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From krill to convenience stores: Forecasting the economic and ecological effects of fisheries management on the US West Coast

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ABSTRACT

There is a need to better understand the linkages between marine ecosystems and the human communities and economies that depend on these systems. Here those linkages are drawn for the California Current on the US West Coast, by combining a fishery ecosystem model (Atlantis) with an economic model (IO-PAC) that traces how changes in seafood landings impact the broader economy. The potential effects of broad fisheries management options are explored, including status quo management, switching effort from trawl to other gears, and spatial management scenarios. Relative to Status Quo, the other scenarios here involved short-term ex-vessel revenue losses, primarily to the bottom trawl fleet. Other fleets, particularly the fixed gear fleet that uses pots and demersal longlines, gained revenue in some scenarios, though spatial closures of Rockfish Conservation Areas reduced revenue to fixed gear fleets. Processor and wholesaler revenue tracked trends in the bottom trawl fleet, which accounted for 58% of total landings by value. Income impacts (employee compensation and earnings of business owners) on the broader economy mirrored the revenue trends. The long-term forecast (15 years) from the Atlantis ecosystem model predicted substantial stock rebuilding and increases in fleet catch. The 15 year projection of Status Quo suggested an additional ∼\$27 million in revenue for the fisheries sectors, and an additional \$23 million in income and 385 jobs in the broader economy, roughly a 25% increase. Linking the ecological and economic models here has allowed evaluation of fishery management policies using multiple criteria, and comparison of potential economic and conservation trade-offs that stem from management actions.

1. Introduction

End-to-end models of marine ecosystems simulate the physics, chemistry, ecology, and socio-economics of coastal and pelagic regions. Such models typically include processes at multiple spatial and temporal scales, and interactions in two directions – such as bottom-up influences of climate and top-down influences of fishing. End-to-end models offer substantial potential to inform ecosystem-based management and to understand the multiple processes controlling species of fishery and conservation importance [1,2]. One end-to-end modeling framework, Atlantis, has recently been applied to 13 marine regions throughout North America and Australia, primarily to understand drivers of ecosystem dynamics and to test management strategies [3]. Other examples of end-to-end models include OSMOSE [4], Ecosim/Ecospace [5], and NEMURO.Fish [6], among others. Developing these models involves notable challenges, such as improving algorithms for key processes such as animal movement; representing global change and biodiversity; modeling human behavior and economic responses; model skill assessment and handling of uncertainty; and facilitating interdisciplinary collaboration [1,2]. Nonetheless, the models are improving rapidly and are now capable of providing strategic advice to policy makers (e.g., [7]). The challenge now is to translate such advice into currencies that are meaningful in the policy context – for instance not just abundance and catch of fish, but metrics related to species of conservation concern as well as economic indicators such as jobs, wages, and earnings of business owners.

As part of an Integrated Ecosystem Assessment (IEA; Levin et al., [8]) for the California Current on the US West Coast, Kaplan et al. [9,10] explored the potential influence of broad fisheries management options. These fishery management options included status quo management, switching effort from bottom trawl to other gears, and spatial management scenarios. These explorations involved the application of the Atlantis modeling framework to represent the spatially explicit food web, oceanography, and fisheries of the California Current [11]. Kaplan et al. [9,10] scored these scenarios in

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terms of metrics related to ecosystem health and abundance and condition of groundfish (bottom fish), foci of that ecosystem assessment. Economic impacts were reported only in terms of changes in ex-vessel (dockside) landed values per fleet and summed over all fleets.

The present study expands beyond prior analyses by coupling outputs from the aforementioned Atlantis fisheries management scenarios to an Input–Output model for Pacific Coast Fisheries (IO-PAC [12]) that traces the indirect effects that changes in seafood landings have on the economy. For instance, reductions in catch and revenue in a trawl fishery may lead fishermen to need less diesel fuel for their vessels. In the terminology of input–output models, less output (fish catch) requires less input (diesel), and this will lead to reductions in income for workers and owners of diesel fuel delivery businesses. Decreases in income to workers also translate into lost jobs. Thus the input–output model translates from seafood sector revenue to supporting industries' revenue, income, and employment.

Input–output models such as IO-PAC can also be used to calculate how changes in income, for instance at the level of a fishing fleet or diesel suppliers, lead to changes in overall household spending. This subsequently alters revenue and income to a variety of businesses, such as grocery stores, convenience stores, medical providers, and state and local government. The intent is to expand beyond the typical focus of end-to-end models – the biology and ecology – and trace the economic impacts beyond the dock, to the level of the economy of US West Coast states.

2. Materials and methods

2.1. System description

The oceanography of the US West Coast is dominated by the southward-flowing California Current, which along with wind-driven upwelling delivers nutrients to the surface waters and determines overall system productivity. El Niño-Southern Oscillation and the Pacific Decadal Oscillation also heavily influence productivity of fish stocks and other marine organisms, often in ways that vary regionally along the US West Coast [13]. Groundfish resources such as flatfish and rockfish (*Sebastes* spp.) that are the focus of this study historically yielded very high harvests, peaking in the 1970s and 1980s [14]. However, overfishing, particularly of long-lived and slow growing rockfish species [15], led to depletion of many stocks, and in 2000 the region was declared a federal fishery disaster. Concerns about overfishing led to further reductions in landings limits and a series of spatial fishery closures (Rockfish Conservation Areas and Essential Fish Habitat [16]). Most recently, in January of 2011, a catch share system was implemented for the groundfish trawl fishery, in part as an attempt to reduce bycatch and fishery overcapacity [17]. The catch share system also allows switching from trawl to alternate gears that may have lower bycatch. Currently, major commercial groundfish harvesting sectors include bottom trawl, fixed gear (pot and demersal longline), and a midwater trawl fleet that targets Pacific hake (*Merluccius productus*).

In addition to the harvesting sectors mentioned above, in 2008 there were 317 seafood processors and wholesalers that received roughly 100,000 mt of groundfish [18]. The majority of landings are handled by a relatively small number of processors; for instance, in 1997 65% of landings and 46% of landed value were handled by 15 large processors [19]. The shoreside hake fleet landed catch at 16 processors in 2008, with five of these accounting for the majority of volume [18]. Direct suppliers to the fishery sector, such as fuel suppliers, welders, boat and net manufacturers, and marine hardware suppliers included at least 86 businesses in Oregon and 472 in Washington (though some of these supply vessels involved in the Alaska fisheries as well) [18]. The analysis below focuses on groundfish, but for an overall perspective, US West Coast seafood processors (including some only involved in processing fish from Alaska) had approximately 22,500 employees and $668 million in payroll in 2007. Wholesalers had 4400 employees and payroll of $175 million [20].

2.2. History of the modeling approach: Atlantis

The Atlantis modeling framework and the specific application discussed here for the California Current are detailed in Kaplan et al. [9,10]. Briefly, Atlantis simulates ocean physics, nutrient cycling, ecology, and fishery dynamics in a three-dimensional, spatially explicit domain [21,22]. The Atlantis code base is described in Fulton [21,22], and Fulton et al. [23,24] detail several implementations for systems in Australia. Fulton et al. [3] summarize global examples of Atlantis models, research questions to which these models have been applied, and lessons learned regarding scientific hypotheses and best practices for ecosystem modeling.

The California Current Atlantis Model (CCAM) is detailed in Horne et al. [11]. The biological component of CCAM contains 62 functional groups, ranging from primary producers to marine mammals. Several harvested groundfish of high commercial importance, such as Pacific hake and sablefish (*Anoplopoma fimbria*), are represented at the species level, but most fish are aggregated into functional groups (e.g., small planktivorous fish). The model extends along the U.S. West Coast, from Point Conception to the Canadian border, and west to the 2400-m isobath. This region is divided into 82 boxes or polygons, each with up to seven depth layers. CCAM is driven by chemical, physical, and biological processes in each spatial box and depth layer. Physical forcing is governed by a regional ocean modeling system that dictates water fluxes, salinity, and temperature in each model box and depth layer [25]. Water flux drives the advection of plankton and nutrients. Spatial abundance of biological groups is controlled by processes such as growth, reproduction, predation, movements and migrations, and habitat suitability. Fisheries are represented by 20 fleets that represent distinct gear types, each with a set of target and bycatch groups.

2.3. Atlantis fishery management scenarios

All scenarios developed in Kaplan et al. [9,10] and presented here begin with the same base parameterization of the ecology and oceanography; the only variation is in the dynamics of fishing. Fishing is simulated on a per fleet basis, where a fleet is generally a gear (e.g., groundfish trawl, shoreside hake trawl). For each fleet (gear), the proportion of each model spatial cell that is open or closed to that fleet is specified, as is the fishing mortality (percent/year) applied to each spatial cell that is open to fishing. The scenarios start in 2010 and project forward for 20 years. The fishery management scenarios tested here are simple caricatures and are not vetted by stakeholders; future public scoping may overcome this.

Kaplan et al. [9,10] tested 18 scenarios, which ranged in the degree to which they deviated from Status Quo in terms of the intensity and spatial scale of new management actions. Most of the scenarios that involved minor management changes yielded results similar to Status Quo, and those are not reported here. Instead, this complete economic analysis focuses on Status Quo plus four major scenarios that involved coast wide changes in management, as detailed below. As with the original analysis, the intention here is not to evaluate specific policy options, but rather to illustrate how coupling two modeling tools allows simultaneous consideration of

Table 1
Fleets (gears), in the Atlantis model (Horne et al., 2010) and the IO-PAC model (Leonard and Watson, 2011).

Atlantis fleet	IO-PAC Fleet or Sector	Multiplier for Income Impact on Broader Economy
Limited entry bottom trawl	Large groundfish trawler	0.97
California halibut (trawl)	-	-
Pink shrimp (trawl)	-	-
Non-nearshore fixed gear (pot and demersal longline)	Sablefish fixed gear	1.25
Non-nearshore fixed gear (pot and demersal longline)	Other groundfish fixed gear	1.03
Nearshore fixed gear (hook and line, jigging)	–	–
At sea hake midwater trawl	–	–
Shoreside hake midwater trawl	Shoreside hake midwater trawl	0.96
Purse seine (coastal pelagics)	–	–
Crab pot	–	–
Highly migratory species (tuna, shark, swordfish; longline, gillnet, troll)	–	–
Lobster pot	–	–
Mollusks (diving)	–	–
Urchin (diving)	–	–
Pacific halibut (longline)	–	–
Sea cucumber (diving)	–	–
Hagfish (pot)	–	–
Salmon	–	–
Shellfish	–	–
Spot prawn trap	–	–
Recreational hook and line		–
–	Processor	0.66
–	Wholesaler	1.14

multiple management alternatives, both from ecological and economic perspectives.

Scenarios discussed here are detailed in Kaplan et al. [9,10], and include:

- **Scenario 1, Status Quo:** This scenario aims to evaluate the predicted performance of existing levels of harvest, state MPAs, rockfish conservation areas (RCAs), and essential fish habitat (EFH) closures. The scenario projects the Atlantis ecosystem model for 20 years, imposing fishing mortality from all existing fleets onto all relevant species or functional groups. Fishing mortality was apportioned between each of 20 gears (Table 1). A single fishing mortality rate per fleet and species was calculated, and applied equally to each cell that was open to fishing. Fishing mortality (% mortality per year) remained constant over the course of the simulation. Cells partly closed to fishing had proportional decreases in fishing mortality. The combination of these exploitation rates and spatial closures was set such that model predictions of 2007 total catch per fleet and functional group matched 2007 catch estimates, as described in Kaplan et al. [9,10].
- **Scenario 2, Gear Switch:** This scenario switches fishing effort from ¼ of bottom trawl gear to fixed gear (pot or longline), for the purpose of reducing bycatch. Per vessel, fixed gear had 80% lower catch and bycatch rates of all functional groups except sablefish and small demersal sharks. This scenario imposed a 25% coast-wide decrease in limited entry trawl fishing mortality rates, and a 25% increase in fixed gear fishing mortality.
- **Scenario 3, Rockfish Conservation Area Closure to bottom-contact gear:** Status Quo spatial management involves an offshore RCA that prohibits bottom trawl gear and a separate inshore RCA that prohibits nontrawl commercial gear. The offshore trawl RCA allows other bottom-contact gears (longline and pot) that may harm biogenic habitat. Scenario 3 converts all RCAs to prohibit all bottom-contact gears (trawl, longline, and pot). Fishing effort from the RCA is completely removed from the model, rather than being displaced to other areas.
- **Scenario 4, Consolidating Spatial Management:** The Status Quo EFH closures ban bottom trawling across large areas [16], but allow other bottom-contact gears (longline and pot) that may cause moderate amounts of damage to coral, sponges, and other bottom habitat. Therefore the Status Quo regulations may result in moderate habitat impacts over a large geographic area. Scenario 4 provides an alternative to this by concentrating the spatial extent of fishing. Scenario 4 bans all bottom-contact gear in 50% of the EFH, but opens the other 50% of EFH to trawling. In these scenarios, EFH areas deeper than 550 m are open to fishing with bottom trawl and fixed gear (longline and pot); inshore areas are closed.

2.4. Input–Output models, IMPLAN, and IO-PAC

In general, input–output analyses are used to track the changes in the broader economy that are caused by changes in output from a particular sector. The present case uses the Atlantis model to determine the fishery sectors' output, measured as ex-vessel revenue of landed fish or sales revenue from processors and wholesalers. The input–output model is then used to calculate how the rest of the US West Coast economy responds to these changes in fishery sector output. For example, businesses such as diesel fuel suppliers provide inputs to the fishery sectors, and will increase their sales of diesel if fishery sectors require more fuel to land more fish. Readers new to input–output models may find it useful to think about inputs to a specific business, and outputs from that business, not inputs and outputs to the model.

Input–output models track three types of effects. *Direct* effects refer to direct changes in the fishery sectors, in this case driven by changes in landings as predicted by the Atlantis model. These direct effects on fishery sectors lead to *indirect* effects at the level of industries that supply inputs to the fishery sectors. Examples include shipyards and diesel fuel suppliers. Direct and indirect effects lead to changes in household spending, and the subsequent effects – say at the level of convenience stores – are *induced* effects. The analysis below focuses mostly on the combined direct, indirect and induced effects related to *income*, for example wages to workers or earnings of business owners. The analysis does not focus on *revenue*, i.e., total sales ($) before costs, except specifically for the seafood sectors.

Briefly, the mathematics of IO models are as follows [26, 27]

$$\text{Output} = \text{Final demand by consumers} + \text{Intermediate demand by businesses or sectors} \quad (1)$$

$$\boldsymbol{x} = \boldsymbol{y} + A\boldsymbol{x} \quad (2)$$

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} + \begin{bmatrix} a_{1,1} & \cdots & a_{1,n} \\ a_{2,1} & \ldots & a_{2,n} \\ \vdots & \ddots & \vdots \\ a_{n,1} & \cdots & a_{n,n} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \quad (3)$$

where $\boldsymbol{x}$ is a column vector of outputs from each of n economic sectors, $\boldsymbol{y}$ is a column vector of final demand, and A is a matrix of coefficients dictating how many units of output from each sector are required as input to produce a unit of output in other sectors; its dimensionality is therefore number of sectors x number of sectors, $n \times n$. For instance, the element in row 2, column 1 of A ($a_{2,1}$) represents the number of units from sector 2 required to produce a unit of output by sector 1. In this analysis the units of output and demand are dollars.

Solving for $\boldsymbol{x}$, the output from each sector, as a function of final demand and the coefficient matrix,

$$\boldsymbol{x} = (I - A)^{-1}\boldsymbol{y} \quad (4)$$

IO-PAC [12] is a detailed extension of the basic input–output framework described above, applied to the continental US West Coast. IO-PAC was designed to estimate the gross changes in economic contributions and economic impacts resulting from policy, environmental, or other changes that affect fishery harvest. IO-PAC was built by customizing the IMPLAN regional input–output software in a manner similar to that developed by Steinback and Thunberg [28]. IMPLAN (Impact Analysis for PLANning, http://implan.com) is a commercially available data collection and regional modeling system developed by the USDA Forest Service with cooperation of the Federal Emergency Management Agency and the USDI Bureau of Land Management for use in land and resource management planning. It has been in use since 1979. Development of IO-PAC included customizing IMPLAN with an addition of 19 commercial fishing vessel categories. The present application uses a version of IO-PAC that was developed to cover the entire US West Coast. Economic impact estimates in IO-PAC include the effects of changes in fish harvest to harvesting vessels, seafood wholesalers, and processors, and they can be exhibited as a change in total economic output, income, or employment.

Major assumptions of IO-PAC as well as most IO models include: (1) Supply of outputs is not constraining. An increase in demand, for instance demand by the fishing sectors for diesel fuel, is always met by an increase in supply. (2) Prices of commodities, such as processed fish, and factors of production, such as diesel fuel, are fixed, and here are denominated in 2010 dollars. (3) There is no substitution in production and consumption. This means that a fishery sector will always require the same set of inputs (diesel, ice, etc.) to land a dollar's worth of fish. Similarly, households always purchase the same set of commodities in the same proportions. Households, as well as state and local governments, are explicitly included in the present application of IO-PAC using social account matrix multipliers [12].

Linking Atlantis scenario outputs to IO-PAC

For each of the four scenarios above, landings per fleet are converted into ex-vessel (dockside) revenue, using price data for 2006 from PacFIN (http://pacfin.psmfc.org/pacfin_pub/data.php). Where Atlantis predicted landings of an aggregated functional group, rather than species, prices are averaged over the price of the individual species that comprised that functional group [11], weighted by the relative catch per species from PacFIN. IO-PAC is able to calculate the economic impacts that result from revenue changes from three of the fleets in the Atlantis model: the limited entry bottom trawl, shoreside hake midwater trawl, and non-nearshore fixed gear (Table 1). Also, in contrast to Atlantis, IO-PAC divides the fixed gear fleet into two categories – sablefish fixed gear and other groundfish fixed gear – on the basis of the vessel classification scheme by Radtke and Davis [19]. Here the catch of all sablefish from the Atlantis fixed gear category is assigned to the IO-PAC sablefish fixed gear, and the catch of all other species from the Atlantis fixed gear category is assigned to the IO-PAC other groundfish fixed gear fleet.

In addition to tracking broad economic effects resulting from changes in fleet revenues, IO-PAC can also calculate the effects resulting from changes in processors and wholesaler revenue. As described in Leonard and Watson [12], in IO-PAC processor revenue is based on the assumption that processors handle 32% (by value) of the landings of these four fleets, with processor revenue then equal to 3.33x this amount. Again following Leonard and Watson [12], wholesaler revenue assumes that wholesalers handle 30% (by value) of the landings of these four fleets, with wholesaler revenue then equal to 19% of this amount.

The impacts on income in the economy associated with a $1 change in revenue for each fishing fleet or sector are listed in Table 1. These income impacts include both labor income (wages and other compensation) and proprietary income (earnings of business owners). Income impacts resulting from a change in revenue include direct, indirect, and induced effects. Note that in most cases the income impact is near 1.0, meaning that a $1 increase in revenue for a fishing fleet or sector leads to $1 in additional labor income or proprietary income in the economy, at the level of those involved in the fishing sector, support industries, and suppliers of goods to households.

Based on the assumptions listed above, IO models such as IO-PAC are best for forecasting short term economic impacts that do not involve extreme changes likely to result in commodity scarcity, price elasticity, substitution effects, or technological change. For this reason, analyses here focus on short term (1–5 year) forecasts, offering a 15-year forecast only for comparison and to illustrate the ecological projections stemming from the ecosystem modeling approach. The approach here also focuses on scenarios from Kaplan et al. [9, 10] that do not involve very large manipulations to the fisheries (e.g., avoiding those that double or halve effort).

3. Results

3.1. Coast-wide biomass and catch

Under the Status Quo scenario, 17 of the 21 stocks of fish, squid, and crab that are targets or bycatch were predicted to increase over the course of the 20-year simulation [9, 10]. Similar rebuilding trends were evident in all scenarios, as a result of low overall fishing mortality rates relative to productivity of these stocks. Marine mammals and birds, as well as fish, showed strong recoveries. By year 15, several rockfish stocks had begun to approach quasi-equilibrium. Major fleets' catches were stable or increasing (up to ~20%) through time.

In the other three scenarios, deviations from Status Quo trajectories were primarily driven by direct changes in fishing mortality rates. For instance, the coast-wide 25% Gear Switch from bottom trawl to pot/longline gears reduced fishing mortality rates and led to higher biomasses of Dover sole (*Microstomus pacificus*), lingcod (*Ophiodon elongatus*), large piscivorous flatfish

Table 2
Values for performance metrics for each scenario. Biological performance metrics are scaled relative to the best performing scenario (which therefore has a value of 1.0). Note that a 15-year projection of "impact on the economy" should be considered uncertain due to the assumptions of input–output models.

Metric	Status Quo	Gear Switch	RCA Closure to all Bottom Contact	Consolidating Spatial Management
Habitat index	0.56	0.60	1.00	0.54
Rockfish biomass by year 15	0.93	1.00	0.92	0.92
Prop rockfish mature by year 15	0.89	0.85	1.00	0.90
Mammal+bird biomass by year 15	1.00	1.00	1.00	1.00
Avoid rockfish bycatch, in year 1	0.60	0.78	1.00	0.60
Year 1 Economic effects: (jobs or million $)				
Income impact on economy	97.6	89.6	76.6	100.2
Fishery sectors' revenue	115.8	105.1	90.5	119.1
Employment Effects, whole economy	1608	1521	1277	1645
Large groundfish trawler revenue	31.8	23.8	21.2	33.6
Sablefish fixed gear revenue	10.0	12.6	8.9	9.9
Other groundfish fixed gear revenue	1.5	1.8	1.2	1.3
Shoreside hake midwater trawl revenue	11.4	11.4	11.4	11.4
Processor revenue	58.0	52.7	45.4	59.7
Wholesaler revenue	3.1	2.8	2.4	3.2
Year 15 Economic effects: (jobs or million $)				
Income impact on economy	120.8	113.4	98.4	122.9
Fishery sectors' revenue	143.3	133.1	116.3	145.9
Employment effects, whole economy	1993	1922	1648	2020
Large groundfish trawler revenue	41.9	33.3	29.6	43.5
Sablefish fixed gear revenue	12.3	15.5	11.6	12.0
Other groundfish fixed gear revenue	1.8	2.3	1.7	1.7
Shoreside hake midwater trawl revenue	11.7	11.7	12.0	11.7
Processor revenue	71.8	66.7	58.3	73.1
Wholesaler revenue	3.9	3.6	3.1	3.9

(e.g., arrowtooth flounder *Atheresthes stomias*), and yelloweye rockfish and cowcod (*Sebastes ruberrimus* and *S. levis*). The full RCA Closure to bottom contact gear led to reduced fishing mortality rates and increased abundance of large piscivorous flatfish, lingcod and cabezon (*Scorpaenichthys marmoratus*), small demersal sharks, and yelloweye and cowcod. Consolidating Spatial Impacts caused only slight changes in total fished area per gear type (<7% change) and fishing mortality rates (<11% change). No vertebrate group's biomass response was >3% in this scenario.

3.2. Biological metrics

Scenarios were scored based on the quantitative metrics (Table 2) that capture the ecosystem attributes of interest to the fishery managers involved in the IEA [10]. These include metrics of habitat integrity, bycatch of rockfish (in year 1), abundances of protected species, rockfish biomass, and rockfish spawning stock. Details of these calculations are as discussed in Kaplan et al. [9,10], with the exception that year 15 values were substituted for year 20 values considered in the earlier work.

As discussed in Kaplan et al. [9,10], the response of biological metrics was primarily a function of the manipulations included in these management scenarios (Table 2, Fig. 1). Mammals and birds were not directly affected by the management actions, while in contrast the changes in performance metrics reflect direct management actions involving habitat and rockfish. Habitat conservation was highest with the RCA Closure to bottom contact gears. Similarly, that scenario performed best in terms of avoiding rockfish bycatch. The Gear Switch led to the highest rockfish biomass; on the other hand, spatial RCA Closures allowed concentrations of old rockfish individuals and the largest improvements in the proportion of rockfish mature. In short, the biological response to these coast wide management actions primarily stemmed from alterations to fishing mortality, with the RCA Closure and the Gear Switch exhibiting positive effects on most biological metrics, but neither scenario performed best in terms of all metrics.

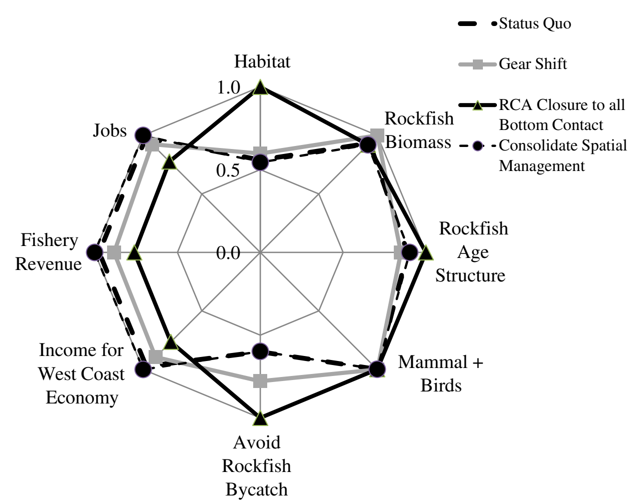

Fig. 1. Relative performance of Status Quo versus three alternate scenarios for fishery management. Each of the eight axes represents one performance metric; values along each axis represent the performance of that scenario relative to the best performance. Metrics are as reported in Table 2. Note that the Consolidate Spatial Management scenario differs little from Status Quo, and these two scenarios overlap on the plot.

3.3. Economic metrics

Based on the landings projected by the Atlantis model and 2006 prices, the simulated Gear Switch was equivalent to an immediate (year 1) 25% revenue decrease for the large groundfish trawl fleet, from $31.8 million to $23.8 million in dockside value of the landings (Table 2). The RCA Closure to bottom contact gear resulted in an immediate 33% decline in large groundfish trawl revenue. For large groundfish trawl and all other sectors, Consolidating Spatial Management led to year 1 revenue that was within 6% of Status Quo.

Each of the three fleets other than bottom trawl had year 1 revenue that was between 87% and 125% of Status Quo, regardless of

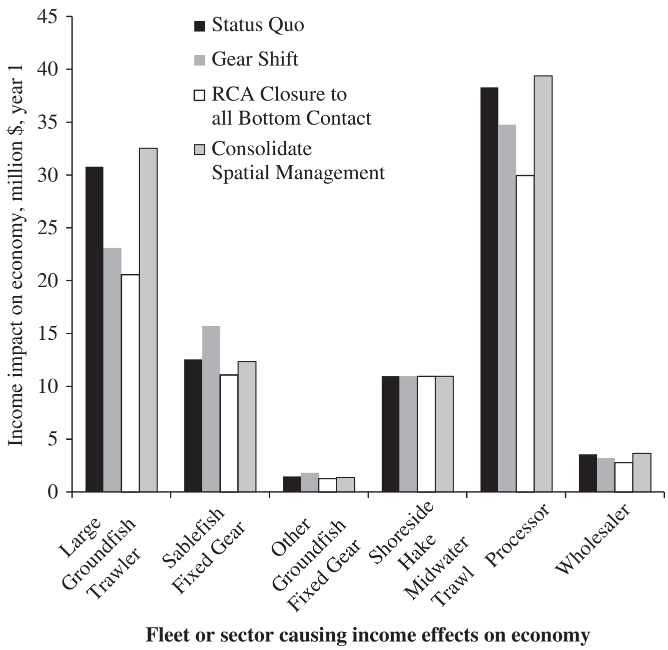

Fig. 2. Economic impact per fishery sector per scenario. Economic impact is the sum of labor income and other income (e.g., rents, royalties, dividends) in the US West Coast economy.

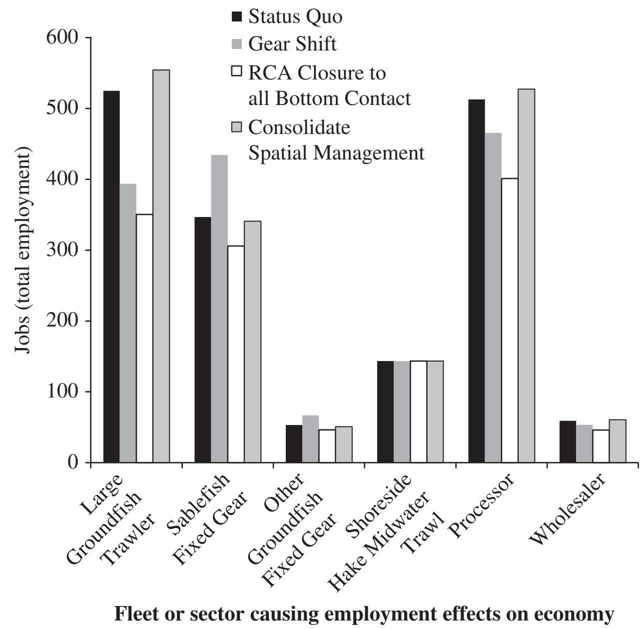

Fig. 3. Each fishery sector's employment impact on the broader economy of the US West Coast. Year 1 values. Employment effect includes fishery and non-fishery sectors.

scenario (Table 2). Sablefish fixed gear, other groundfish fixed gear, and shoreside hake trawl had year 1 revenues equal to $10 million, $1.5 million, and $11.4 million, respectively, in the Status Quo scenario. The largest revenue increases (25%) occurred when the Gear Switch scenario pushed effort to the two fixed gear fleets; the decrease of 13% occurred when the fixed gear fleets were fully removed from all RCAs in the RCA Closure scenario. Processor and wholesaler revenues generally tracked the pattern of revenue for the large groundfish trawl fleet, since that fleet accounted for 58% of gross revenue under Status Quo. Processors and wholesalers handled a similar amount of landed value, but wholesalers had a lower markup, and therefore had substantially less revenue ($58 million vs. $3.1 million).

As would be expected based on the linear multipliers (Table 1) used in IO-PAC, impact from each sector on the US West Coast economy was proportional to revenue (price x landings) for that sector. Since the impact multipliers per sector were typically near 1 (range 0.66–1.25), one dollar of fisheries revenue generally translated into approximately one dollar of income (e.g., wages or earnings of business owners) for the US West Coast economy. Employment effects mirrored the trends in economic impact. Impacts from the large groundfish trawl ranged from highs of $31 to 33 million and 525 to 554 jobs (respectively for Status Quo and Consolidating Spatial Management) down to $21 million and 350 jobs in the RCA Closure scenario (Figs. 2 and 3). Impacts from sablefish fixed gear ranged from $16 million and 434 jobs (when it was increased in the Gear Switch) down to $11 million and 306 jobs (with the RCA Closure). Processor impacts followed the trends in large groundfish trawl revenue and impacts, ranging from $30 million to $39 million and 401–527 jobs.

The strongest income effects of the scenarios involved direct changes to the seafood sector. However, many other businesses and institutions also were affected (Fig. 4). These include institutions and employment related to general wholesale trade, home ownership, insurance, medical providers, state and local government, and food and beverage stores (including convenience stores). Fig. 4 shows the non-seafood institutions with the largest responses in the first year, which range from −$1.7 million to

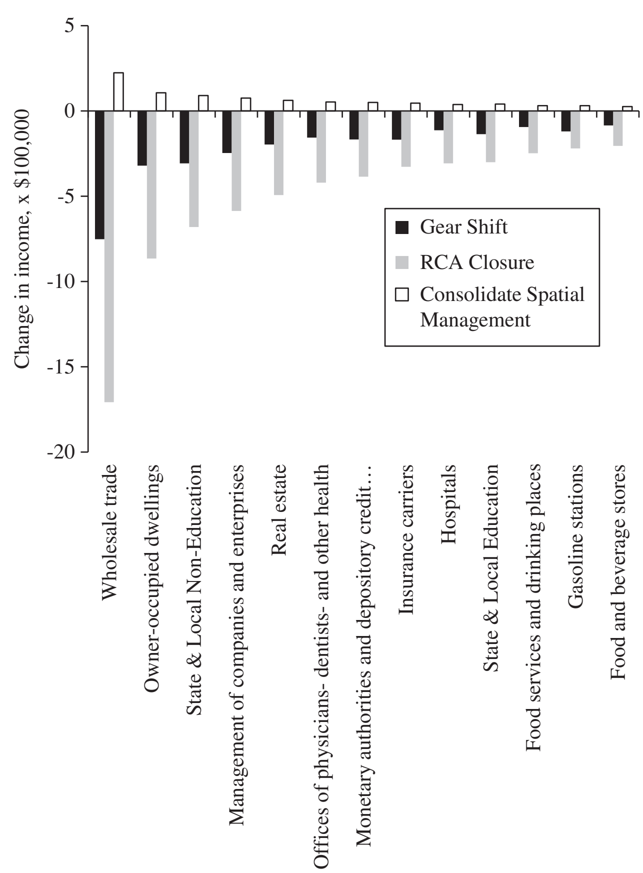

Fig. 4. Change in income for thirteen US West Coast institutions (business types), in response to three fishery management scenarios. Values are plotted as the difference between the first year's income under Status Quo and the first year's income under the three alternate management scenarios. Institutions with the largest absolute change in income, excluding the fishery sectors, are shown here. In total, 559 non-fishery institution types were included in IO-PAC; those not shown here have absolute changes in income less than $200,000.

+$220,000, relative to Status Quo. Generally these sectors with large responses (in terms of absolute dollar amount) are major components of household expenditures in the broader US West Coast economy and also produce commodities with high regional purchase coefficients [12], meaning that they are supplied by providers located on the West Coast. Examples include Food and Beverage Stores, which in the RCA Closure lost $200,000, and State and Local Government, which in the RCA closure lost $680,000 of income. Consolidating Spatial Management led to a $26,000 gain in income by Food and Beverage Stores and a $90,000 gain by State and Local Government.

The Atlantis model allows spatial, multispecies projections of stock trends through time, which translate here into 15-year forecasts of fleet revenues, economic impact, and jobs (Table 2). For all fleets, revenues and economic impacts were fairly constant between year 1 and 5, but increased beyond that to year 15 as target stocks rebuilt due to management actions that pre-date year 1 and thus affected all scenarios. The rebuilding effect is apparent in the Status Quo scenario, in which total fishery sector revenue increased $27 million, income in the whole economy increased $23 million, and employment in the whole economy increased by 385 jobs. Relative to year 1, the combined revenues of all sectors increased 23–28% over the course of 15 years, with the greatest percentage increase under the RCA Closure. Economic impacts are linear multipliers of sector revenue, and therefore followed the same percentage increases.

Similar to the biological results, the economic performance metrics indicate clear trade-offs between scenarios. In year 1, Consolidating Spatial Management had the highest summed revenue over all fishery sectors, followed closely by Status Quo (Table 2). This was also true for three sectors – large groundfish trawlers, processors, and wholesalers – but fixed gear fleets had highest year 1 revenue when the Gear Switch increased their effort. Overall, the Status Quo scenario and Consolidating Spatial Management had high performance in terms of economic metrics, but low performance in terms of two conservation metrics – protecting habitat and avoiding bycatch (Fig. 1). The Gear Switch scenario was a compromise between economic and conservation metrics, and also outperformed other scenarios in terms of total rockfish biomass at the end of 15 years. The RCA Closure scenario performed strongly for most of the conservation metrics, but relatively poorly on the economic metrics.

4. Discussion and conclusions

There is a growing consensus that ecosystem-based management is necessary to move marine management into an arena where multiple stressors can be considered, and multiple objectives can be evaluated. Leslie and McLeod [29] identified four principles of marine ecosystem-based management: (1) addressing multiple spatial and temporal scales, (2) recognizing the linkages among marine ecosystems and the human communities that depend on these systems, (3) acknowledging land-sea linkages such as nutrient loading, and (4) engagement with stakeholders. Three distinct fields have developed that address the second point: prediction of fishery revenue as predicted by fleet behavior in response to changes in ecology and management [30,31]; predictions of fishery sector and non-fishery sector responses to different harvest levels, via input/output models and general equilibrium models [32–34]; and ecosystem service valuation, which places quantitative or qualitative values on services provided by the ecosystem to human communities [35,36]. These services include not only extractive services (e.g., fish), but also non-consumptive services such as recreation, esthetic, cultural, and existence value, and stabilizing services such as erosion control.

The analysis here took a tack different from the three above, developing a full multi-species and multi-fleet end-to-end ecosystem model, and coupling it to a relatively simple input/output model. Linking the ecological and economic models here has allowed evaluation of fishery management policies using multiple criteria. In terms of economics, fishermen may be most interested in fishery sector revenue, politicians may be interested in jobs or total economic impact, and convenience store owners may be interested in household spending. In terms of conservation issues, the full ecosystem model allows summaries focused on of target stocks, species of conservation concern, forage groups, and habitat. This multiple criteria approach identifies and compares potential economic and conservation trade-offs that stem from management actions, and that trade-off analysis is a central part of ecosystem-based management through the IEA (Levin et al., 2009). Fleet dynamics are not modeled in detail, but the framework could be extended to include such dynamics and investment/disinvestment, as has been done with other applications of the Atlantis model [24]. Given adequate cost and earnings data, the models can incorporate a range of marine industries, extractive and non-extractive, and their subsequent effect on the broader economy. In the future, the work here can include non-consumptive ecosystem services, and also recreational fishing, both of which may align more closely with biological performance measures than with the commercial fishery sector economic measures presented here.

Leslie and McLeod's [29] first principle – addressing multiple spatial and temporal scales – is critical in interpreting the results presented here. The results are relevant to the Atlantis model domain, with economic calculations at the scale of the US West Coast. The IO-PAC model alternatively can calculate economic impacts at the state and port level, and future work with the Atlantis model should allow simulation of regional fleet behaviors and landings. As with ecological processes, spatial scale is important for the economics. For instance, the income multipliers (Table 1) are calculated at the scale of the US West Coast, and per dollar of revenue, certain industries such as processors have lower multipliers because of larger expenditures that flow outside the US West Coast (e.g., purchase of machinery). Additionally, the institutions (businesses) with the largest changes in income tend to be those with local labor pools or local owners, since that income tends to remain on the US West Coast. As the spatial scale of the economic analysis constricts, the expectation may be for more revenue to ''leak'' out of the region, and for local impacts to decline.

Temporal scales are clearly important for both ecological dynamics and economics. The long-term forecast (15 years) from the Atlantis ecosystem model predicted substantial stock rebuilding and increases in fleet catch. Though IO-PAC and all IO models are most appropriate for shorter term forecasts, the 15-year projection suggested a ~$23 million increase in income (for fishery and non-fishery sectors), roughly a 25% increase, based on $27 million in additional fishery sector revenue. This potentially large impact illustrates the importance of linking multi-species or ecosystem models to dynamic models of fishery or market behavior [31, 37–39], which may perform better in terms of mid-term forecasting than the simpler linear forecasts used here. To date, however, such models typically focus on the fishery sector only. The emphasis here was also not on long-term equilibrium solutions nor optimization; transient behavior and short-term economic performance are important in policy contexts [40].

The primary impacts of the simulated fishery management actions were on the fishery sectors, and in particular the groundfish trawl and fixed gear fleets. On the scale of the US West Coast economy, the immediate (year 1) effects of fishery management actions on non-fishery sectors were small, less than $1.7 million in income loss for any single institution category (business type). However, these links between the fishery sector and the rest of the economy are supported by a well-documented, reviewed, and replicable input–output model (IO-PAC) that is informed by extensive cost-earnings data. The approach here is novel in that it couples a full ecosystem model, with species ranging from krill to sharks, to such an input–output model. The ecosystem model includes key features of the California Current ecology, such as upwelling of nutrients, seasonal migrations by species such as Pacific hake, flexible predator-prey functional responses, growth as a function of consumption, and low productivity of the rockfish stocks to which many conservation goals and targets are tied [15]. The approach can be used to strategically evaluate a range of management actions and stressors that can be captured with the Atlantis model and evaluated using IO-PAC. Such management actions and stressors include individual quotas [24], such as those recently adopted for the US West Coast trawl fleet; changes in nutrient loading [23]; and ocean acidification [41].

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