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Screening California Current fishery management scenarios using the Atlantis end-to-end ecosystem model

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ABSTRACT

End-to-end marine ecosystem models link climate and oceanography to the food web and human activities. These models can be used as forecasting tools, to strategically evaluate management options and to support ecosystem-based management. Here we report the results of such forecasts in the California Current, using an Atlantis end-to-end model. We worked collaboratively with fishery managers at NOAA's regional offices and staff at the National Marine Sanctuaries (NMS) to explore the impact of fishery policies on management objectives at different spatial scales, from single Marine Sanctuaries to the entire Northern California Current. In addition to examining Status Quo management, we explored the consequences of several gear switching and spatial management scenarios. Of the scenarios that involved large scale management changes, no single scenario maximized all performance metrics. Any policy choice would involve trade-offs between stakeholder groups and policy goals. For example, a coast-wide 25% gear shift from trawl to pot or longline appeared to be one possible compromise between an increase in spatial management (which sacrificed revenue) and scenarios such as the one consolidating bottom impacts to deeper areas (which did not perform substantially differently from Status Quo). Judged on a coast-wide scale, most of the scenarios that involved minor or local management changes (e.g. within Monterey Bay NMS only) yielded results similar to Status Quo. When impacts did occur in these cases, they often involved local interactions that were difficult to predict *a priori* based solely on fishing patterns. However, judged on the local scale, deviation from Status Quo did emerge, particularly for metrics related to stationary species or variables (i.e. habitat and local metrics of landed value or bycatch). We also found that isolated management actions within Monterey Bay NMS would cause local fishers to pay a cost for conservation, in terms of reductions in landed value. However, this cost was minimal when local conservation actions were part of a concerted coast-wide plan. The simulations demonstrate the utility of using the Atlantis end-to-end ecosystem model within NOAA's Integrated Ecosystem Assessment, by illustrating an end-to-end modeling tool that allows consideration of multiple management alternatives that are relevant to numerous state, federal and private interests.

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1. Introduction

1.1. Context

Marine ecosystems provide a wealth of goods and services, but are also directly and indirectly affected by a litany of human activities. Sustaining productive, resilient ecosystems or rehabilitating degraded systems ultimately relies on our understanding and ability to forecast the impacts of natural and human perturbations on those systems.

Increasingly, policy makers and resource managers are calling on scientists to predict changes to ecosystems caused by anthropogenic or natural pressures. Indeed, such ecological forecasting is becoming central to ecosystem-based approaches in marine natural resource management. Forecasting allows managers to ask 'what–if' questions about diverse policy options, and thus provides a conduit between science and policy.

NOAA and other agencies responsible for managing marine resources have incorporated ecosystem forecasting as part of Integrated Ecosystem Assessments (IEAs). IEAs are a synthesis and quantitative analysis that organizes science to inform ecosystem based management (Levin et al., 2009). IEAs explicitly evaluate ecosystem status in light of a variety of drivers and pressures that may influence system structure and function. Importantly, IEAs also evaluate possible future ecosystem states under different management scenarios. There are a number of approaches to forecasting future ecosystem states, including qualitative narratives arising from conceptual models, statistical extrapolation of trends, Delphi techniques, and analytical or simulation models (Levin et al., 2010). While these methods can be complementary and all have been used in a variety of settings (e.g. Tallis et al., 2010), simulation models

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have recently received a great deal of attention as forecasting tools. In this paper, we report the results of ecological forecasts in the California Current conducted using Atlantis, a forward-projecting simulation model (Fulton, 2004; Fulton et al., 2005).

Atlantis is a so-called "end-to-end" model because it simulates the entire ecosystem from climate and oceanography through the food web to human activities. Here we apply an Atlantis ecosystem model of the California Current (Horne et al., 2010) to predict the impacts and performance of a suite of management scenarios proposed by managers from the NOAA National Marine Sanctuary Program (NMSP) and the NOAA National Marine Fisheries Service (NMFS). The objective of our forecasts focused on the strategic (rather than tactical) evaluation of management actions; our intention was to rank and compare fisheries policies, rather than to predict fishery yields or biomass responses with extreme precision. Thus, our aim was to broadly explore the impact of fisheries management actions on policy objectives at different spatial scales, from single Marine Sanctuaries to the entire Northern California Current. Importantly, we do not focus on a single management objective; rather, we forecast how different management actions influence trade-offs between several ecosystem objectives.

1.2. History of the modeling approach

The Atlantis code base has been developed by scientists at CSIRO in Australia, and includes submodels that simulate oceanography (flux of water, heat, and salt), biogeochemistry (primarily nitrogen cycling), food web interactions, and fisheries in a three dimensional domain (Fulton, 2001, 2004; Fulton et al., 2005, 2007). The C code base simulates ecosystem dynamics, solving a set of differential equations on a 12 h time step. The model includes several key features, such as two way coupling (meaning that predators influence prey abundance and vice versa), dynamic weights-at-age, multiple options for predator–prey relationships such as Holling types I–III, density dependence arising from both stock recruit relationships and explicitly modeled resource limitation, and seasonal migration and foraging movement. To date, most Atlantis implementations represent target species at the level of detail necessary to evaluate direct effects of fishing, but aggregate other species into functional groups sufficient to capture anthropogenic, trophic, and climate impacts on the ecosystem. A precedent for the use of Atlantis to screen fishery management policies was Fulton et al.'s (2007) work in Australia that informed the restructuring of the Southern and Eastern Scalefish and Shark fishery. Fulton et al. (2011) summarize the technical details of Atlantis, the applications to date, and lessons learned regarding these models as tools for ecosystem based management.

We constructed the Central California Atlantis Model (CCAM) specifically to address scientific and management needs related to fisheries and conservation expressed by both federal (NMFS, NMSP) and state entities (California Ocean Science Trust, California Department of Fish and Game). The central California model is largely based on a California Current Atlantis ecosystem model (Brand et al., 2007) that covered the same geographic extent, but with a coarser spatial resolution. The California Current Atlantis model has been used to identify ecosystem indicators (Kaplan and Levin, 2009), to evaluate harvest strategies under catch shares, and to consider the impacts of ocean acidification on the food web (Kaplan et al., 2010). The key model features described above allow representation of patterns driven by the California Current's oceanography and historical fishing patterns, including truncation in age structure of long-lived taxa such as rockfish, changes in weight-at-age, migration and movement of key species such as hake (*Merluccius productus*), annual variability in diet compositions, and productivity driven by upwelling-driven nutrient inputs.

2. Materials and methods

2.1. California Current Atlantis

The California Current Atlantis Model (CCAM) is detailed in Horne et al. (2010). The model extends from the US–Canada border to Point Conception, and from the shoreline to the 2400 isobath (Fig. 1). The model area is divided into 12 regions from north to south based on biogeography and management boundaries, and between three and seven depth zones (dividing the model boxes in the east–west direction). Each model box or polygon (Fig. 1) includes water-column depth layers, ranging from one layer for near-shore boxes to seven for offshore boxes. Each box also contains one sediment layer. CCAM is driven by chemical, physical, and biological processes in each spatial box and depth layer. The flux of water, salt and heat across each model box and depth layer is governed by a Regional Oceanographic Model System (ROMS) (Hermann et al., 2009). Water flux drives the advection of plankton and nutrients. Though the CCAM scenarios described below project into the future, the available ROMS time series that we have included represents 1958–2004. Thus we have assumed that past climate may be representative of future conditions; more accurate future projections of ROMS will require careful coupling to global atmospheric models, including CO_2 emissions.

The biological component of CCAM contains 62 functional groups, including 26 fish groups, three seabird groups, six mammal groups, eight plankton/algae, 14 invertebrate, and five bacteria/detritus (Horne et al., 2010). All vertebrate groups have 10 age classes, but primary producers and invertebrates are modeled as simple biomass pools with no explicit age structure. Initial abundances for each biomass pool and vertebrate age class are defined for each spatial box and depth layer based on estimates from stock assessments and other literature sources (Horne et al., 2010). Biological processes are governed by formulations that describe ingestion, growth, reproduction, local foraging movement, and migration (Fulton, 2001, 2004; Horne et al., 2010; Kaplan et al., 2010). As described in Horne et al. (2010), the model has been calibrated to fit historical abundance time series data, when driven with time series of catch per biological functional group.

2.2. Incorporating scenarios into CCAM

Through a scoping process within the Integrated Ecosystem Assessment (Levin and Schwing, 2011), we worked with managers and scientists to develop a set of alternative scenarios for fisheries management. Overall, the scenarios capture a range of viable options for spatial management and shifts in prevalence of particular fishing gears. Using the Atlantis ecosystem model, we simulated the impact of each of these scenarios for 20 years. All scenarios 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 generally corresponds to a single gear type (e.g. groundfish trawl, recreational hook and line).

For each fleet (gear), we specify:

(1) The proportion of each model spatial polygon that is open or closed to that fleet.
(2) The fishing mortality (%/year) applied to each spatial polygon that is open to fishing.

The scenarios begin in 2010 and apply a particular combination of spatial management and fleet-specific fishing mortalities for 20 years.

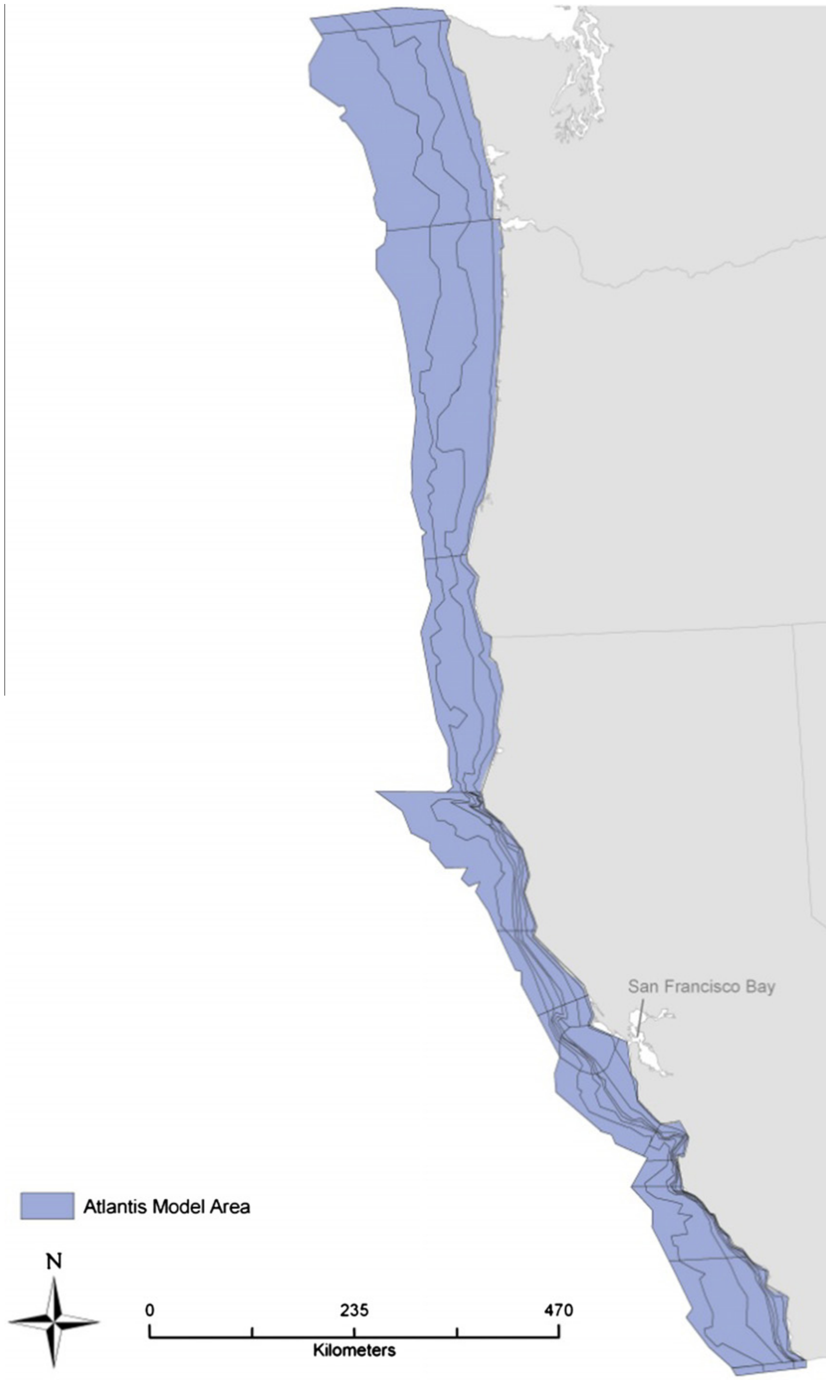

Fig. 1. Atlantis model domain for US West Coast.

2.2.1. Status Quo scenario

This scenario evaluates the predicted performance of existing management, including levels of harvest and a simplified representation of spatial management (Fig. 2 and Appendix A). The actual recent history of spatial management in the region is moderately complex. In 2002, Rockfish Conservation Areas (RCAs) were established by NMFS. The RCAs extend the length of the US West Coast. Boundaries are set in order to minimize bycatch of overfished rockfish, by eliminating fishing in areas where and times when those overfished species are likely to co-occur with healthy stocks. Consequently, RCA boundaries vary for particular gear types, change at different times of the year, and have changed over time. In 2006, NMFS also designated 209, 215 km^2 as Essential Fish Habitat (EFH). This resulted in gear restrictions to protect bottom habitat in some of this area, and included designation of various habitats such as kelp, sea grass and estuaries as "habitat areas of particular concern." Additionally, current spatial management consists of Marine Protected Areas (MPAs) in California state waters. This series of MPAs was established beginning in 2007 and offers varying levels of protection, ranging from no-take reserves to areas that allow recreational and some commercial harvest (California Dept. of Fish and Game, 2004, 2010).

The Status Quo scenario projected CCAM for 20 years, imposing fishing mortality from all existing fleets onto all relevant species or

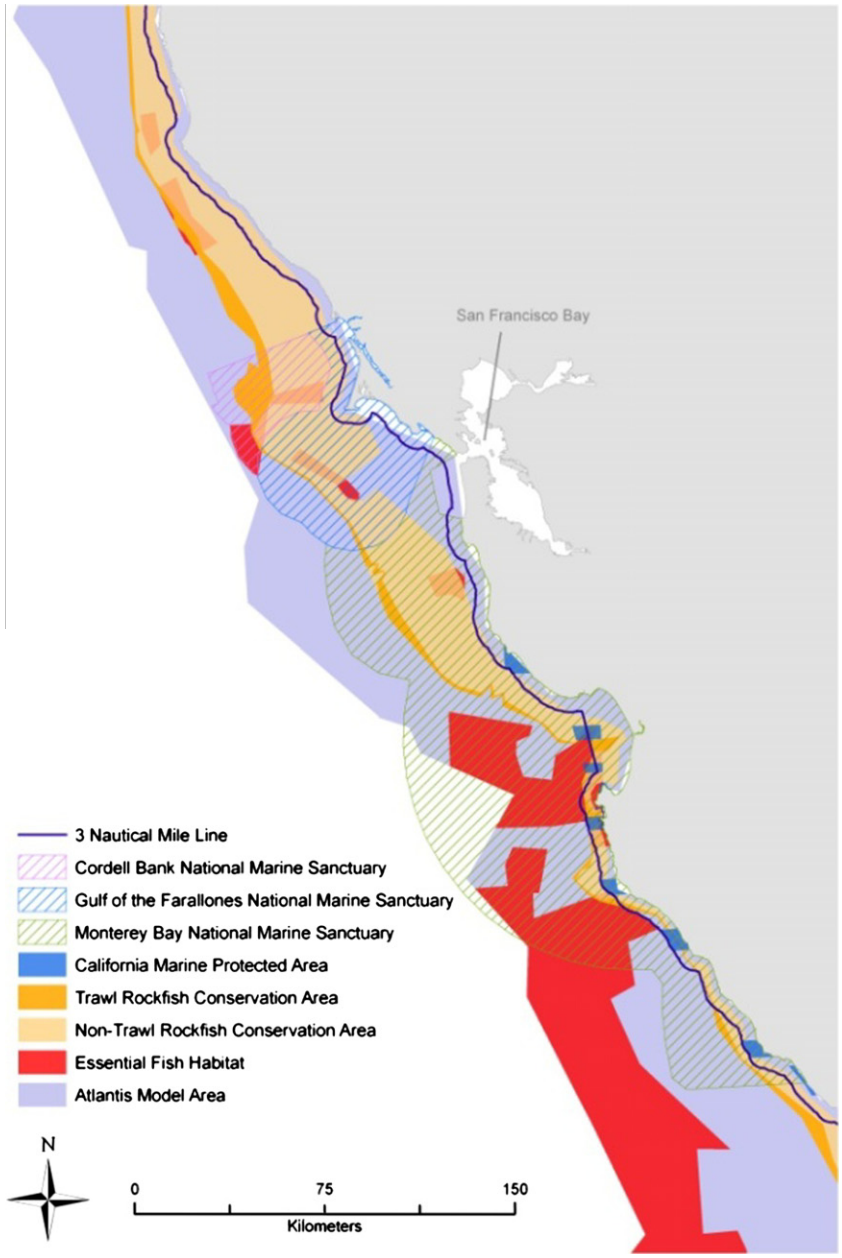

Fig. 2. Status Quo spatial management for Central California. A map of coast-wide Status Quo spatial management is provided in Appendix A.

functional groups. Spatial fishing closures in the model were based on EFH, RCAs, and central California state MPAs in place in 2007 (Fig. 2 and Appendix A). EFH, RCA, and Central California state MPA closures were assumed to persist to the end of the simulation. We included only these three types of spatial management, detailed in Appendix A. Smaller areas such as the Yelloweye Rockfish Conservation Area, Recreational Rockfish Conservation Area, marine gardens, research reserves, and the like were generally not included (see Pacific Fishery Management Council (2008) for a full list of spatial management units).

Fishing mortality was apportioned between each of 20 gears (Table 1). For the groundfish gears (#1–7), fishing mortality was derived from estimates of total mortality, including discards, from Bellman et al. (2008). For the non-groundfish gears (#8–20), fishing mortality was based on landings reported in the PacFIN database (2009). For these simple simulations, we assumed that fishing mortality (% mortality per year) remained constant over the course of the simulation. We did not vary fishing mortality or attempt to model time-varying quotas, nor did we include bycatch or entanglement of marine mammals or birds. Catch and bycatch were imposed on the model, and values of catch and bycatch for each fleet and functional group in the initial year of the simulation are listed in Appendix B.

In the Status Quo simulation, a single fishing mortality rate per fleet and species was calculated, and applied equally to each polygon that was open to fishing. For instance, the limited entry bottom trawl fleet's exploitation rate of $4.6\%\cdot yr^{-1}$ was applied to the large flatfish group in all polygons that were fully open to fishing by this gear. Polygons partly closed to fishing had proportional decreases in fishing mortality. The combination of these exploitation rates and spatial closures was set such that total catch per fleet and functional group matched the 2007 catch estimates from Bellman et al. (2008) and PacFIN (2009). In simple terms, one can think of our approach as applying a uniform exploitation rate ($\%\ yr^{-1}$) across the entire model domain, but then using a ''cookie cutter'' to remove fishing by certain fleets from certain polygons. Despite

Table 1
Fleets (gears), spatial management closures, and gear description (whether bottom contact, and impact factor on hard, soft, and biogenic habitat, taken from National Marine Fisheries Service (2005)). Gear impact factors of 1.0 indicate the most damage, and 0 the least.

	Fleet	Bottom Contact?	Gear impact factor			Status Quo spatial management (X = closed)				
			Hard	Soft	Bio genic	State MPA	EFH	EFH Cordell Bank	Trawl RCA	Non-Trawl RCA
1	Limited entry bottom trawl	Yes	0.81	0.31	0.74	X	X	X	X	
2	California halibut (trawl)	Yes	0.81	0.31	0.74	X	X	X	X	
3	Pink shrimp (trawl)	Yes	0.81	0.31	0.74	X	X	X	X	
4	Non-nearshore fixed gear (pot and demersal longline)	Yes	0.18	0.12	0.23	X		X		X
5	Nearshore fixed gear (hook and line, jigging)		0.18	0.06	0.22	X				X
6	At sea hake midwater trawl					X			X	
7	Shoreside hake midwater trawl					X			X	
8	Purse seine (coastal pelagics)					X				X
9	Crab Pot	Yes	0.18	0.12	0.23	X		X		X
10	Highly migratory spp. (tuna, shark, swordfish, longline, gillnet, troll)					X				X
11	Lobster pot	Yes	0.18	0.12	0.23	X		X		X
12	Mollusks (diving)					X				X
13	Urchin diving					X				X
14	Pacific halibut (longline)	Yes	0.18	0.06	0.22	X		X		X
15	Sea cucumber (diving)					X				X
16	Hagfish (pot)	Yes	0.18	0.12	0.23	X		X		X
17	Salmon					X				X
18	Shellfish					X				X
19	Spot prawn trap	Yes	0.18	0.12	0.23	X		X		X
20	Recreational hook and line					X	*	*	*	*

* – Rec Fishing open in coastal boxes (except for CA MPA), X in all other boxes.

this extremely simple approach to simulating fishing mortality per fleet, when combined with observed biomass distributions (e.g. from trawl surveys such as Keller et al., 2006) the method yielded a roughly realistic spatial distribution of catch.

2.2.2. Sensitivity analysis scenarios

In addition to the Status Quo, we explored a series of simple scenarios that were meant to provide context for the more nuanced scenarios that follow. In the first of these we simply altered fishing mortalities caused by all fleets for all species. Specifically, we multiplied Status Quo fishing mortality by 0%, 50%, 150%, 200%, and 500%.

We next implemented a scenario in which Status Quo fishing mortality rates were maintained, but we removed all existing spatial management. Consequently, Status Quo fishing mortality rates were applied to all polygons, including polygons that were previously closed as RCA or EFH. Thus total catch and total mortality increased coast-wide.

2.2.3. Management scenarios

2.2.3.1. Gear shift. These scenarios capture the desire to reduce bycatch by encouraging fishers to switch from trawl gear to pot or longline gear that has lower bycatch rates. New individual quota regulations recently enacted by the Pacific Fishery Management Council allow for such gear switching.[1] Bellman et al. (2008) estimated total mortality for limited entry bottom trawl and fixed gear (longline + pot), and this can be used to parameterize a switch between these two gears. All details of the scenarios will be the same as Status Quo, except for the following:

Within Monterey Bay National Marine Sanctuary (MBNMS, Fig. 2), we reduced limited entry trawl fishing mortality rates by 25%, 50%, and 100% from Status Quo, and to represent a transfer of vessels from the trawl to the longline and pot fleet, we increased longline and pot fishing mortality by 25%, 50%, or 100% from Status Quo. This resulted in a decrease in fishing mortality on most non-target species, due to the higher selectivity of longline or pot gear. By simply scaling the mortality caused by longline and pot, we were assuming that the ratio of pot vessels to longline vessels remained constant within the fixed gear (longline + pot) category. The MBNMS covers 12% of the model domain.

We repeated this scenario, but in this case, we applied a 25% coast-wide decrease in limited entry trawl fishing mortality rates, and a 25% increase in longline + pot fishing mortality. This corresponds to 40 permitted vessels switching gears (NOAA Northwest Regional Office, 2010).

2.2.3.2. Close Rockfish Conservation Area (RCA) to bottom contact gear. Status Quo spatial management involves an offshore RCA that prohibits trawl gear and a separate inshore RCA that prohibits non-trawl commercial gear. The offshore trawl RCA allows bottom contact gear (longline and pot) that may harm biogenic habitat. In these scenarios involving the RCA, we converted all RCAs to prohibit all bottom contact gear (trawl, longline, and pot).

As in other scenarios, RCAs were permanent and did not vary seasonally. In the real world, the RCA covers depths ranging from 0 to 200 fathoms (0–366 m), but varies by gear and latitude (Appendix A). To represent the RCAs in this scenario, the model depth zones that collectively span 0–200 m were completely closed to fishing by trawl and fixed gear (pots and demersal longline). In Northern California, Oregon, and Washington the model depth zone spanning 200–1200 m was also partially closed, and in Central California the model depth zone spanning 200–550 m was also partially closed; these differences are due to the higher spatial resolution (and more model zones) in Central California.

[1] http://www.pcouncil.org/groundfish/gffmp/gfa20/FinalAlternatives_080112.pdf.

In this scenario and others that involved spatial management, we assumed there was no effort displacement, i.e. there was no spatial redistribution of fishers due to the closure. Our approach here for CCAM assumed that the relatively small vessels involved in these fisheries cannot easily change to fishing grounds farther from shore or from port if additional spatial restrictions are imposed within the RCAs. The fishing mortality rate calculated in the Status Quo scenario was applied to all model polygons open to fishing; spatial management changed only the set of polygons that were open and closed. Though we did not simulate effort displacement, Fulton et al. (2007) have used Atlantis to do so in Australia.

We implemented this scenario at three scales. First, we prohibited all bottom-contact gear in the RCAs within the Monterey Bay National Marine Sanctuary. We next repeated this scenario, but expanded the prohibition on bottom-contact gear to all of Central California, including the Gulf of Farallones and Cordell Bank National Marine Sanctuaries. Lastly, we implemented the bottom-contact prohibition for RCAs along the entire coast.

2.2.3.3. Consolidate spatial management. The Status Quo EFH closures ban trawling across large areas (Fig. 2 and Appendix A). However, EFH closures allow other bottom contact gear (i.e., longline and pot) that may harm biogenic habitat. Thus, existing regulations may produce moderate habitat impacts over a large geographic area. In this scenario, we concentrated the spatial extent of fishing in some areas, while closing other areas to fishing. The goal in this scenario was to ban all bottom contact gear in 50% of the EFH, but open the other 50% of EFH to trawling. EFH areas deeper than 550 m were open to fishing with trawl and fixed gear (longline + pot); inshore EFH areas were closed. Thus, the key difference between this scenario and Status Quo was not the total amount bottom-contact, but rather how it was spatially distributed.

As with the RCA scenario, we implemented this scenario at two spatial scales: within Monterey Bay National Marine Sanctuary only, or coast-wide.

2.3. Evaluation of scenarios

We evaluated scenarios based on a number of metrics that are calculated by CCAM and that capture the ecosystem attributes of interest to the fishery managers involved in the IEA process (Table 2; see also Levin and Schwing, 2011). These metrics include habitat integrity, and projections of year 20 landed value and abundances of protected species, rockfish biomass, and rockfish age structure. We also calculated rockfish bycatch (i.e. tons/yr) in year 1 rather than year 20; reporting year 20 bycatch would confound population size with bycatch rate. We normalized these scores relative to the Status Quo scenario (i.e. the metrics are always equal to 1.0 for Status Quo). We calculated these performance metrics for all scenarios, first on a coast-wide basis (using data from our entire model domain), and then from the perspective of Monterey Bay National Marine Sanctuary (using data only from within MBNMS).

2.3.1. Habitat integrity metric

CCAM does simulate the dynamics of benthic invertebrates and biogenic habitat such as corals and sponges, and the Atlantis code could allow exploration of some impacts of scenarios on biogenic habitat. However, we lack quantitative data to adequately parameterize the dynamic impacts of particular gears on particular types of benthos and benthic habitat in the California Current. Thus, to explore the potential impact of different management strategies on habitat, we estimate an index of habitat integrity outside of CCAM. The habitat index was based on an Essential Fish Habitat Environmental Impact Statement that reports qualitative estimates of the relative impacts of particular gear types on substrate (NMFS, 2005). We used these impact estimates, combined with the maps of spatial management and scalars of effort that define our scenarios, to create a qualitative index of habitat integrity for each scenario. The result is a metric that is scaled relative to Status Quo habitat integrity, with 0 representing full exposure of all habitat to gear that can fully damage it (at least in the short term). The habitat integrity metric responds positively when areas are closed to spatial management or when fishing effort is switched toward gears that are less destructive to the benthos. The metric is static; we are calculating only exposure of habitat to fishing gears in the scenarios, rather than the biological response over time.

NMFS (2005) lists the relative impacts of gears on habitat type. For instance, bottom trawls may cause >4× more damage than pot gear, and they may cause >2.5× more damage to hard substrate than soft sand or mud. Scaling the relative impacts to a maximum of 1 (which would represent extreme impacts of dredge gear in estuaries with soft substrate) yields the values in Table 3. This scaling also converts the original qualitative estimates to quantitative values consistent with estimates from Collie et al. (2000), who reported mean initial declines in abundance of benthic invertebrates due to trawling of 51%. Collie et al. (2000) reported that trawling and dredging caused declines in benthic invertebrate abundance of 59% in biogenic habitat, 57% in mud, 58% in gravel, and 21% in sand.

The habitat integrity metric was calculated based on impact per gear and substrate, substrate per polygon, fishing effort per gear and polygon relative to Status Quo (2008), and the proportion of each polygon open to fishing. We assumed that each gear acted independently on a polygon; therefore the proportion of the habitat that remains intact, taking into account the effects of all gears, is the product of the proportion of habitat that remains intact from each gear:

$$P_p = \prod_{g=1}^{num\ gears} \left(1 - E_{g,p} * A_{g,p} * \sum_{s=1}^{num\ substrates} (I_{g,s} * H_{s,p})\right) \quad (1)$$

where P_p is the proportion of habitat in polygon p that remains intact; $A_{g,p}$ is the proportion of polygon p open to fishing by gear g, $E_{g,p}$ is the effort by that gear in that polygon, relative to initial levels; $I_{g,s}$ is the impact factor per gear and substrate from Table 1, and $H_{s,p}$ is the proportion of the habitat that is substrate s. The habitat integrity metric is then:

$$\text{Habitat integrity metric}_i = \frac{\sum_{p=1}^{num\ polygons} P_{p,i} * a_p}{\sum_{p=1}^{num\ polygons} P_{p,Status\ Quo} * a_p} \quad (2)$$

where the habitat integrity metric is the undisturbed habitat in scenario i relative to Status Quo, and a_p is area of the polygon (km^2).

3. Results

3.1. Status Quo coast-wide biomass and catch

Coast-wide abundance (biomass) and catch per fleet (total catch of all species) at year 20 of the Status Quo simulation are shown in Figs. 3 and 4, using the AMOEBA plot format of Collie et al. (2003) and Ten Brink et al. (1991). The AMOEBA plots represent the magnitude of biomass of each group (or catch per fleet) as a vector, normalized relative to a reference circle that represents Status Quo biomass (or catch). Principal component analysis is used simply to array the angles of these vectors, both for visual clarity and to roughly align fleets with the biomasses of their major target species. We focus on the fleets that account for 95% of landings in the California Current, and the species caught by these fleets. By year 20, abundance of 17 of the 21 species increased above initial levels, some by more than three fold. This is indicative of overall

Table 2
Performance metrics for scenarios. Metrics were normalized relative to Status Quo to generate the values presented in the text, figures, and Table 3.

Management goal	Performance metric	Formula for scenario *i*
Habitat integrity	Based on area closed to each gear, and impact factor of each gear on each habitat type	See Eqs. (1) and (2) in main text
Rockfish age structure	Ratio of mature rockfish to total population size, for all rockfish groups, year 20	$\sum_{group=1}^{8}(ProportionMature_{group,yr20,i}/ProportionMature_{group,yr20,SQ})$
Rockfish abundance	Biomass of all rockfish groups, year 20	$\sum_{group=1}^{8}(Biomass_{group,yr20,i}/Biomass_{group,yr20,SQ})$
Marine mammal and bird abundance	Biomass of marine mammals and birds, year 20	$\sum_{group=1}^{9}(Biomass_{group,yr20,i}/Biomass_{group,yr20,SQ})$
Avoid bycatch of non-target species	Catch of yelloweye and cowcod, canary, midwater, and deep large rockfish in year 1	$\sum_{group=1}^{4}(Catch_{group,yr1,i}/Catch_{group,yr1,SQ})$
Economic yield	Landed value, year 20	$\sum_{gear=1}^{20}\sum_{group=1}^{30}(Catch_{group,gear,yr20} * Price_{group,gear})$

Table 3
Values for performance metrics for each scenario. See Table 2 for definition of metrics. The metric "Avoid Rockfish Bycatch" in the No Fishing scenario is undefined because there is no catch or bycatch of any species in this scenario.

Scenario	Rockfish age structure (proportion mature)	Rockfish abundance (biomass)	Mammal and bird abundance (biomass)	Habitat integrity	Economic yield (landed Value)	Avoid Rockfish Bycatch
Performance metrics calculated on a coast-wide basis						
Status Quo	1.00	1.00	1.00	1.00	1.00	1.00
Gearshift, MBNMS, 25%	0.93	0.97	1.00	1.01	1.06	0.61
Gearshift, MBNMS, 50%	0.93	0.97	1.00	1.01	1.06	0.61
Gearshift, MBNMS, 100%	0.93	0.97	1.00	1.03	1.06	0.61
Gearshift, 25%	1.02	1.02	1.00	1.07	0.97	1.17
RCA no bottom contact, MBNMS	0.88	0.98	1.00	1.05	1.04	0.45
RCA no bottom contact	1.06	1.06	1.00	1.79	0.89	1.57
RCA no bottom contact, Central CA	0.90	1.00	1.00	1.10	0.99	0.50
Consolidate spatial man., MBNMS	1.00	1.00	1.00	0.99	1.00	0.99
Consolidate spatial management	1.00	1.00	1.00	0.97	1.00	0.97
No fishing	1.17	1.31	1.08	5.45	0.00	NA
Fishing, no spatial management	0.66	1.52	1.09	0.39	1.84	0.07
$F \times 0.5$	0.94	0.74	0.90	2.36	0.73	1.86
$F \times 1.5$	0.82	0.72	0.83	0.41	1.08	0.62
$F \times 2$	0.78	0.69	0.80	0.16	1.21	0.47
$F \times 5$	0.63	0.60	0.73	0.0	3.56	0.19
Performance metrics calculated from within MBNMS only						
Status Quo	1.00	1.00	1.00	1.00	1.00	1.00
Gearshift, MBNMS, 25%	0.93	0.97	1.00	1.07	0.85	1.90
Gearshift, MBNMS, 50%	0.93	0.97	1.00	1.14	0.83	2.09
Gearshift, MBNMS, 100%	0.93	0.97	1.00	1.26	0.78	2.53
Gearshift, 25%	1.02	1.02	1.00	1.07	0.98	1.17
RCA no bottom contact, MBNMS	0.88	0.98	1.00	1.57	0.81	1.30
RCA no bottom contact	1.06	1.06	1.00	1.57	1.00	1.28
RCA no bottom contact, Central CA	0.90	1.00	1.00	1.57	0.82	1.30
Consolidate spatial man., MBNMS	1.00	1.00	1.00	0.93	1.04	0.95
Consolidate spatial management	1.00	1.00	1.00	0.93	1.02	0.95
No fishing	1.17	1.31	1.05	6.41	0.00	NA
Fishing, no spatial management	0.66	1.52	1.09	0.47	1.67	0.06
$F \times 0.5$	8770.43	0.76	1.72	2.60	1.11	0.55
$F \times 1.5$	1.21	0.92	1.70	0.36	1.92	0.19
$F \times 2$	5859.88	0.91	1.69	0.12	2.19	0.14
$F \times 5$	0.77	0.67	1.50	0.00	4.45	0.06

low Status Quo fishing mortality rates, as mandated in fishery rebuilding plans; note also that some groups (e.g. canary rockfish and yelloweye and cowcod) were initially at low levels due to historical overfishing. By year 20 of the Status Quo simulation five of the rockfish groups had increased to quasi-equilibrium levels, and midwater rockfish were still increasing in abundance. Groups that declined included small demersal sharks, cephalopods, megazoobenthos (crabs), and small planktivores. Of the six major fleets in Fig. 4, all showed stable catches or increases of up to 10–20% due to long term rebuilding of the modeled stocks.

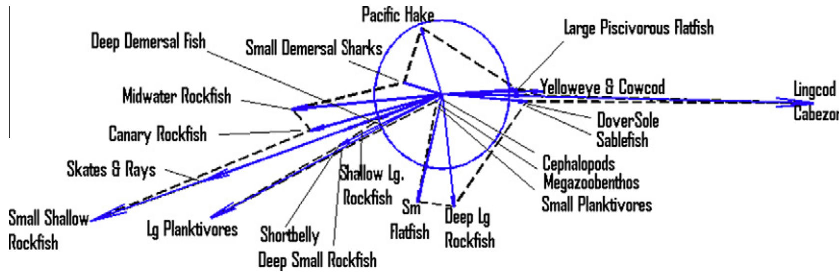

Fig. 3. Coast-wide abundance of each functional group at the end of the 20 year simulation, relative to initial abundance. The blue reference circle has a radius of 1.0, so for instance blue arrows that extend 50% beyond the circle represent a 50% increase in abundance over the course of the simulation. Black solid lines are for labeling the arrows only. The angles of the arrows are determined such that the fleets in Fig. 5 are aligned with their major target species. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

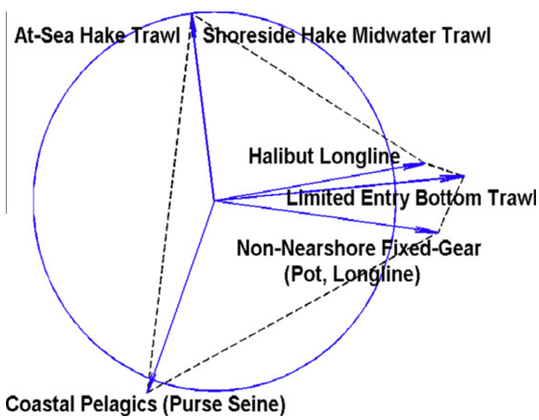

Fig. 4. Coast-wide catches of each fleet, summed over all functional groups, at the end of the 20 year simulation relative to initial catches. The six fleets that account for 95% of catches are shown here. The blue reference circle has a radius of 1.0, so for instance blue arrows that extend 50% beyond the circle represent a 50% increase in catch over the course of the simulation. The angles of the arrows are determined such that the fleets here are aligned with their major target species in Fig. 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Similar to many harvested species, all mammal and bird groups increased in abundance over the course of the 20 year Status Quo simulations. Marine mammals increased between 10% (transient orcas) and 190% (toothed whales), with the exception of pinnipeds, which increased 540%. This large increase is consistent with most California Current pinniped populations' ongoing recovery and maximum population growth rates of 6–14% (Carretta et al., 2011). In the model, migratory birds (e.g. shearwaters), piscivorous seabirds (i.e. guillemots and cormorants) and planktivorous birds (e.g. auklets) increased 260%, 210%, and 50%, respectively. In Appendix C we provide additional details about the species-level responses of biomass and catch in each of the scenarios, relative to Status Quo. Below, we focus on six broad criteria that capture the ecological and economic performance of the scenarios, at the scale of the entire coast and within MBNMS.

3.2. Performance metrics

Here we briefly discuss the relative sensitivity and spatial scaling of the metrics, and then report the performance of the sensitivity analyses. We then illustrate the predicted performance and trade-offs involved in the management scenarios, which we believe are of most interest to decision makers.

The performance metrics ranged from relatively insensitive (mammal and bird biomass) to much more sensitive metrics related to rockfish, landed value, and habitat (Table 3). Generally, perturbations at large scales (coast-wide) or of higher magnitude (e.g. 100% gear switching in MBNMS) were required to force strong responses. In the scenarios involving small scale perturbations (i.e. MBNMS or Central CA), strong responses of >10% tended to involve unexpected local trophic interactions, rather than reflecting direct responses to fishing pressure. Specifically, when the gear shift or RCA closures were implemented in MBNMS or Central California only, this led to declines in the three performance metrics related to rockfish, even though direct fishing pressure on most rockfish groups was reduced (details in Appendix C).

Not surprisingly, the spatial scaling of the performance metrics was highly influenced by the spatial scale and mobility of the relevant species or variables. For instance, in the management scenarios, the three metrics related to the dynamics of highly mobile biological groups (rockfish age structure and biomass, and marine mammal and bird biomass) were nearly identical when calculated from coast-wide data vs. from data within MBNMS. This is a result of the fact that CCAM, as a spatial model, includes movement by these species, including local foraging movement, seasonal migrations and (for fish) a coast-wide stock-recruit relationship. In contrast, the three performance metrics that were based on static or explicitly local variables (landed value, habitat integrity, and year 1 rockfish bycatch) showed more variation when calculated based on MBNMS data vs. coast-wide data.

3.2.1. Sensitivity analysis scenarios

Across all scenarios, abundance of most rockfish groups increased over the 20 year simulations. This is reflected in a fairly narrow range of variability in the rockfish biomass performance metric (Table 3). The No Fishing scenario led to only 31% more rockfish biomass than the 20 year simulation of Status Quo. Higher fishing (5×) still allowed a biomass increase relative to initial levels, but resulted in 0.6× the final biomass under a 20 year Status Quo simulation (Table 3). Rockfish biomass showed similar trends whether it was evaluated using coast-wide data or data from within MBNMS only, though MBNMS was slightly more resilient to increased fishing.

Rockfish age structure (i.e. proportion of rockfish older than the age at maturity, relative to Status Quo), measured on a coast-wide scale, ranged from 1.17× in the case with no fishing to 0.63× in the scenarios with heaviest fishing (Table 3). At both a coast-wide scale and within MBNMS, removing spatial management led to a 1/3 drop in the proportion of rockfish mature. Two unusually high values for this metric from within MBNMS reflect local anomalies within the canary rockfish population; for this species, in these scenarios most of the juveniles move out of MBNMS.

As discussed for Status Quo above, marine mammals and birds generally showed increasing biomass trends. Relative to the final Status Quo values, most scenarios with higher levels of fishing caused moderate reductions in forage resources and ultimately mammals and birds (Table 3). However, removing spatial management (and thereby slightly increasing harvest of target species) led to a slight increase in mammal and bird abundance, due to reduction in predators such as sharks. This was evident within MBNMS as well as at a coast-wide scale. For instance, increasing fishing to 1.5× led to a 70% increase in this metric of mammals and birds within MBNMS, due to reduced predation on them. Though the model does include these indirect trophic impacts on mammals and birds, it is important to note that it does not currently include direct bycatch of these groups.

In the sensitivity analysis scenarios, coast-wide landed value was positively related to fishing effort, either as area was opened to fleets, or as effort was scaled as high as 5× (Table 3). Across the range of fishing effort (0–5× Status Quo), coast-wide landed value ranged from 0 to 3.6× Status Quo. Even though the total revenue was high in the scenarios with high fishing, much of this revenue came from productive stocks such as mackerel, sardines, and small flatfish. Catches of less productive stocks, such as small demersal sharks, large piscivorous flatfish (e.g. arrowtooth flounder), and shallow large rockfish, declined to low levels. Considering catches within MBNMS only, at the highest fishing rates, landed value increased to as much as 4.5× relative to Status Quo. Unlike at the coast-wide scale, a 50% reduction in fishing effort led to a slight increase (11%) of landed value within MBNMS, suggesting moderate overfishing within MBNMS under Status Quo.

The No Fishing scenario of course performed best in terms of avoiding rockfish bycatch, and changes in fishing effort relative to Status Quo caused inversely proportional changes in the metric. Judged in terms of bycatch from within Monterey Bay, these same effort multipliers caused somewhat higher rockfish bycatch and lower values of the performance metric (e.g. 2× Status Quo fishing mortality led to performance of 0.14 in MBNMS vs. 0.47 coast-wide, equivalent to a 7× vs. 2× increase in bycatch, respectively). At both the coast-wide scale and in MBNMS, removing all spatial management led to very poor performance in terms of rockfish bycatch, equivalent to an approximate 15× increase in bycatch above Status Quo levels.

The habitat index was simply based on the "footprint" of the fishing gear, rather than on CCAM outputs. Our habitat integrity metric ranged from 0 for the scenario with 5× Status Quo fishing, to 5.5 for No Fishing (Table 3). These sensitivity analyses generally involved wholesale increases or decreases in fishing from all fleets, rather than trade-offs between areas and fleets, and thus resulted in more dramatic changes in this habitat metric than those seen below in the management scenarios. Considering MBNMS only, the No Fishing scenario led to habitat integrity of 6.41× Status Quo, while the scenarios with no spatial management reduced habitat integrity by approximately half.

3.2.2. Management scenarios

In the management scenarios, variability in rockfish biomass did not exceed 6% on either a coast-wide basis or within MBNMS (Table 3), and biomass of all rockfish groups increased above initial levels, except for shallow large rockfish and yelloweye + cowcod. The scenario involving closure of the RCA to bottom contact gear led to the largest increase in rockfish biomass (Table 3). The 25% gear shift coast-wide also led to slight increases in rockfish biomass. There was no difference between the rockfish biomass metric measured at the scale of MBNMS vs. coast-wide. At both of these scales, in cases where management actions were taken within MBNMS only, the model predicted a slight decrease (−3%) in rockfish biomass. The decreases in our rockfish biomass metric were caused specifically by decreases in abundance of yelloweye and cowcod, large shallow rockfish, and small shallow rockfish; one or more of these groups experienced higher bycatch rates in each of the MBNMS or Central California scenarios.

The proportion of rockfish mature increased slightly relative to Status Quo in both the coast-wide RCA closure and gear shift, but with only 6% and 2% gains, respectively (Table 3). This was true both when considering coast-wide population age structure, and considering only age structure from within MBNMS. As mentioned above for the sensitivity analysis scenarios, even the scenario with no fishing showed only a 17% gain in this metric. This contrasts with the sensitivity analysis scenarios with increased fishing mortality, which quickly truncated the age structure, leading to as much as 1/3 reductions in the proportion of mature individuals. The relative insensitivity of age structure, particularly to decreased fishing, is a result of the general trend in recovery for the rockfish stocks described above. The management scenarios included fishing mortality rates that were conservative enough to lead to increasing biomass, in many cases to levels that began to reach stable age structure by year 20.

The management options that we tested primarily involved groundfish fleets, and had little indirect effect on mammals and birds. Therefore trends in abundance of mammal and birds were consistent across these scenarios. This was true at both the coast-wide and MBNMS scale (Table 3).

Aggregating across fleets, coast-wide landed value in year 20 varied at most 11% between the management scenarios (Table 3). The coast-wide gear switch led to slightly lower catches of small flatfish, lingcod and cabezon, resulting in a 3% decline in landed value. On the other hand, in the case when the gear switch occurred within MBNMS only, increased catch of species such as sablefish led to a 6% increase in coast-wide landed value. From the perspective of MBNMS only, gear switching only within MBNMS led to 15–22% reductions in local landed value, due to the lower landed value from the longline or pot vessels that replaced trawlers in this scenario. However, when the gear switch was simulated on a coast-wide basis the model predicted an overall increase in the abundance of target stocks, and subsequently landed value within MBNMS was within 2% of Status Quo. In the two scenarios with RCA closures coast-wide or in Central California, declines in coast-wide landed value were driven by the change in area available to bottom contact gears such as trawl, longline, and pot. Not surprisingly, from the perspective of MBNMS, local closures of the RCA caused substantial declines in local landed value (−19%). However, as with the gear shift, when the RCA closure involved the entire coast, landed value within MBNMS did not decline, since target species stocks increased coast-wide.

The coast-wide RCA bottom contact closure performed best in terms of avoiding rockfish bycatch, followed by the 25% coast-wide gear shift (Table 3). These might be expected *a priori*, based on the magnitude of these management changes and the species caught by trawl vs. longline/pot gear (Appendix B). Unexpectedly, gear shifts and RCA closures within only MBNMS or Central California led to higher coast-wide rockfish bycatch than Status Quo. This was due primarily to an increase in catch of the midwater rockfish, a group that includes several overfished rockfish (Pacific Ocean perch, widow rockfish, and darkblotched rockfish). Gear shifts either coast-wide or within MBNMS had the highest performance in terms of reducing rockfish bycatch within MBNMS, with scores of 2.53 and 2.09 (i.e. reducing bycatch by 52–60%). None of the RCA closures within MBNMS reduced bycatch in the Sanctuary by more than 33% (metric of 1.3), since in this region these scenarios did not restrict fishing activity to the extent that they did in other regions (i.e. in Central California these scenarios closed area to the trawl fleet but not pot/longline). The higher catches of midwater rockfish mentioned above occurred outside MBNMS, and thus did not influence this metric of rockfish bycatch within the Sanctuary.

Coast-wide habitat integrity generally fell within 10% of Status Quo, with the largest exception involving prohibition of all bottom contact gear in the RCA (value of 1.79× Status Quo). Scenarios that involved only MBNMS had ⩽5% deviation from Status Quo, while scenarios changing spatial management in all of central California had no more than a 10% deviation from Status Quo. To put this in perspective, MBNMS covered 12% and Central California 16% of the model domain. The gear shift scenarios caused only a moderate improvement in the habitat index (<7%), less than some of the spatial management options. The limited improvement under the gear shift is due to the fact that though some trawling was eliminated, it was replaced with pot and longline gear that has a moderate impact on the benthos (though less than trawl). Also, in the gear shift scenarios the footprint of other non-trawl bottom contact fleets remained unchanged. Not surprisingly, values of this metric were quite different when calculated within MBNMS only vs. coast-wide. Within MBNMS, the 100% MBNMS gearshift led to a 26% increase in local habitat integrity, and the prohibition of bottom contact gear in the RCA led to a 57% increase.

3.3. Visualizing trade-offs for management options

As part of the IEA scoping process, we developed our scenarios to address themes that originated with scientists and managers from both the National Marine Sanctuaries program and NOAA's Regional Offices. Of the 16 scenarios tested here, three distinct scenarios that involve management actions at the coast-wide scale are presented in Figs. 5 and 6. These simulated policies were able to outperform Status Quo (Fig. 5), but with clear trade-offs between performance metrics, rather than a single "silver bullet" management strategy. Closing the RCA to bottom contact gear minimized habitat impact and reduced rockfish bycatch, but sacrificed coast-wide landed value (−11%). Consolidating spatial impacts performed within 1% of Status Quo for all six performance metrics, but performed more poorly than either the gear shift or the RCA closure in terms of habitat integrity and simple avoidance of rockfish bycatch. The gear shift scenario performed only 7% better than Status Quo in terms of our habitat impact metric, but did not greatly sacrifice yield (−3%). In terms of rockfish bycatch, this gear shift performed better than Status Quo, but not as well as the RCA closure. Thus, though the gear shift scenario holds some promise as a compromise strategy, it is not a clear optimal strategy. These trade-offs are evident regardless of whether performance is judged on a coast-wide basis (Fig. 5) or only within MBNMS (Fig. 6): the rank order of these scenarios for each performance metric does not vary between these scales, with the exception of landed value. At a coast-wide scale, landed value declines because the RCA closure scenario prohibits bottom contact gear within a substantial area. This RCA closure scenario does not have large effects on spatial effort within MBNMS, and thus at the scale of MBNMS landed value does not change relative to Status Quo.

Three scenarios that involve changes in management actions only at the scale of the Monterey Bay National Marine Sanctuary are presented in Figs. 7 and 8. The local manipulations within MBNMS do not have a large impact on coast-wide performance metrics (Fig. 7), due to the small magnitude of these policy changes relative to the scale of the model domain. The exception to this is that the local gear shift and the local prohibition on bottom contact in the RCA have lower performance in terms of avoiding rockfish bycatch (i.e. the higher bycatch of midwater rockfish discussed above). However, viewed from the perspective of MBNMS (Fig. 8), the local gear shift scenario and the prohibition on bottom contact within the RCA are able to outperform Status Quo, particularly in terms of habitat integrity and avoiding rockfish bycatch. The gear shift outperforms the RCA closure in terms of avoiding bycatch, and vice versa for habitat integrity. On the other hand, both of these policies involve ∼20% declines in landed value within MBNMS.

3.4. Landed value per fleet

In addition to the performance metric 'landed value', which summed over all fleets, we also calculated landed value per fleet (gear) in year 20 of the simulations. Fig. 9 illustrates the results for the six fleets with the highest revenue, accounting for 95% of landed value in the Status Quo scenario. Limited entry trawl fleet revenue declined up to 18% due to the direct effect of the gear switching, and up to 45% due to the increased spatial closures involved in the RCA scenarios. The gear switch led to a 28% increase in fixed gear (longline + pot) revenue, slightly more than the direct 25% increase in effort in this scenario. The halibut longline fleet

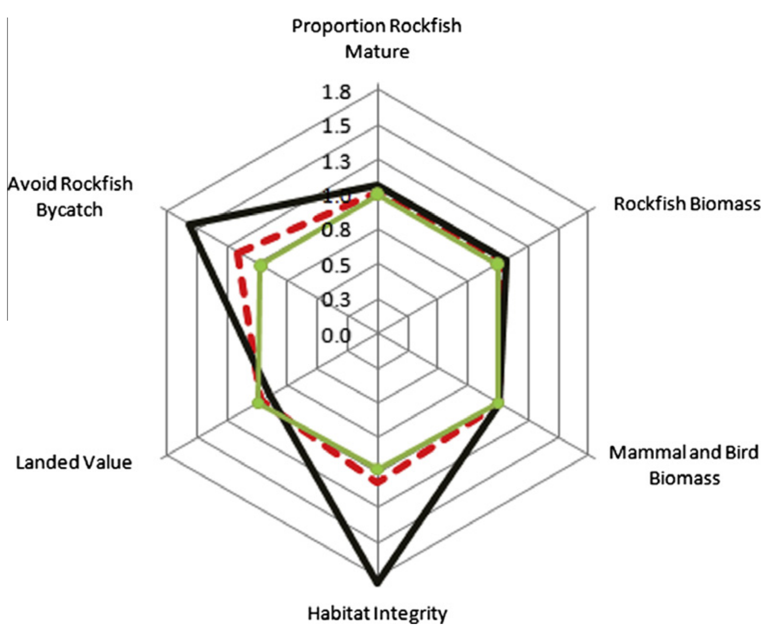

Fig. 5. Performance of three scenarios: the coast-wide 25% gear shift (red dashed line), ban on bottom contact in the RCA (black solid line), and an attempt to consolidate bottom contact impacts (green solid line with points). Scores of each axis have been normalized by performance in Status Quo. Here performance is calculated from data at the coast-wide scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

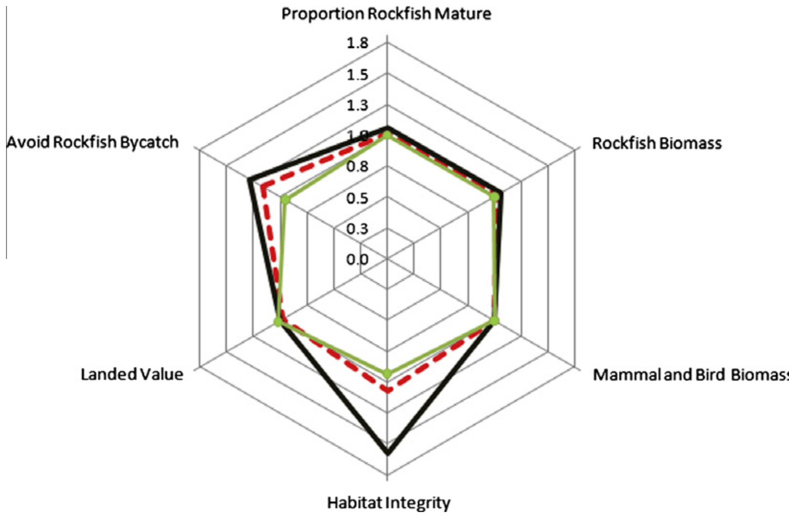

Fig. 6. Performance of the coast-wide 25% gear shift (red dashed line), ban on bottom contact in the RCA (black solid line), and an attempt to consolidate bottom contact impacts (green solid line with points). Scores of each axis have been normalized by performance in Status Quo. Here performance is calculated from data within MBNMS only. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

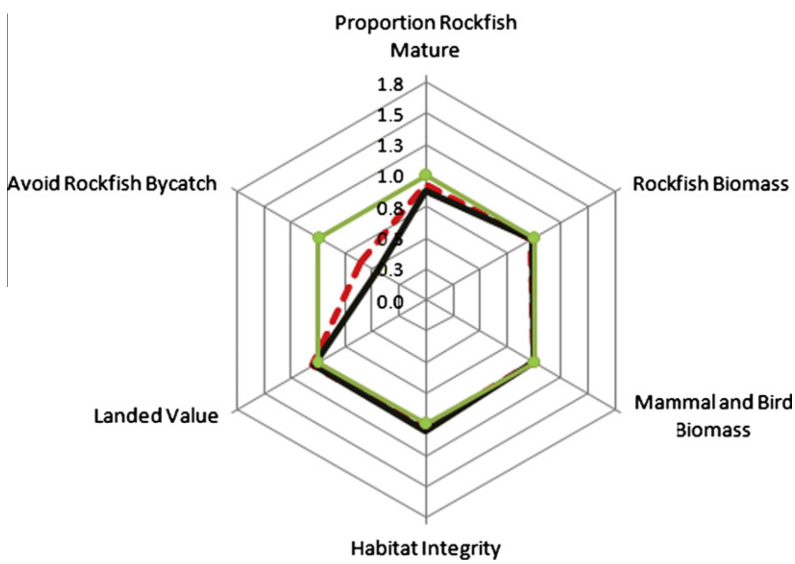

Fig. 7. Performance of scenarios involving a 100% gear shift within MBNMS (red dashed line), prohibiting bottom contact gear within MBNMS (black solid line), and attempting to consolidate bottom contact impacts within MBNMS (green solid line with points). Scores of each axis have been normalized by performance in Status Quo. Here performance is calculated from coast-wide data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

was not directly manipulated (in terms of area closed or effort) in the coast-wide RCA closure scenario, but halibut and other large piscivorous flatfish are catch and bycatch of other demersal gears. Reductions in these other demersal gears led to a 73% increase in revenue for the halibut longline fleet in the RCA closure scenario. Consolidating bottom contact impacts in MBNMS did not affect any of these six fleets by >1%, while consolidating bottom impacts coast-wide led to a 7% decline in halibut longline fleet revenue as this fleet was pushed farther offshore.

4. Discussion

4.1. Lessons learned from model results

The management scenarios that we explored in this paper involved moderate management changes, which at the scale of the entire coast yielded results that were generally within 10% of Status Quo. Large, coast-wide management actions were typically required to cause substantial improvements in coast-wide ecological and economic performance. Judged on a coast-wide scale, most of the scenarios that involved minor or local management changes (e.g. within Monterey Bay NMS only) yielded results similar to Status Quo. When impacts did occur in these cases, they often involved local interactions that were difficult to predict *a priori* based solely on fishing patterns. However, judged on the local scale, deviation from Status Quo did emerge, particularly for metrics related to stationary species or variables (i.e. habitat and local metrics of landed value or bycatch). As might be expected, the results at this local scale were dependent upon the exact configuration of current and simulated spatial management. For instance, in terms of reducing rockfish bycatch, an RCA closure that ranked as the best option at a coast-wide scale performed more poorly within Monterey Bay, due to the particular geographic configuration of the Status Quo trawl and non-trawl RCA.

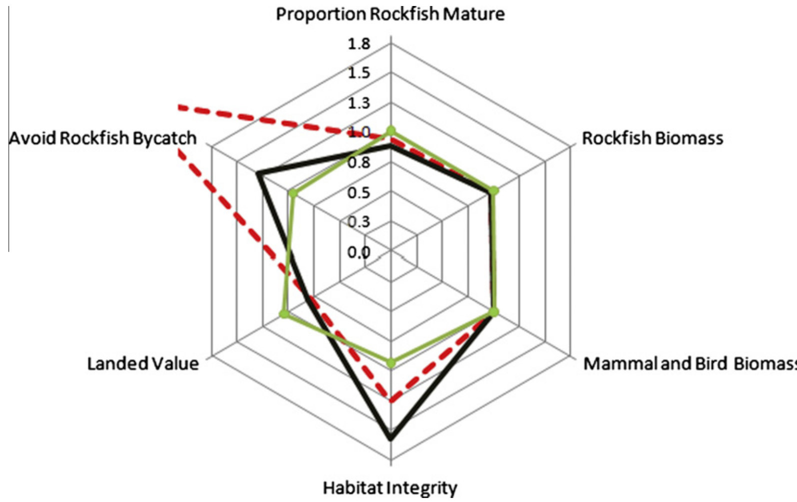

Fig. 8. Performance of scenarios involving a 100% gear shift within MBNMS (red dashed line), prohibiting bottom contact gear within MBNMS (black solid line), and attempting to consolidate bottom contact impacts within MBNMS (green solid line with points). Scores of each axis have been normalized by performance in Status Quo. Here performance is calculated from data within MBNMS only. The metric "Avoid Rockfish Bycatch" has a value of 2.53 for this MBNMS gear shift, but the axis has been truncated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

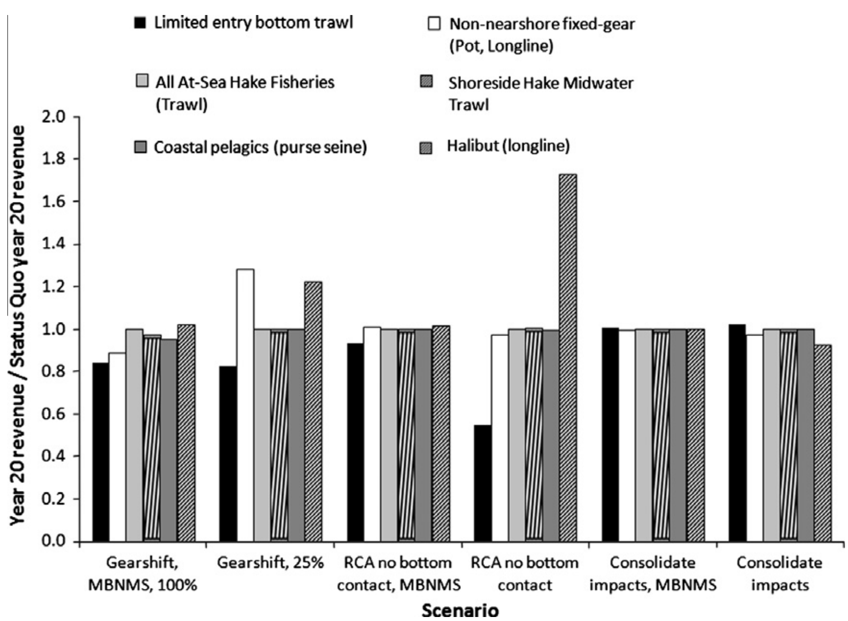

Fig. 9. Proportional difference in landed value per fleet, for six scenarios. The six fleets shown account for 95% of landed value. For each group of bars (one scenario), from left to right the bars represent the following fleets: limited entry bottom trawl; non-nearshore fixed gear (pot, longline); at-sea hake fisheries (trawl); shoreside hake midwater trawl; coastal pelagics (purse seine); and halibut (longline). The 25% and 50% gear shift within MBNMS are no shown, but responded similarly to the 100% gear shift within MBNMS. The RCA closure for Central California is not shown, but responded similarly to the RCA closure within MBNMS.

A key finding in our work is that no single scenario maximized all performance metrics. Any policy choice would involve trade-offs between stakeholder groups and policy goals. Of the management scenarios we examined, the coast-wide 25% gear shift appeared to be one possible compromise between the coast-wide closure of RCA to bottom contact (which sacrificed revenue) and scenarios such as the one consolidating bottom impacts to deeper areas (which did not perform substantially differently from Status Quo). However, stakeholders who place more weight on protection of biogenic habitat (e.g. corals and sponges) might prefer the full closure of the RCA to bottom contact.

We found that the economic cost within MBNMS of gear switching or RCA closures was related to the scale of the management action. In cases where these management actions occurred only within the Sanctuary, landed value within the Sanctuary declined. However, when the management action was coast-wide, landed value within the Sanctuary did not decline, due to increases in abundance of target stocks. This suggests that isolated management actions within the Sanctuary would cause local fishers to pay a cost for conservation that would be unnecessary if conservation actions were part of a concerted coast-wide plan.

The scenarios involved winners and losers among both fleets and species. For instance, there were direct impacts of the scenarios on fleets (e.g. on trawl and longline/pot fleets), as well as indirect effects such as halibut longline fisheries that gained revenue when trawl effort declined. For individual species in the scenarios of most relevance to managers, the key impact was in the gear shift scenarios, which cut fishing mortality on flatfish and some rockfish, and led to biomass increases for many of these groups. In the sensitivity analysis scenarios, broad life history differences drove the responses, with unproductive groups declining at moderate fishing pressures and being replaced by more productive groups or species. From the standpoint of current fisheries management, it is encouraging that in the scenarios with fishing rates near Status Quo, fish biomasses generally increased and plateaued over the course of the 20 year simulations, and age structure stabilized. The strong recovery trends for fish, marine mammals, and birds, suggest that we must carefully interpret our performance metrics. Some performance metrics may be more sensitive to stock depletion than recovery (e.g. metrics of rockfish age structure), and certain metrics related to protected species may not directly respond to changes in fishing pressure.

The scenarios revealed strong trophic effects in the food web. For instance, 50% reductions in fishing led to declines in small planktivores (sardines and anchovies) due to fish predation; this subsequently caused declines in marine mammal and bird abundance. Scenarios with strong increases in fishing on all groups indirectly led to increases in abundance of some small bodied prey groups, such as nearshore fish (surfperch) and small flatfish. Declines of diving seabirds, due to predation, were an unexpected consequence of spatial fishery closures within the Sanctuaries. These results demonstrate the strength of using the full ecosystem model, which captures these food web effects, rather than traditional single species models.

4.2. Caveats and opportunities for learning

These results and all results from forward simulation models of marine ecosystems should be viewed as strategic complements to the traditional tools of fisheries assessment. These traditional techniques include single species stock assessment, fishery independent surveys, monitoring of commercial catch and landings, and calculation of ecological indicators. End-to-end ecosystem models illustrate the feedbacks and trade-offs between ecosystem components (e.g. Dorn et al., 2008), and can be used to screen and rank policy options (e.g. Fulton et al., 2007). However, the complexity and slow run times of these models make it difficult to conduct formal sensitivity analyses or to fit parameters in a statistical manner. Many key state variables (e.g. abundance of benthic infauna or jellyfish) and relationships (e.g. predator–prey relationships) are poorly known, even for well-studied systems (e.g. Table C28 from Aydin et al. (2007)). For the California Current Atlantis Model, we have partially validated the model by fitting it to historical abundance time series, and by comparing its estimates of stock productivity and unfished abundance to those from published single-species assessments (Horne et al., 2010). Future work to further handle uncertainty will involve running scenarios that bound the overall productivity of key groups, as discussed for Atlantis models in Fulton (2010). One additional method for improved validation would involve quantitative comparison to data from outside the original calibration set, using measures such as the root mean square difference, and estimates of the model bias and efficiency at matching observed values. Fitting diagrams such as those found in Taylor (2001) and the target diagrams of Jolliff et al. (2009) and Friedrichs et al. (2009) are one set of tools for visualizing such validation results.

Several key points arose from preparing the input data, creating the relevant maps, and converting the scenario descriptions into quantitative inputs, rather than from the CCAM simulation outputs. One example that became evident directly from the input data (Bellman et al., 2008) stems from the relative catch composition of trawl gear, which targets a wide range of flatfish and rockfish, vs. longline and pot gears, which primarily target sablefish. A switch from trawl to longline and pots therefore involves a substantial transfer of fishing mortality from the former species to the latter. Thus the fact that a gear switch involves winners and losers among species is obvious from both the inputs to, and outputs from, CCAM. Another example involves the spatial closures for each of the 20 fleets (gears). The geographic analysis alone reveals characteristics of the scenarios. For instance, one set of our simulations was intended to prohibit trawl gear in the current non-trawl RCA, and to prohibit longline and pot gear in the current trawl RCA. However, for Central California specifically, where the current trawl RCA is largely contained within the non-trawl RCA, these scenarios did not close additional portions of Central California to longline and pot gear.

Finally, independent of specific model results, it is clear that we have only a qualitative understanding of the impact of certain gears on benthic habitat. Here we have weighted the footprint of each gear based on gear impact factors from an Essential Fish Habitat environmental impact statement, consistent with Collie et al. (2000). Our simple habitat metric assumes that each gear acts independently; for instance the overall survival fraction of coral in a polygon is the product of the probabilities of it surviving each gear. This may understate cumulative effects if there are synergistic effects between gears, and overstate effects if low-impact gears cause little additional damage to areas previously trawled. Essentially our metric is a placeholder framework for an approach informed by quantitative local data on gear impacts.

4.3. Summary

Rose et al. (2010) identified nine challenges related to development of end-to-end ecosystem models such as the Central California Atlantis Model. These issues include the need for improved understanding and algorithms related to three biological processes (zooplankton dynamics; movement; acclimation and adaptation), technical challenges (model skill assessment; handling multiple temporal and spatial scales; and the need for two-way model coupling), and issues involving human capital and collaboration (e.g., data standards; collaborative approaches on large programming projects; and the challenges of communicating across disciplines). While we have not yet addressed all these challenges, we are making progress in these directions, and the current study is a proof-of-concept that illustrates the utility of end-to-end marine models. The simulations demonstrate the utility of using the Atlantis ecosystem model within the Integrated Ecosystem Assessment, by illustrating an end-to-end modeling tool that allows consideration of multiple management alternatives that are relevant to state, federal and private interests.

Acknowledgments

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.pocean.2012.03.009.

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