Dover sole (*Microstomus pacificus*), english sole (*Parophys vetulus*), rex sole (*Glyptocephalus zachirus*), sanddabs (*Citharichthys* spp.), and others
Pelagics	Includes Pacific sardine (*Sardinops sagax*), jack mackerel (*Trachurus symetricus*) and Pacific mackerel (*Scomber japonicus*)
Pandalid shrimp	*Pandalus jordani*
Dungeness crab	*Cancer magister*
Salmon	Chinook and coho salmon (*Oncorhynchus* spp.)
Elasmobranchs	Includes dogfish (*Squalus acanthias*), cat sharks (*Apristurus* spp.), soupfin (*Galeorhinus galeus*) and thresher (*Alopias* spp.) sharks, and skates (*Raja* and *Bathyraja* spp.)
Rockfish	Includes all *Sebastes* species, most abundant species include widow (*S. entomelas*), yellowtail (*S. flavidus*), canary (*S. pinniger*), and Pacific Ocean perch (*S. alutus*)
Thornyheads	Shortspine (*Sebastolobus alascanus*) and longspine (*S. altivelis*) thornyheads
Pacific hake	*Merluccius productus*
Sablefish	*Anoplopoma fimbria*
Lingcod	*Ophiodon elongates*
Albacore	*Thunnus alalunga*
Large flats	Includes arrowtooth flounder (*Atheresthes stomias*), Pacific halibut (*Hippoglossus stenolepus*) and Petrale sole (*Eopsetta jordani*)
Seabirds	Includes shearwaters (*Puffinus* spp.), common murres (*Uria aalgae*), other alcids, gulls (*Larus* spp.), albatross, phalaropes, petrels and others.
Toothed whales	Primarily Dall's porpoise (*Phocoena dalli*), Pacific white-sided dolphin (*Lagenorhynchus obliquidens*), sperm whales (*Physeter macrocephalus*), and Orcas (*Orcinus orca*)
Pinnipeds	Primarily Steller sea lions (*Eumetopias jubatus*), California sea lions (*Zalophus californianus*), fur seals (*Callorhinus ursinus*) and harbor seals (*Phoca vitulina*)
Baleen whales	Primarily humpback whales (*Megaptera novaeangiliea*), but including minke (*B. acutorostrata*), fin, (*B. physalus*), and gray whales (*Eschrichtius robustus*)

dynamics and plausible ecosystem futures [74]. Perhaps their greatest asset is that they can complement the insights gained from single-species models through a more strategic consideration of past and current abundance and productivity, and consequently provide a means to quantify the interconnectedness of parts within the system, and evaluate plausible trade-offs between these parts as a result management decisions.

3.3. Demographics, life history and biocomplexity

As suggested by the discussion of the compositionalist and the functionalist perspectives, even a robust and successfully implemented combination of single and multi-species data, models, reference points and thresholds would be insufficient to fully adopt an ecosystem perspective. The challenging but critically important measures of diversity, biocomplexity, and ecological integrity may be just as important to managing for an ecosystem perspective as more ''functionalist'' single-species reference points and objectives. Although models play a critical role by allowing the management community to relate to the consequences of their decisions, both single species and ecosystem models tend to reflect a functionalist perspective with regard to their presumed properties of resilience [21]. Yet, even the impacts of successfully implemented management measures to demographic and life history characteristics of some species may be contrary to perspectives of sustainability based on evolutionary ecology. Fishing has been widely accepted (and experimentally demonstrated) to be a form of artificial selection towards smaller size or younger age at reproduction [75,76], and the potential consequences of such selection are important for both conservation and economic reasons.[4] In particular, the assumptions of fisheries science and the stock assessments upon which management is based ignore the potential evolutionary consequences of harvesting, which could reduce the sustainable yield of a population by decreasing the amount of somatic growth relative to reproductive effort [77]. This has resulted in what some have dubbed the ''tropicalization'' of many marine fish populations, meaning the imposition of traits such as faster growth rates, smaller size, and earlier maturity schedules which may be ill-suited to the environment in which such populations live, and could result in reductions in long-term yield [78].

Lotka [79] was among the earliest to propose that the ability of populations to persist or recover is constrained if the distribution of age structure is pushed beyond a certain threshold, a threshold that has since been referred to as the ''boundary of sustainability'' [80]. In particular, longevity appears to be an archetypical life history adaptation of many temperate water populations to episodic recruitment failure in a variable and an uncertain environment, and it has consequently been suggested that age structure should not be forced to diverge far from the values that evolved for each stock prior to human exploitation [81–83]. Prior to the development of large-scale fisheries, a majority of the biomass of commercially important sablefish, Dover sole and many rockfish populations consisted of fish greater than 20 years of age, with individuals of many species capable of reaching ages of 80 or more [84,85]. As of 2005, seven species of rockfish (Sebastes spp.) as well as lingcod are managed under NMFS overfished species rebuilding plans. These species declined to depleted levels as a result of a combination of low productivity, poor environmental conditions, and high harvest rates, and have expected recovery times of several to many decades [86]. In addition, substantial community changes may also be associated with groundfish declines, as four of the species (cowcod, bocaccio, yelloweye rockfish and lingcod) are large, long-lived piscivores that may have played an important role in maintaining the community structure of the rocky reef ecosystems that they used to dominate [87,88].

There is also growing evidence of variability in the reproductive abilities of younger and older individuals of many species, the inference being that a broad distribution of age structure is beneficial to the recruitment and productivity of many stocks [89–91]. For example, it has been shown that older female black rockfish produce larvae with faster growth rates and greater larval survival than younger fish, with age being a more significant predictor than size alone [92]. Older females also gave birth earlier in the year than younger females [93]. Such considerations are not limited to long-lived species, as it has been demonstrated that the ''biocomplexity'' of stock structure in western Alaskan sockeye salmon plays a critical role in providing both stability and sustainability to fisheries [94], findings that echo those for West Coast salmon populations [95,96]. All of these examples reveal that for many fish populations, long-term sustainability is based on complementary patterns of production from different stock components under varying environmental conditions. Complementary patterns of production help sustain fishermen as well, as Hanna [97] found that the diversification of fishing strategies between groundfish, shrimp and crab benefited fishermen by reducing the variability of landings and earnings.

The application of marine protected areas (MPAs) and other spatially based management efforts (such as rotating closures and ocean zoning) have been increasingly proposed as potential tools in future marine resource management [16,98,99]. An NRC panel charged with investigating the potential application of MPAs in marine resource management concluded that there was compelling evidence for their use in managing fisheries, protecting habitat and biodiversity, and otherwise enhancing the anthropogenic value of marine habitat [100]. As management tools, MPAs offer a form of insurance against overexploitation and recruitment overfishing, help preserve a broad age distribution, and protect vulnerable non-target species and habitat. Both proponents and critics point out, however, that the nature of any implementation could be associated with increased fishing mortality and impacts outside MPA boundaries [101,102]. Yet, the need for spatial management to achieve current conservation objectives, such as rebuilding depleted rockfish stocks for the Pacific Council, suggests that such measures may have much to offer with regard to maintaining life history characteristics and biocomplexity in marine populations. Regardless of the mechanism, it is increasingly important for all stakeholders to recognize that maintaining life history traits and otherwise facilitating each population's insurance strategy for coping with the environment is a critical element of any sustainable approach to long-term fisheries management.

4. Moving towards ecosystem-based management in the California Current

The Sustainable Fisheries Act clearly altered the nature of fisheries management in the United States,

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[4] Although the current National Standard guidelines recognize the significance of demographic and evolutionary impacts of fishing on both populations and ecosystems, this recognition does not require the gathering or analysis of new data to address life history uncertainties or the protection of marine ecosystems [120].

and in the California Current such changes came in the midst of an extended period of poor environmental conditions that contributed substantially to fisheries crises. These crises, in association with growing recognition of the low productivity of many stocks, brought about wave after wave of reductions in total allowable catches and trip limits. Consequently, much of the PFMC's current activities are focused on ongoing crises, resulting in substantial limitations on the ability to develop and implement new initiatives. Thus, regardless of whether the process is mandated or voluntary, there should be an emphasis on an evolutionary, rather than revolutionary, move towards an ecosystem approach [103]. As discussed earlier, there have been major improvements in the monitoring and management of California Current fisheries, including efforts to evaluate and protect essential fish habitat [104], new bycatch evaluation and reduction measures [105,106], the use of environmental indicators in setting harvest rates, capacity reduction programs [107–109], and the recently initiated consideration of rights-based fishing regimes [110]. Obviously, all of these developments have occurred in the context of the current management regime, which in turn suggests that movement towards an ecosystem-based approach is consistent with the current fisheries management institutions. While an appropriately funded mandate to develop FEPs would be desirable from the perspective of truly developing an ecosystem perspective, this should not preclude the development of a road map towards adopting an ecosystem-based approach to management, or otherwise integrating ecosystem considerations into the current management regime to the greatest extent possible.

As an active adaptive approach, McEvoy [22] suggested that the best managers might be able to do "is to monitor and adjust the interaction between a volatile ecology, a creative economy, and society's understanding and control as they go along." Similarly, Gunderson et al. [111] and Holling and Meffe [21] argue that the key to maintaining resilience in ecosystems is to facilitate existing processes and variability, rather than to try to control them. In other words, the key objective of an ecosystem approach is to facilitate healthy interactions between ecological, socio-economic and governance elements of the fisheries system. Clearly the need to recognize and assess the roles of climate and ecological complexity must be balanced with the need for understanding the socio-ecological interactions between fishermen and fishery resources and the sustainability of the fisheries system as a whole. Such recognition is increasingly widespread in the resource management community, which has led to the growth of a new discipline, dubbed the socio-ecological approach by Berkes et al. [23] and "sustainability science" by Kates et al. [112]. Although the ability to model the key interactions between humans and the ecosystem are critical to this emerging discipline, advances in modeling human processes have lagged far behind the modeling of biophysical processes [113]. The consequences of salmon and rockfish crises now resonate widely across fisheries sectors, where modeling the projected impacts of regulatory changes has required making increasingly tenuous assumptions regarding the behavior of both fishermen and the resources themselves, as managers struggle to balance the need to minimize mortality of overfished species against the need to maintain fishing opportunities on healthier stocks.

A useful framework for formally phasing in ecosystem considerations from a management perspective was presented by Goodman et al. [114], and here that framework is used to consider how the PFMC might phase from implicit to explicit consideration of ecosystem processes. In the conventional assessment worldview (Fig. 6), the ecosystem is considered principally in the context of target populations. There is both direct feedback between these populations and the fishing fleets (industry) and indirect feedback through the governance sector. This indirect feedback occurs through the evaluation of survey, effort and catch data, which is used to develop stock assessments and other evaluations of the status of resources. Where direct feedback between the resource and the fishery is strong (such as seems to be the case with pandalid shrimp and Dungeness crab in the California Current), the role of governance can be limited without substantial risk to the resource. However, where the direct feedback between resources and fisheries is weak, as it is with many of the long-lived and slow growing groundfish, sustainability is almost fully dependent on the indirect feedback of governance. If that feedback is too slow, or management actions are ineffective, the resource is far more likely to be overexploited, leading to negative impacts on both the ecosystem and the economy.

In the first stage of moving towards an ecosystem approach, described as the explicit ecosystem effects worldview, the status of target stocks, their prey, and their predators are formally considered by the governance sector in the context of environmental conditions and trophic interactions (Fig. 7). Fishing activities would continue to be largely governed by estimates of target stock status and yield as in the conventional worldview, and the governance sector would remain heavily dependent upon the indirect feedback of stock and target species status from catches, surveys and effort data. For the PFMC, an initial mechanism to implement this approach would be to establish an ecosystem considerations technical team, which would be tasked primarily with the responsibility for advising the Council on the state of the environment and providing ecosystem guidance on management decisions, just as management teams and advisory panels do for current FMPs. This team or panel could also potentially act as

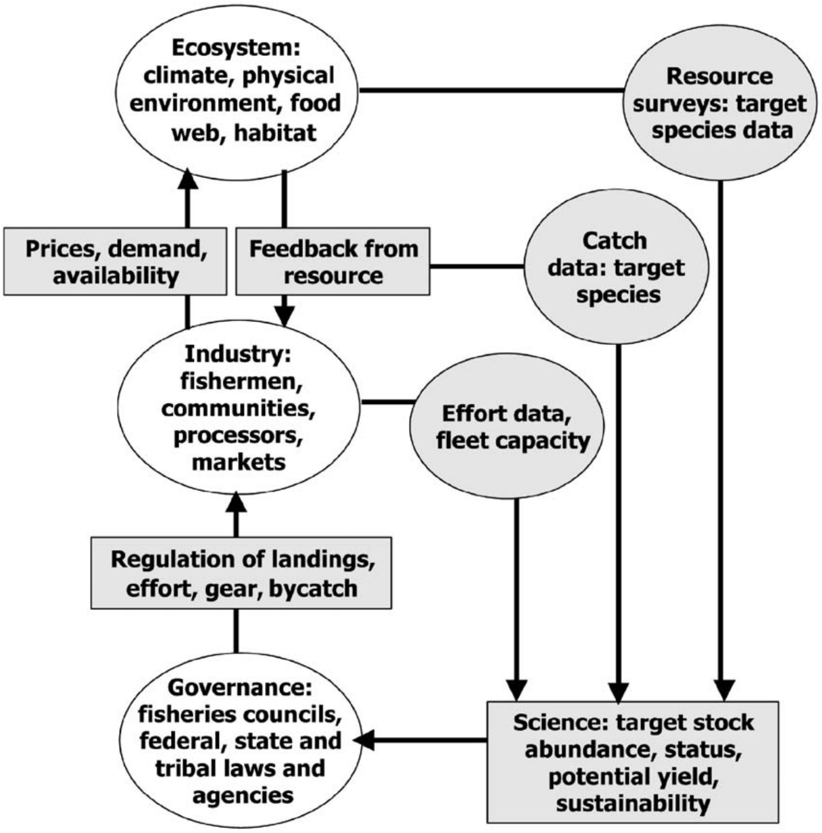

Fig. 6. The conventional fisheries management worldview, in which there is both direct feedback between these populations (the ecosystem) and the fishing fleets (economy) and indirect feedback through management (governance). This indirect feedback occurs through the evaluation of survey, effort and catch data, which is used to develop stock assessments and other evaluations of the status of exploited resources. Adapted from Goodman et al. [114].

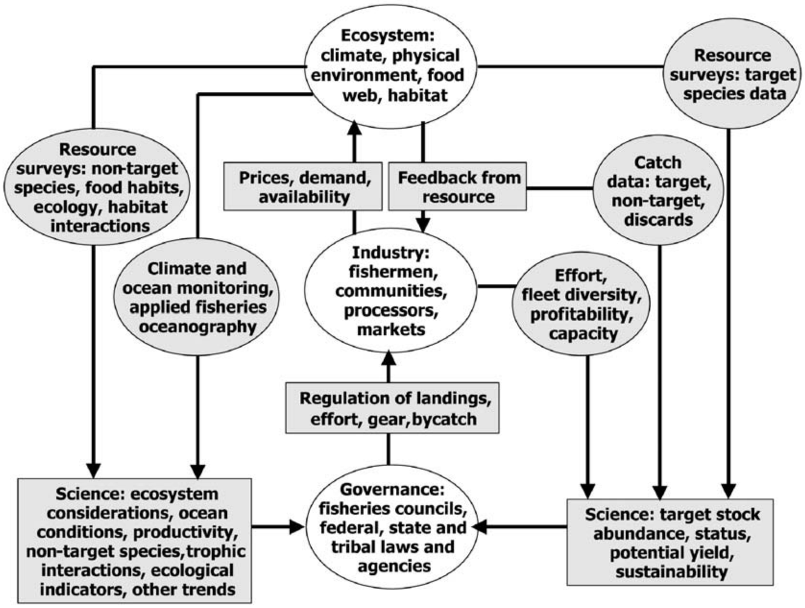

Fig. 7. A transitory stage between the conventional fisheries management view and a wholly ecosystem-based management perspective. Tractable problems are addressed by the governance sector to the extent practicable, while climate, productivity, habitat, and the needs of predators are implicitly considered in the context of making decisions. Adapted from Goodman et al. [114].

the primary source of skill and effort for crafting a FEP, revising a programmatic EIS, or otherwise coordinating management efforts across management plans or for species not currently managed by the Council (e.g., krill). The principal obligation of this team would be to provide ecosystem guidance, as related to climate, trophic, life history or other considerations, to the consideration of harvest guidelines and other decisions in the management cycle (advise relevant to habitat considerations, clearly critical to any ecosystem perspective, is currently provided by an existing habitat committee). By explicitly evaluating linkages between climate and productivity, or the role of the stocks in question as key predators or forage item for other species in the ecosystem, this body would also be capable of providing an ecosystem context for single-species assessments, and would serve as a conduit and intermediary for contemporary ecosystem information and research that might be directly relevant to Council activities or decisions.

This is essentially the current approach of the NPFMC, where a formalized system of assessing status and trends in the environment, and providing managers and decision makers with indicators of environmental and human impacts on the ecosystem, has been evolving over the last decade [28,51,115]. The key ecosystem objectives for the NPFMC have also been identified, and include maintaining predator/prey relationships, energy flows and balance, and diversity. Yet, despite the NPFMC's track record of largely maintaining harvest rates at or below MSY (or proxies thereof) levels, and with the majority of stocks managed by the Council at or above the target biomass levels, conservation concerns have dominated the North Pacific Council's management agenda. These concerns have been related to ecosystem changes that include altered productivity and distribution of many finfish populations, tremendous changes in the physical environment, and ongoing declines in marine mammals. To address these concerns, the NPFMC and the NMFS have had to integrate and apply scientific information across disciplines (marine mammals, finfish stock assessments, climate research) to the ecosystem level. The NPFMC experience demonstrates both the ability to achieve success in formally bringing ecosystem considerations to the table, and the challenges of actually using ecosystem models, data, or guidance within the contemporary fisheries management framework.

Clearly, there is a middle ground to be found in transitioning from a single species to a truly holistic ecosystem perspective, and this middle ground likely represents what may be feasible in any implementation of an ecosystem-based approach to fisheries management in the near future. In the idealized ecosystem management view, governance is provided with nearly complete knowledge regarding ocean conditions, productivity and the status of both target and non-target biota, as well as indicators of diversity and other measures of ecological health and integrity. In theory, this integrated ecosystem approach would make management decisions based on fully integrated estimates of ecosystem productivity and ecological interactions (such as the needs of other predators), and explicitly minimize the consequences of fishing on habitat, ecological structure, and life history traits. In practice, however, models may be able to offer some prediction of possible future trends under various climate scenarios and management strategies, but these models will in the near term unavoidably be constrained by a high degree of uncertainty. While the application of a range of models would increase the confidence in model scenarios, there are still far too many unanswered basic ecological questions to expect that such intimate knowledge of ecological processes, mechanisms or dynamics will soon be forthcoming [116]. The future of fisheries management may be one of increasing uncertainty, particularly as the cumulative impacts of localized and global change interact in patterns that vary from those in the historical past.

5. Conclusions

Management bodies and decision makers are making ecosystem management decisions every day, and there is increasingly relevant ecosystem information available that may help inform such decisions. Although management decisions will continue to be made with incomplete information, they can be improved upon with greater appreciation and knowledge of the state of the ecosystem, with respect to the role of climate, the complexity of trophic interactions, the importance of life history considerations, and the recognition of socio-economic interactions with these factors. In the short term, the Pacific Council could establish an ecosystem committee charged with developing and integrating existing ecosystem considerations as briefing materials, to inform and acclimate the Council community to existing data, knowledge, and potential directions for monitoring, modeling or research efforts. In the longer term, both the Council and the NMFS should develop a road map for phasing in ecosystem considerations within the current management context, and in the absence of a legal mandate for the development of FEPs, use the existing NEPA framework to assemble those elements proposed by the Ecosystem Principles Panel that have not already been initiated.

Despite the problems and challenges associated with today's fisheries crises, recognition of the important conservation role that MSY, reference points, and stock rebuilding requirements have made is key [117]. As Larkin [118] said in his premature eulogy to the theory of MSY, to appreciate what that single-species models and management based on MSY has done, we should consider what the state of the world's fisheries might be today if the concept had not been developed and widely implemented: "The fish, I'm sure, would shudder to think of it." Yet, the growing recognition for the role of the short- and long-term environmental variability, of habitat, trophic interactions and life history considerations leads one to the conclusion that there is much room for improvement. To paraphrase Gunderson and Holling [119], the single-species approach is not wrong, it is just incomplete. So too are the compositionalist, functionalist, and socio-economic approaches to ecosystem management described earlier: none are necessarily wrong, but all are based on worldviews that are to some extent incomplete. Consequently, each view may resonate with a different group of stakeholders. The real near-term contribution of any of these worldviews is that all would provide a greater ecosystem context for the existing set of single-species-based models and management strategies. In demonstrating the breadth of our uncertainty, ecosystem assessments, models, and management approaches should help to implement management strategies that are more robust to environmental and ecological variability and change.

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