MANAGEMENT TESTING AND SCENARIOS IN THE CALIFORNIA CURRENT

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CCIEA SCENARIOS CONCEPTUAL FRAMEWORK

SUMMARY OF CONCEPTUAL FRAMEWORK

Scenarios and Management Testing aim to provide a glimpse into alternate futures for the California Current and the implications of alternate management decisions. Here we first develop narrative scenarios that consider how drivers of the system may link to pressures, for instance how human population growth increases conflicts between salmon recovery and human water needs (**Figure MS1**). We then use quantitative models to predict how changes in pressures impact attributes of interest for the IEA, such as particular protected species or human communities. The quantitative analyses are a preliminary test of the capabilities of six distinct modeling frameworks to identify and project future trends for the California Current. The scenarios and management actions that are tested in the quantitative analyses range from nearly certain to highly unlikely, given current legal frameworks and other factors. Nonetheless, the coupled scenarios and modeling analyses illustrate the impacts of both system-level drivers and potential management responses.

DESCRIPTION OF THE CONCEPTUAL FRAMEWORK

Through preliminary engagement with managers, scientists, and stakeholders we have identified potential drivers of the California Current (**Engagement section**). Other efforts within this IEA have identified patterns related to pressures, risk, status, and trends of the ecosystem (**Drivers and Pressures, Risk, and Ecosystem Components sections**). Those analyses are the motivation for Scenarios and Management Testing, which aim to provide a glimpse into alternate futures for the California Current and the implications of alternate management decisions. Scenarios and Management Testing differ from risk assessment, in that we are explicitly interested in projecting forward in time, whereas risk assessment deals with current status. Here we develop narrative scenarios that consider how drivers of the system may link to pressures, for instance how human population growth increases the demand for fresh water for urban and agricultural uses (**Figure MS1**). We then use quantitative models to predict how changes in pressures impact attributes of interest for the IEA, such as particular protected species. Timescales for the quantitative analyses are fifty years into the future or less.

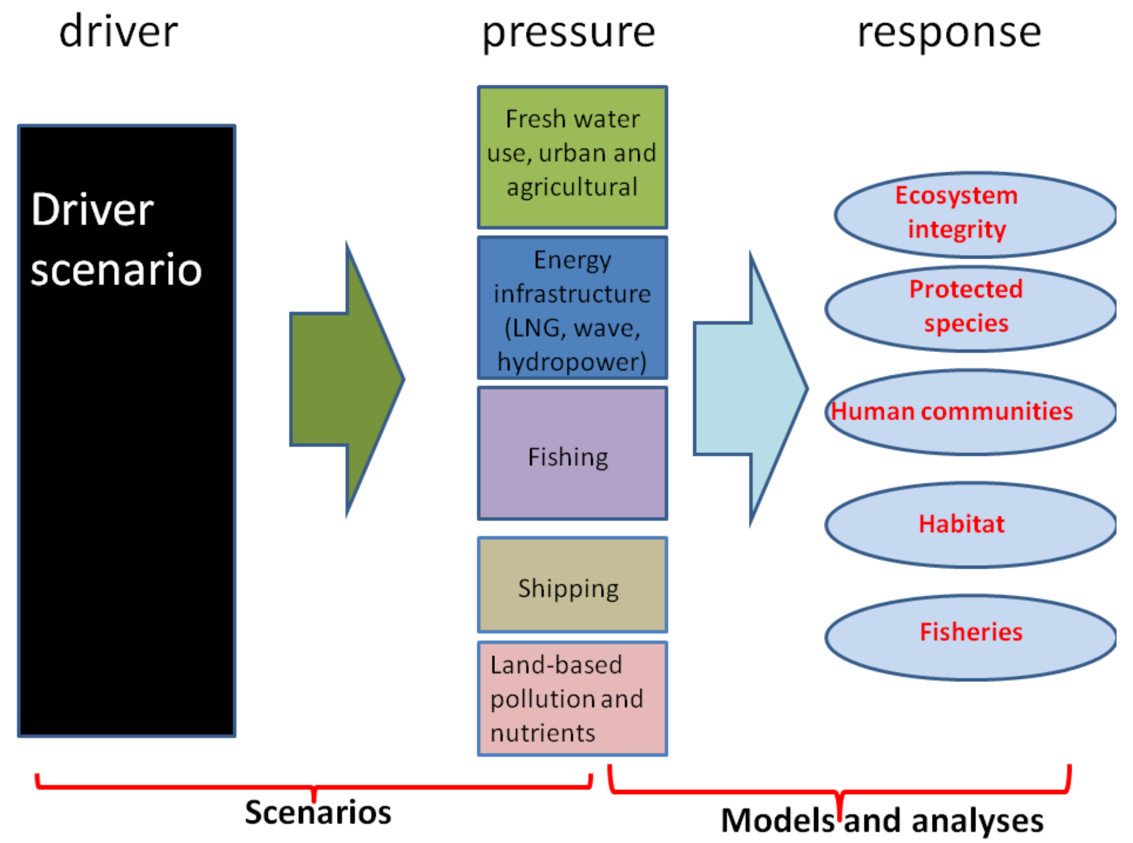

Figure MS1. Schematic of Management Testing approach, where drivers are linked to pressures via narrative scenarios, and then quantitative models link pressures to responses.

Linking from drivers to pressures (**Figure MS1)** falls outside the realm of most quantitative modeling, but can be used to inform such modeling. Scenario planning is one highly effective means of creating sensible and powerful narratives that help stakeholders envision the future, and help modelers specify meaningful measures of pressure on the ecosystem. Scenario planning has been applied to environmental issues for over 40 years (Alcamo 2008). Recently the Millenium Ecosystem Assessment (2005) successfully used scenario development to envision futures for the global environment and human populations. As described in the Millenium Ecosystem Assessment, scenarios are "plausible and often simplified descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces and relationships." Ash et al (2010) note that "an important function of scenario analysis—particularly in the context of ecosystem assessments—is that it provides an approach to reflect on and think through the possible implications of alternative decisions in a structured manner. Simply put, a scenario exercise offers a platform that allows [decision makers] to reflect on how changes in their respective context (that is, developments not within their immediate spheres of influence) may affect their decisions."

Scenarios are a new tool for marine resource management, but have many parallels with established approaches that are used to account for uncertainty and complex human behavior. One analogous approach from single species management is the decision table framework (Hilborn and Walters 1992) that tests performance against alternate "states of nature", which typically bracket key uncertainties in biology, data, or fishermen's behavior. Often these uncertainties are framed in terms of narrative "what if" scenarios posed by expert review panels. Resource managers are also familiar with scenarios, albeit under a different terminology. For instance, given considerable uncertainty in fishermen's behavior under a groundfish catch share program, the Pacific Fishery Management Council (2010) envisioned four sets of harvest and bycatch rates based on a blend of expert opinion and data. This approach of considering potential alternative futures is warranted when no reliable quantitative model can address a particular complex human, economic, or ecological challenge.

Though we do not have quantitative models to link all pressures to ecosystem attributes (**Figure MS1**), we can begin to apply and refine a set of relevant tools. Such quantitative tools are already in daily use by NOAA scientists and others, and include single species stock assessments (Methot 2007), GIS mapping, spatial planning tools (Tallis *et al.* 2008), food web models (Steele and Ruzicka 2011), and ecosystem models (Kaplan *et al.* 2012). Other links from pressures to impacted attributes cannot be addressed with the current generation of quantitative models.

RATIONALE AND LOGIC OF THE SCENARIOS

SUMMARY

Drawing from themes raised in our preliminary engagement with managers and other experts (**Engagement section**), we develop narrative scenarios that act as links between drivers and pressures (**Figure MS1**). These are "scenarios for drivers", essentially "what if" stories about alternate paths that drivers and pressures may take in the future. Scenarios include drivers related to human population growth, climate change, demand for conservation, energy, and evolution of status quo management and responses to it. Scenarios detail potential effects on pressures considered in this IEA: urban and agricultural freshwater use, energy infrastructure, fishing, pollution, and shipping. The table below diagrams the major trends in pressures for each scenario, followed by a more nuanced description. Subsequent sections link selected portions of these narrative scenarios to quantitative models.

Note: The color coding below roughly indicates whether the pressure (shipping, fishing, land-based pollution, energy infrastructure, freshwater use) will **increase**, **decrease**, or **remain** at current level. For the web version of this document, hyperlinks are provided, linking to quantitative analyses (described below). Text sections lacking hyperlinks have been developed here as narratives, but lack quantitative methodologies for testing these implications of the scenarios.

	Pressure				
Scenario	Freshwater use, urban and agricultural	Energy Infrastructure	Fishing	Land-based pollution	Shipping
Human Population Growth	↑	↑	↑	↑	↑
Climate Change	↑	↑	↔	↔	↔
Conservation Demands	↓	↓	↓	↓	↓
Energy Crunch	↔	↑	↓	↔	↑
Status Quo	↔	↔	↔	↔	↔

FULL DESCRIPTION OF SCENARIO RATIONALE

Below, we first develop narrative scenarios that act as a link between drivers and pressures (**Figure MS1**). These are "scenarios for drivers", essentially "what if" stories about alternate paths that drivers and pressures may take in the future. Our aim is to explore divergent paths for the California Current, not to evaluate which is most likely biologically or given legal or political constraints. We consider management actions including some that are illegal under current laws, and drivers that are possible but not necessarily likely. Importantly, not all drivers can be linked logically to each pressure, via narratives that capture our current qualitative understanding of the system. Similarly, not all pressures can be linked to impacts on each attribute, either in a logical or quantitative way. The scenarios focus on impacts related to living marine resources, with some limited consideration of other social and economic impacts. Though preliminary engagement with experts identified the drivers and pressures (**Engagement section**), the narrative scenarios are constructed by the authors.

POPULATION GROWTH SCENARIO

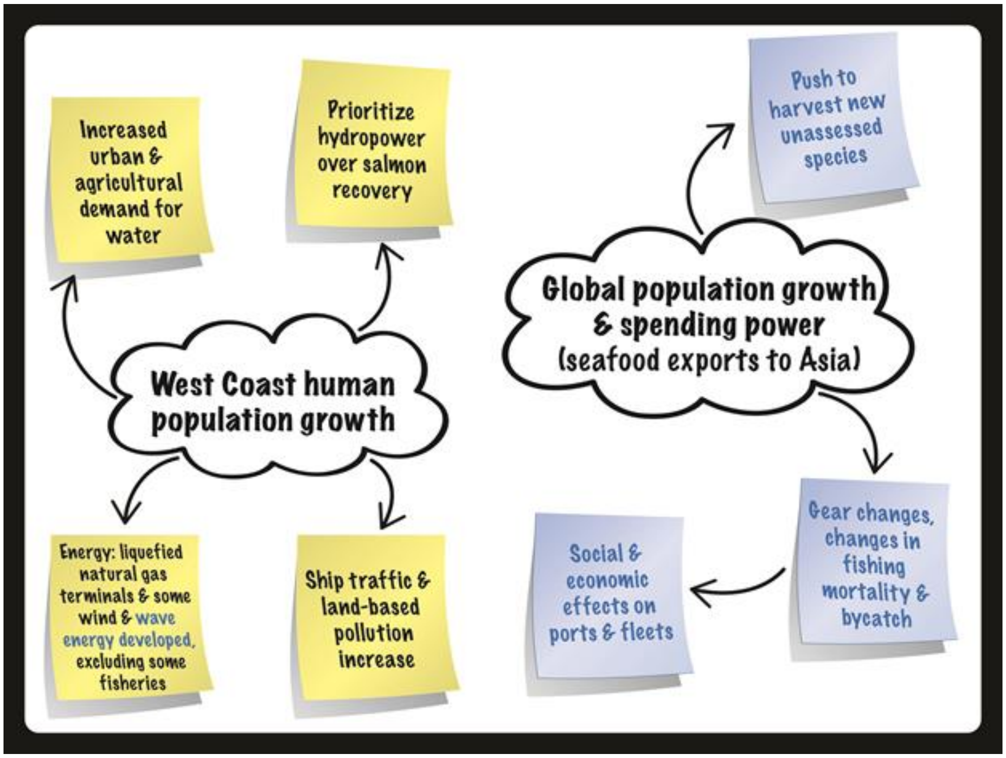

Figure MS2. Results from preliminary engagement with managers and experts (Engagement section), related to the Population Growth scenario. Blue topics are addressed with quantitative models in this IEA.

INSIGHTS FROM EXPERTS

As described in the preliminary engagement with managers and experts (**Engagement section**), human population growth on the US west coast was identified as a driver of freshwater and nearshore habitats, particularly for salmon (**Figure MS2**). Global population growth was identified as a driver of seafood demand, including demand for new species. Using themes and details from these conversations, we constructed the following narrative:

NARRATIVE FOR HUMAN POPULATION GROWTH

FRESHWATER USE, URBAN AND AGRICULTURAL: Urban demands for freshwater will increase concomitantly with the increase in human population on the West Coast. The EPA has defined baseline population growth scenarios that will increase the population of western states by 50% from 2005 to 2060 (Bierwagen 2009). This demand will compete with the needs of salmon, particularly during the summer and for "stream type" stocks (i.e. those that rear for extended periods in freshwater). Desalination plants might be built in Southern California, with local negative impacts on some plankton, fish eggs and larvae.

ENERGY INFRASTRUCTURE: The growing human population requires increased electricity production. Dam removal on major salmon rivers might be politically unviable. Wave and wind energy installations may be built, but most investment focuses on LNG terminals.

FISHING: West Coast population growth does not lead to immediate increases in demand for West Coast wild seafood, primarily due to declines in US per capita seafood consumption and increased aquaculture production and imports. In a variation of this scenario, global increase in population and economic development, particularly in Asia, could drive substantial increases in demand for West Coast seafood, including increased focus on species such as grenadier, crab, octopus, geoduck, and live-caught rockfish.

LAND-BASED POLLUTION: Land-based pollution, including pathogens and nitrogen inputs, is assumed to continue proportional to population growth. No major improvements in sewage or storm-water treatment are envisioned.

SHIPPING: Ship traffic is assumed to continue proportional to population growth. No major changes are envisioned related to ship speeds or shipping lanes.

See population growth graph: www.bit.ly/xZK9pW

CLIMATE CHANGE SCENARIO

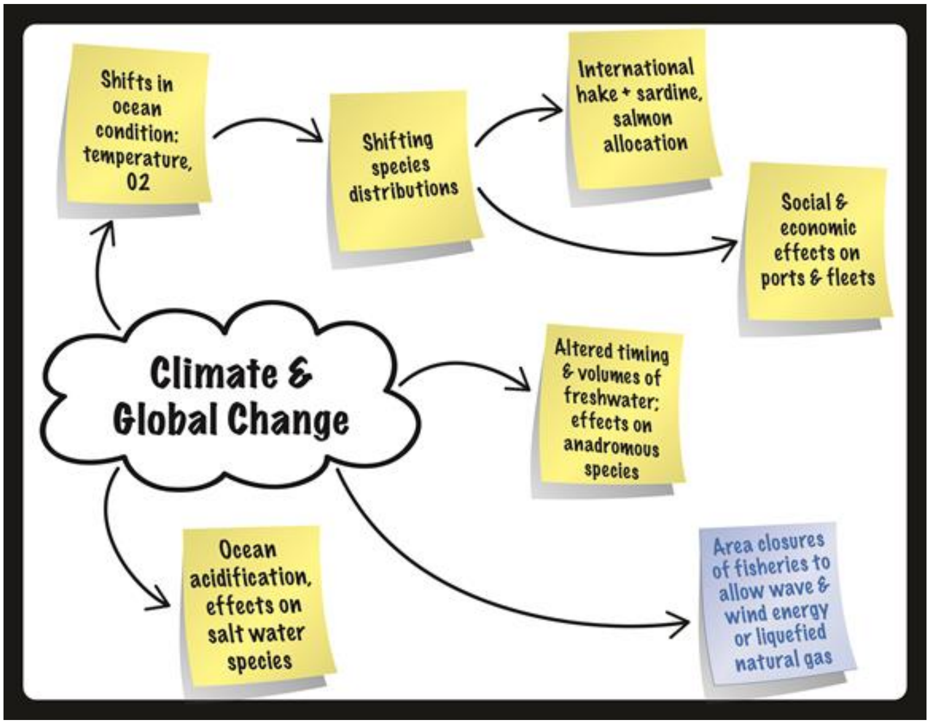

Figure MS3. Results from preliminary engagement with managers and experts (Engagement section), related to the Climate and Global Change scenario. Blue topics are addressed with quantitative models in this IEA.

INSIGHTS FROM EXPERTS

As described in the preliminary engagement with managers and other experts (**Section 1**), climate change and ocean acidification were predicted to impact salmon, sardine, anchovy, and hake (**Figure MS3**). Policy responses were limited but included altering harvest, stream restoration, and community-based management. Using themes and details from these conversations, we constructed the following narrative:

NARRATIVE FOR CLIMATE CHANGE

In the oceans, global warming may lead to a 1.8 - 4°C (3-6°F) increase in sea surface temperature this century. This may cause northward shifts in species ranges and migration patterns, changes in growth and reproductive rates, and reductions in the oxygen content of water (potentially to anoxic levels), particularly in nearshore areas <50m deep. These hypoxic or anoxic areas may lead to local die-offs of crabs or other species with limited mobility. Primary production (phytoplankton) may increase, but smaller phytoplankton may be favored, leading to less food availability for large zooplankton (e.g. krill) but more for smaller zooplankton (e.g. copepods).

Increasing fossil fuel emissions and the resulting increase in atmospheric CO_2 levels will likely lead to a decline in seawater pH of 0.3 by the year 2100. Changes to seawater pH and the saturation state of aragonite and calcite (the minerals many organisms use to build protective structures) could lead to reduced populations of marine species including corals, crabs, shellfish, benthic invertebrates, and plankton groups such as krill. There is considerable uncertainty regarding which species will be impacted, and to what extent (National Research Council (US) 2010) .

In freshwater, global warming may reduce snowpack in mountain streams and reduced summer flows in mountain streams. Stream temperatures may be elevated in summer. These effects may lead to decreased growth and survival of juvenile salmonids, particularly Chinook salmon.

FRESHWATER USE, URBAN AND AGRICULTURAL: Reduced winter snowpack will change the timing of water demand and releases from reservoirs. Even if overall volume of water use is not changed, there could be more agricultural demand for water during the summer, in competition with some salmon stocks. “Stream type” salmon may be particularly impacted. Dams may be used to store more water during winter, rather than releasing this water for flood control purposes over the course of the winter.

ENERGY INFRASTRUCTURE: Large changes in energy infrastructure may results as a policy response to slow climate change. Low-carbon energy such as LNG, hydropower, or wave energy may become more popular.

FISHING: Species distributions may shift in response to climate. Pelagic or midwater species such as hake or sardine may shift their migrations and distribution northwards. Salmonid stocks in California may decline as salmon range shifts northward. The harvest of fishing fleets (at the port level) may shift as well. Low-carbon energy sources will exclude fishing fleets from certain areas, as discussed in “Energy Crunch” scenario.

LAND-BASED POLLUTION: Changes in rainfall and river flow may alter runoff of pollutants.

SHIPPING: No direct impact expected

See related graph of yearly CO^2 emissions: www.bit.ly/zdh95M

CONSERVATION DEMANDS SCENARIO

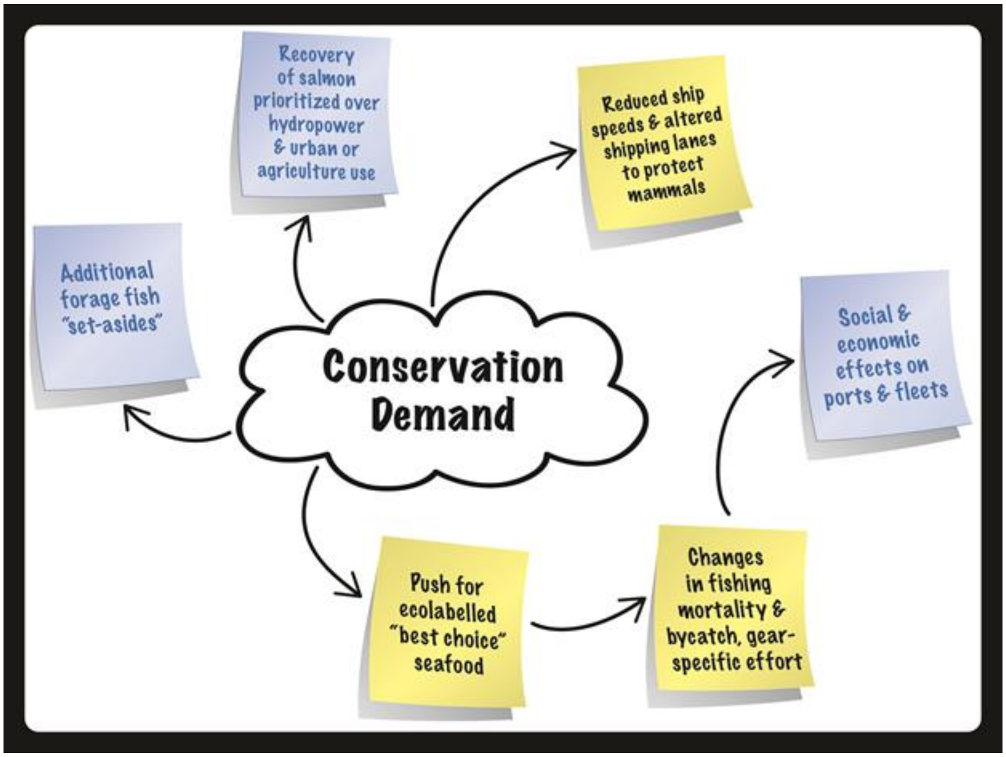

Figure MS4. Results from preliminary engagement with managers and experts (Engagement section), related to the Conservation Demand scenario. Blue topics are addressed with quantitative models in this IEA.

INSIGHTS FROM EXPERTS

As described in the preliminary engagement with managers and other experts (**Section 1**), a growing demand for conservation was envisioned to alter harvest policies, dam operation, shipping, seafood demand, and marine spatial planning (**Figure MS4**). Using themes and details from these conversations, we constructed the following narrative, which might unfold in the next 1-2 decades:

NARRATIVE SCENARIO FOR CONSERVATION DEMANDS

This scenario envisions increased demand from the public, NGOs, and stakeholders for conservation of marine resources. This may be aided by modifications to current federal, state, and tribal policies, or at the federal level by implementation of Marine Spatial Planning and National Ocean Council recommendations. At the state level and smaller scales, increased local input and cooperation between managers and stakeholders could lead to faster management responses and more local solutions and experimentation to achieve conservation goals.

FRESHWATER USE, URBAN AND AGRICULTURAL: Recovery of salmon is promoted, even above current efforts, at times limiting water available for cities and agriculture.

ENERGY INFRASTRUCTURE: Dam removal is attempted to promote recovery of certain salmon stocks. Economic and social costs of removal can be weighed against benefits to salmon stocks.

FISHING: In this scenario, harvest of forage groups (sardine, squid, mackerel) are reduced, to avoid potential negative impacts on their predators. Fishing effort shifts to only stocks that are labeled as eco-certified. A variation on this scenario keeps fishing effort on sardines (often eco-certified as a "best choice") but avoids other forage groups. Scenario impacts may include reductions in fishing effort or fishing grounds, changes in gear that degrades bottom habitat or entangles mammals, "set-asides" of forage species for predators rather than fishermen, and possible trade-offs between stakeholders (e.g. fishermen vs. tourism) or between certain ports or regions.

SHIPPING : In this scenario, protection of marine mammals is prioritized, resulting in changes to shipping lanes and reduced ship speeds. This results in fewer ships striking mammals, and less disturbance of mammals by vessel traffic.

LAND-BASED POLLUTION: Policies reduce discharge of nitrogen and pathogens in nearshore waters, with some benefits such as reduced harmful algal blooms or reduced mortality of sea otters.

ENERGY CRUNCH SCENARIO

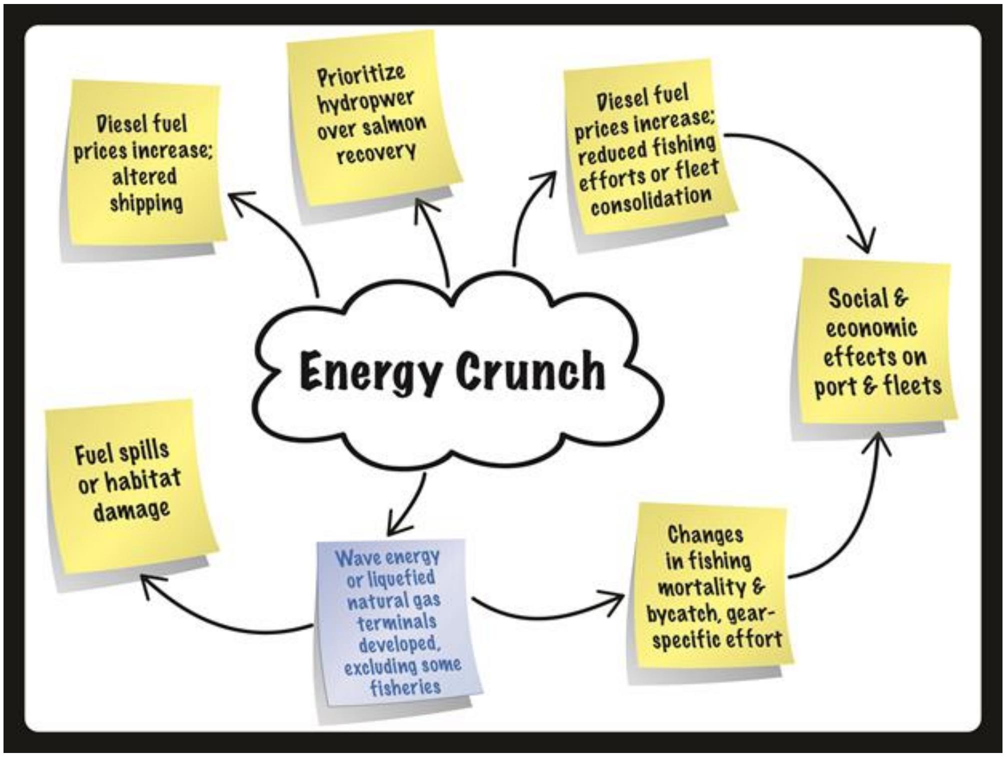

Figure MS5. Results from preliminary engagement with managers and experts (Engagement section), related to the Energy Crunch scenario. Blue topics are addressed with quantitative models in this IEA.

INSIGHTS FROM MANAGERS AND OTHER EXPERTS

As described in the preliminary engagement with managers and experts (**Section 1**), rising demand or price for energy was discussed as a driver of fishing, shipping, and the establishment of wave energy facilities. (**Figure MS5**). Using themes and details from these conversations, we constructed the following narrative, which might unfold over the next thirty years:

NARRATIVE SCENARIOS FOR ENERGY CRUNCH

"By 2015, growth in the production of easily accessible oil and gas will not match the projected rate of demand growth. ... alternative energy sources such as biofuels may become a much more significant part of the energy mix — but there is no "silver bullet" that will completely resolve supply-demand tensions."-- Shell Oil Scenarios

ENERGY INFRASTRUCTURE: The local response to rising energy demand will be to develop wave farms, and to exploit fuels such as liquefied natural gas (LNG). Development of LNG terminals and wave energy installations may lead to exclusion of fishing gears from portions of the coast. Increased ship activity around these facilities could lead to fuel spills, putting vulnerable habitats or National Marine Sanctuaries at risk. The demand for hydropower will also increase, in competition with the needs of species such as salmon.

FISHING: Rising prices for diesel fuel may reduce fishing effort, cause fleet consolidation, or shift the fishing areas or methods of fleets. Fuel-intensive fleets (e.g. albacore trolling) may reduce effort substantially. This in turn could lead to social and economic impacts that vary by fleet and port. Fishery targeting may shift as profitability changes due to rising fuel costs.

SHIPPING: Shipping traffic may increase as industries push for low-cost methods (freighters, tankers) to move goods. Short-sea shipping, between existing cargo hubs and new satellite ports, may increase ship traffic in coastal areas. Increases in shipping could increase ship strikes of mammals and other vessel-related disturbance, as well as pollution discharges from ships.

LAND-BASED POLLUTION: No changes expected

FRESHWATER USE, URBAN AND AGRICULTURAL: No change expected

See graph of global energy use: www.bit.ly/S4VSfC

STATUS QUO

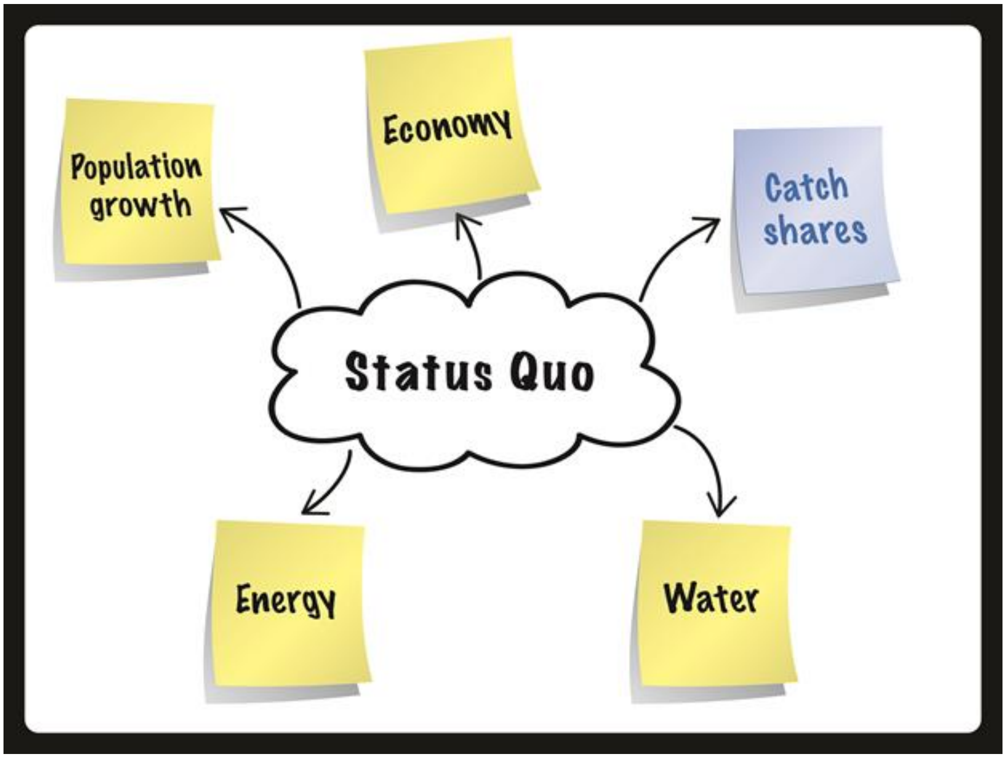

Figure MS6. Results from preliminary engagement with managers and experts (Engagement section), related to the Status Quo scenario. Blue topics are addressed with quantitative models in this IEA.

INSIGHTS FROM EXPERTS

The preliminary engagement with managers, scientists, and other experts (**Section 1**) identified key challenges with status quo fishery management, such as inflexibility, lengthy regulatory review processes, and high costs (**Figure MS6**). Additionally, the groundfish catch share program was initiated in January of 2011, and experts and managers suggested that results from the program would depend on the evolution of fishery targeting, market demand, and fleet consolidation. Using themes and details from these conversations, we constructed the following narrative:

NARRATIVE SCENARIO FOR STATUS QUO

This scenario will project current drivers and pressure on the ecosystem. Note that in some ways 10-20 year projections of this scenario are highly unrealistic if population growth continues. Nevertheless, to understand output from quantitative models, status quo can serve as a baseline that can be compared to more realistic population growth scenarios.

FRESHWATER USE, URBAN AND AGRICULTURAL: No major change in the volume or timing of demand for freshwater.

ENERGY INFRASTRUCTURE: Assume no major expansion of wave or wind energy, LNG, or changes in hydropower infrastructure or operations.

FISHING: Assume current management structure and regulations. Variants of this primarily involve different responses of fishermen to the existing groundfish catch share system, different options to promote flexible responses, and how this can be altered by fuel prices and climate. This can build on an existing Environmental Impact Statement (Pacific Fishery Management Council 2010), which predicted species-level responses of several groundfish populations to different scenarios for fishermen's behavior under catch shares.

LAND-BASED POLLUTION: Left at current levels.

SHIPPING: Assume current volume of ship traffic, shipping lanes, and ship speeds

METHODOLOGY FOR EVALUATING SCENARIOS

SUMMARY

We evaluate the future system response to some of the potential pressures and management actions discussed in the scenarios. Quantitative modeling approaches include spatial analysis using GIS (geographic information systems), single species models, food web models, ecosystem models, and economic input-output analyses. This diversity of approaches is required to address specific aspects of the scenarios; there is no 'silver bullet' model that handles all pressure, drivers, and management actions.

FULL DESCRIPTION OF METHODS

Given the set of links between drivers and pressures described in the scenario narratives, we apply quantitative modeling tools to translate pressures into predicted effects on ecosystem attributes (**Figure MS1**). We tailor the predictions to species and attributes which are relevant to the IEA and for which models could be developed and applied; not all pressures can be logically or quantitatively linked to each attribute. Given the simplicity of quantitative models available for the 2012 Integrated Ecosystem Assessment, in the narratives below we treat drivers separately from one another, even though more complicated scenario planning exercises (e.g. the Millenium Ecosystem Assessment) typically create complicated scenarios that are bundles of drivers, threats, pressures, human decisions, and ecological states. Our goal is to evaluate the future system response to potential pressures and management actions, informed by consideration of drivers on the system.

Quantitative modeling approaches detailed in **Appendices MS1-MS7** range in complexity from spatial analysis using GIS (geographic information systems) up to very detailed modeling of species and fishing fleet dynamics. This diversity of approaches is required to address specific aspects of the scenarios; there is no 'silver bullet' model that handles all pressure, drivers, and management actions.

GIS SPATIAL MODELING

In a first step toward addressing aspects of the **Energy Crunch** scenarios and possible policy responses to **Climate Change**, we use a static, map based approach to consider spatial ramifications of wave energy **(Appendix MS1).** We apply a GIS-based decision-support tool (Marine InVEST, Tallis et al. 2011) to evaluate potential sites for wave energy conversion facilities off the coast of Oregon, and to identify spatial overlap and possible conflicts with other marine uses. Our focus on Oregon is motivated by the availability of data regarding wave energy, power infrastructure, and fishing. The wave energy model consists of three parts: 1) assessment of potential wave power based on wave conditions; 2) quantification of harvestable energy using technology specific information about a wave energy conversion device; and 3) assessment of the economic value of a wave energy conversion facility over its life span as a capital investment. We configure a wave energy facility based on previous work by the Electric Power Research Institute (Previsic, 2004b), which analyzed the system level design, performance, and cost of a commercial size offshore wave power plant installed off the coast of Oregon. Existing marine uses were fishing; transportation and utilities; and marine conservation areas. Spatial fishing effort data for 2002 – 2009 were provided by the At-sea Hake Observer Program and the West Coast Groundfish Observer Program under NOAA's Northwest Fisheries Science Center, Fishery Resource Analysis and Monitoring Division. These data produce a map of different effort levels that can be overlaid with the potential locations of wave energy facilities to reveal possible spatial conflicts. We generated additional maps of possible conflicting uses with the following data. Additional fishing effort maps were provided by Steinback et al. (2010), for several Oregon ports. For transportation, we consider general shipping lanes, and lanes established for tug and barge traffic under on ongoing agreement between tug and barge operators and crab fisherman. For utilities, submarine cable location is identified as recorded on NOAA's Electronic Navigation Charts. Finally, we consider spatial overlap between potential wave energy sites and critical habitat designated for green sturgeon (*Acipenser medirostris*) under the Endangered Species Act, and essential fish habitat conservation areas designated under the Magnuson-Stevens Fishery Conservation and Management Act. Uncertainty is considered primarily at the scenario level, by altering a key variable (cost of transmission cable) that determines the proximity of wave facilities to shore.

SINGLE SPECIES MODEL

Conservation Demand scenarios are likely to be linked to increased desire to recover individual protected species and stocks. Throughout the United States, hundreds of aging and unsafe dams have been removed, including large ones on the Sandy River in Oregon. The largest dam removal to date is in progress on the Elwha River, on the Olympic Peninsula in Washington. This dam removal is expected to increase salmon runs from current levels of several thousand to over one million. There has been considerable interest in removing four dams on the Snake River, but no progress has been made to date. Recently, work has begun to remove four dams on the Klamath River. If implemented, this would represent the largest dam removal in history. We apply a statistical single species population model to evaluate the potential impacts of the removal of the four Klamath River dams (**Appendix MS2)**. The analysis evaluates the impacts of dam removal on Chinook salmon, *Oncorhynchus tshawytscha*. We forecast Chinook abundance and escapement under two alternatives (with and without dam removal) by constructing a life-cycle model composed of: 1) a stock recruitment relationship between spawners and age 3 in the ocean, which is when they are vulnerable to the fishery, and 2) a fishery model that calculates harvest, maturation, and escapement. To develop the stock recruitment relationship under assumptions of no dam removal, we estimated the historical stock recruitment relationship in the Klamath River below Iron Gate Dam in a Bayesian framework. To develop the stock recruit relationship under dam removal, we use the predictive spawner recruitment relationships in

Liermann et al. (2010) to forecast recruitment to age 3 from tributaries to Upper Klamath Lake, which is the site of active reintroduction of anadromy. We also modified the spawner recruit relationship under dam removal to include additional spawning capacity that would be added. In order to facilitate the comparison of the two alternatives, paired Monte Carlo simulations are used to forecast the levels of escapement and harvest with and without dam removal, fifty years into the future. Monte Carlo simulation was used to integrate across the uncertainty in the model parameters, and to translate these into uncertainties in model forecasts.

FOOD WEB AND ECOSYSTEM MODELS

The potential for direct and indirect effects of fishing can be identified using food web models and more detailed spatially-explicit ecosystem models. Such indirect effects of fishing are relevant to the **Human population growth scenario**, with increased demand for new species or lower trophic level species, the **Conservation Demand scenario**, which envisions changes in fishing practice to reduce negative effects on food webs, and the **Status Quo** scenario, that traces direct and indirect effects of the evolution of the groundfish individual quota (catch share) fishery. The simple food web model use here is Ecopath with Ecosim (Christensen and Walters 2004), implemented by Field et al. (2006) for the California Current. The approach begins with a simple mass-balance accounting of production and consumption of species groups (functional groups), linked by diet connections, and projects this forward in time (Ecosim) assuming predator-prey relationships. The ecosystem modeling approach we employ here is Atlantis (Fulton et al. 2011), which embeds a similar food web model in a spatial framework and links it to a physical oceanographic model. We consider two implementations of Atlantis for the California Current, one with finer scale geographic resolution in Central California (Horne et al. 2011; Kaplan et al. 2012), and another (Brand *et al.* 2007a; Kaplan *et al.* 2010) with more uniform geographic resolution that we use to dynamically model fishing fleet dynamics.

We apply Horne and colleagues' (2010) Atlantis ecosystem model and the Ecosim food web model to test the impact that depleting abundant lower trophic level forage groups has on other ecosystem components **(Appendix MS3)**. We then apply a similar approach to test the implications of potential development of new fisheries, including those targeting less abundant species **(Appendix MS4)**. This analysis considers area-specific responses to hypothetical fisheries that would be concentrated in particular parts of the California Current. Given a set of assumptions about future harvests by the groundfish vessels operating under an individual quota system, we then use this Atlantis model to investigate impacts on target and bycatch species biomass and harvest, as well as indirect (food web) effects **(Appendix MS5)**. Finally, we apply the ecosystem model with fleet dynamics to predict the amount and location of groundfishing effort under individual quotas, and to predict the impact on target and non-target species **(Appendix MS6)**. The model considers fishermen's response to quota prices for target and bycatch species, and penalties for exceeding quota. Of these four analyses involving food web and ecosystem models, the first two involve projections fifty years into the future; the other two that include more detailed modeling of fishery targeting are projected for 25 or 30 years. Uncertainty is handled primarily at the scenario level, for instance by defining alternate scenarios for future groundfish catches or for the penalties fishermen expect for exceeding quota. Effects of structural uncertainty (i.e. related to different model forms) are also considered by comparison of the joint application of Atlantis and Ecosim in Appendix MS3.

ECONOMIC INPUT/OUTPUT MODELS

All scenarios considered above will ultimately affect human communities, and here we begin to trace these effects for the portion of the **Conservation Demand scenario** related to Klamath Dam removal, and for the **Status Quo scenario** related to individual quotas (catch shares). After estimating changes in catches and revenues associated with groundfish vessels switching to individual quotas, we apply an input-output model (Leonard and Watson 2011) to estimate how the rest of the US West Coast economy responds to these changes in fishery sector output 1, 5, 10, and 15 years in the future **(Appendix MS5)**. These estimates include direct effects to the fishery sector, indirect effects to industries that supply the fishery sectors, and induced effects related to changes in household spending. Similarly, we apply an input-out model to estimate effects on income and employment over the course of 50 years that derive from changes in salmon harvest in response to Klamath River dam removal **(Appendix MS7)**. Both analyses rely on IMPLAN (Impact Analysis for PLANning, http://implan.com), a commercially available data collection and regional modeling system commonly in use for land and resource management planning. Uncertainty is not handled explicitly in these economic analyses, but uncertainty at the scenario level (related to alternate fishery catches (Appendix MS5) or details of dam removal (Appendix MS2)) are propagated through to the economic model.

SCENARIO ASSESSMENT

SUMMARY

Quantitative analyses based on our scenarios identified the following alternate futures, vulnerabilities, and implications of alternate management decisions in the California Current.

- **The Human Population Growth scenario** can lead to potential increases in wave energy, and increased harvest of lower trophic level species and fishery targeting of new species such as grenadier and croaker. GIS mapping identified potential conflicts between wave energy and other marine uses such as tugboat lanes, sturgeon habitat, and some Oregon fishing ports. Ecosystem models suggest that large increases in harvest of lower trophic levels species (above current levels) would have substantial effects throughout the food web. However, harvest of less abundant species such as grenadier is unlikely to have large-scale effects, except at small spatial scales and for some plankton groups.
- **Climate Change and Energy Crunch scenarios may** also lead to development of wave energy and the potential conflicts listed above. Higher diesel fuel prices in the Energy Crunch scenario also affected profitability of groundfish fleets in the Status Quo scenario.
- **The Conservation Demand scenario** could involve dam removal or reductions in harvest of low-trophic level species. Dam removal on the Klamath River is likely to lead to increases in Chinook salmon abundance, and roughly a 45% increase in fishery revenue and impacts on employment, labor income, and output. Preventing increases in harvest of low-trophic level species, specifically forage fish and euphausiids, benefits their direct predators including fishery target species (in actuality, most forage species are currently unharvested or harvested at minimal rates).
- **The Status Quo scenario** investigated the new groundfish individual quota system. Results suggest that under individual quotas, the groundfish fleet could yield $27-44 million more in revenue and $22-36 million more in total income effects. Increased catches would primarily involve Dover sole and arrowtooth flounder, leading to moderate reductions in abundance of these stocks. Modeling of fleet dynamics under individual quotas suggests that the penalties fishermen expect for exceeding quota have the largest effect on fleet behavior, capping effort and total bycatch. Individual quota systems had high revenue per unit effort, and therefore doubling fuel costs had only moderate 10-14% impacts on net revenue. With alternative management systems (e.g. cumulative landings limits), doubled fuel costs erased all profits in some years.

Note that for these scenarios **Figures MS2-MS6** identify these quantitative analyses (blue), and other research questions for which quantitative analyses are needed (yellow). It is important to note that the scenarios and management actions that are tested in the quantitative analyses range from nearly certain to highly unlikely or illegal, given current legal frameworks and other factors.

DETAILED RESULTS

HUMAN POPULATION GROWTH

We applied quantitative models to consider three aspects of the human population growth scenario: wave energy development, increased harvest of forage fish, and increased harvest of new fishery target species.

Using a GIS-based decision support tool within the InVEST toolkit, we identified three sets of optimal locations for **wave energy facilities in Oregon (Appendix MS1).** Development of such facilities is one avenue to address growing regional populations and power demand. We considered wave energy facilities that connect to the Tillamook, Toledo, and Tahkentich substations of the electrical power grid. Optimal locations were farther from shore in scenarios that assume lower cost of transmission lines. The average distance for the three facilities in each scenario was 16.1, 31.2, and 55.5 kms for the high, medium, and low cost scenario, respectively. There is a strong potential conflict with the tugboat and barge tow lanes for the high cost scenario **(Figure MS7)**. There is also potential conflict with submarine cables connected to the Tillamook area. The locations of some wave energy facilities overlapped green sturgeon critical habitat (**Figure MS8),** particularly in the high cost scenario. For the Pacific groundfish conservation areas, there was an overlap for two of the three facilities in the low cost scenario. The medium cost scenario presented the strongest potential conflict in terms of a wave energy facility interfering with groundfish harvesting. Potential for conflict with particular ports' fishing areas is strongest for the high cost scenario, in which wave energy facilities are closest to shore. The results demonstrate how potential conflicts with existing marine uses can be identified. Simple spatial representations can present planners with a screening tool, identifying areas where a more refined investigation is worthwhile.

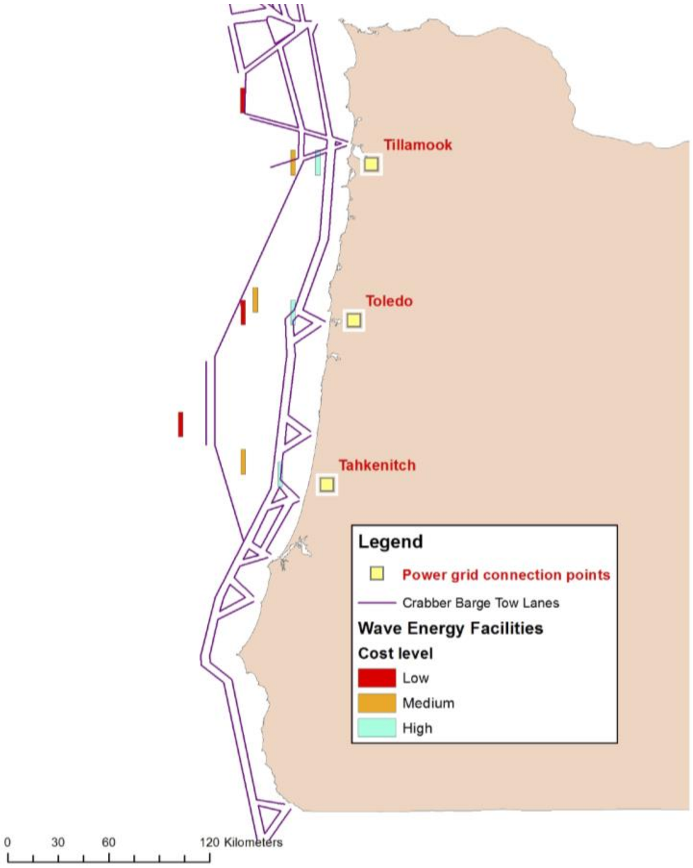

Figure MS7. Sites for potential wave energy facilities, power grid connection points, and barge tow lanes.

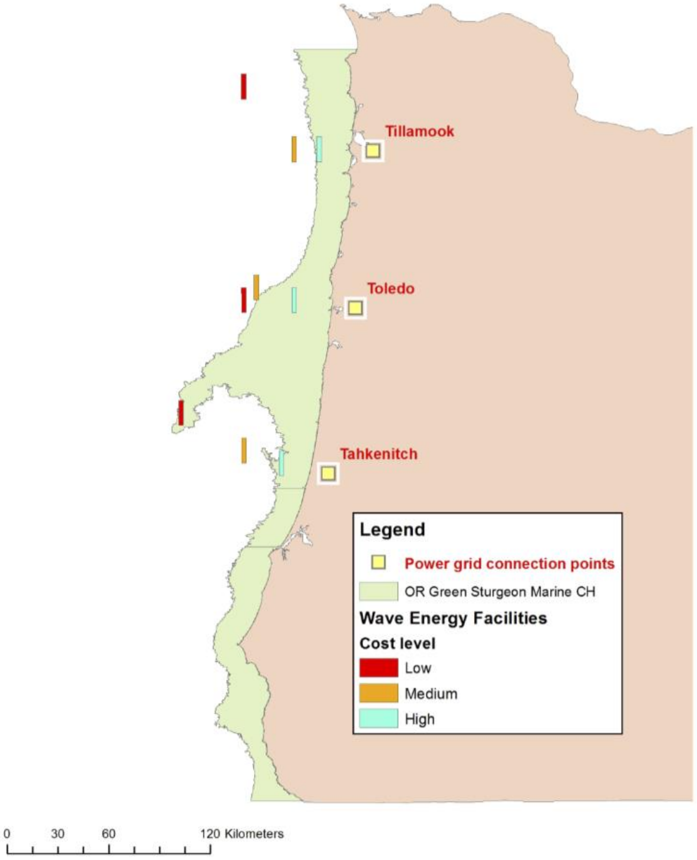

Figure MS8. Sites for potential wave energy facilities, power grid connection points, and green sturgeon critical habitat.

We applied food web and ecosystem models to identify ecosystem-level impacts due to increased demand for, and **depletion of, lower-trophic level forage species (Appendix MS3).** Demand for harvests of forage species will increase due to global increases in population and affluence and associated demand for feed for aquaculture and livestock. Although harvest of many forage species is prohibited within the California Current, using two models we estimated the abundance that would lead to maximum sustainable yield of euphausiids, forage fish, mackerel, and mesopelagic fish (e.g. myctophids), but found that increasing harvests and depleting forage groups to these levels can have both positive and negative effects on other species in the California Current (**Figure MS9**). Though higher trophic level species such as groundfish are often managed on the basis of reference points that can reduce biomass to 40% of unfished levels, scenarios that involved depletion of forage groups to this level commonly led to impacts on predators of forage groups, some of which showed declines of >20%. Depletion of euphausiids and forage fish, which each comprise > 10% of system biomass, had the largest impact on other species. Depleting euphausiids to 40% of unfished levels altered the abundance of 13-30% of the other functional groups by >20%; while depleting forage fish to 40% altered the abundance of 20-50% of the other functional groups by >20%. The results emphasize the trade-offs between the harvest of forage groups and the ability of the California Current to sustain other trophic levels.

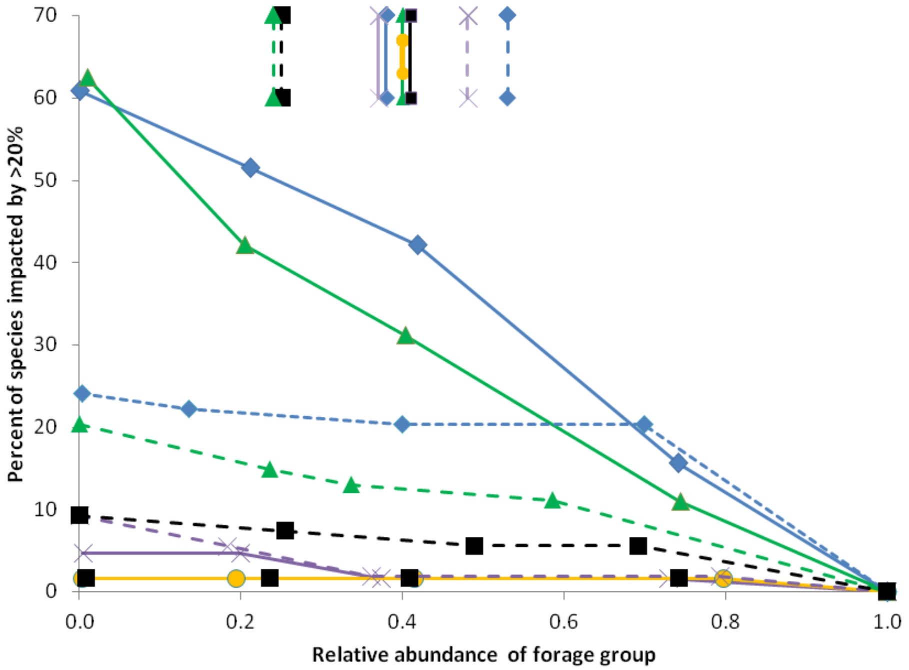

Figure MS9. Percent of species in California Current Ecosim food web model (solid lines) and Atlantis ecosystem model (dashed lines) that exhibit changes in biomass of > 20% (either positive or negative) when forage groups are depleted below unfished levels. A value of 1.0 on the x-axis represents abundance of the forage group when it is not fished, while a value of 0.4 represents depletion of a focal forage group to 40% of unfished abundance. Focal forage groups are as follows: euphausiids -- green triangles; forage fish -- blue diamonds; mesopelagic fish -- purple crosses; mackerel -- black squares; sardines in Ecosim-- orange circles. Vertical lines of the same colors represent abundance of each forage group that leads to maximum sustainable yield in the two models (only position on the x-axis is relevant, y-position is for graphical clarity only).

New fisheries could arise due to global seafood demand. Using a spatially explicit Atlantis ecosystem model, we predicted impacts of three potential fisheries targeting grenadier (Macrouridae), white croaker (*Genyonemus lineatus*), and shortbelly rockfish (*Sebastes jordani*) (Appendix MS4). Unlike the analysis testing effects of depleting more abundant forage species (Appendix MS3), the focus here was on low-biomass species that could arise due to niche markets and new consumer demand, rather than bulk demand for fishmeal. We explored fishing scenarios (fifty year projections) for these groups that resulted in depletion levels of 75, 40, and 25 percent. Results indicate that coast-wide the impacts of developing fisheries on these targets would be relatively small (**Figure MS10**), in terms of impacts on other species and fisheries. The spatial distribution of impacted functional groups was patchy, and concentrated in the central California region of the model. This work provides a framework for evaluating impacts of new fisheries with varying spatial distributions and suggests that regional effects should be evaluated within a larger management context.

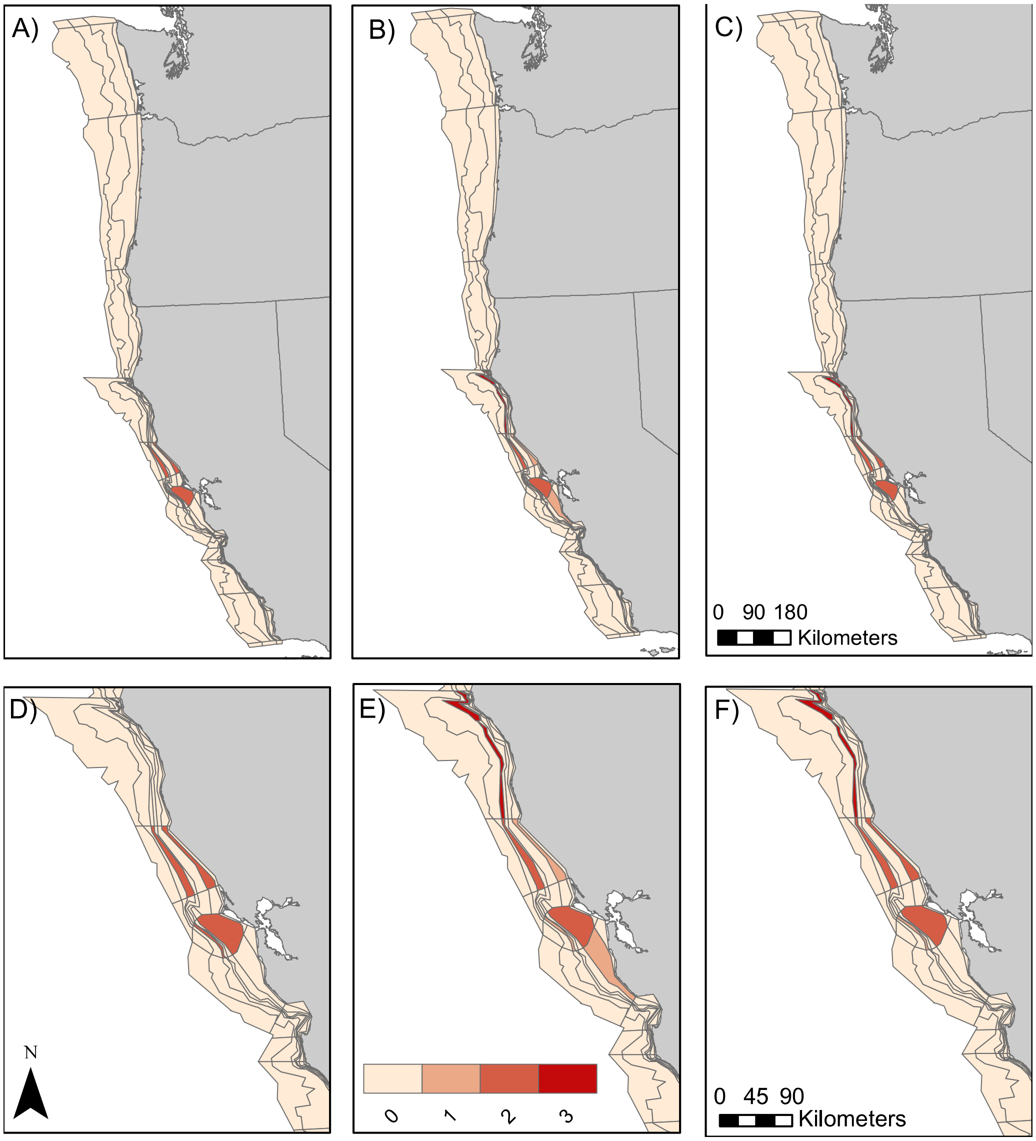

Figure MS10. Number of functional groups affected by a grenadier fishery at three fishing levels (threshold of 10 percent change) by cell. Fishing scenarios represented are F75 (A, D), F40 (B, E), and F25 (C, F). Density of color indicates increasing number of functional groups affected, as indicated by legend.

CLIMATE CHANGE SCENARIO AND ENERGY CRUNCH SCENARIO

One political and economic response to climate change may be a shift to low-carbon power, such as wave energy. Wave energy may also be a response to the energy crunch scenario, which could prompt investment in new energy sources. As noted above, we identified three sets of optimal locations for wave energy facilities in Oregon (Appendix MS1), but also identified potential conflicts with sectors such as tugboat lanes, sturgeon critical habitat, and fishing areas. The total MwH/yr captured by all three facilities would be 3564, 3462, and 3324 MwH/yr for the low, medium, and high cost scenarios, respectively. The average energy captured per device also increases as lower transmission costs are assumed, which corresponds to the higher wave energy potential further offshore along the Oregon coast.

Climate change is also likely to impact small pelagic fish such as sardine and anchovy, and anadromous species such as Chinook salmon. Two avenues for research are discussed in Boxes MS1 and MS2.

Box MS1.

Analyses already exist that predict the response of particular runs of Chinook salmon to climate, and these approaches can be developed further for the IEA. Spring/summer Chinook have been shown empirically to be vulnerable to water temperature and streamflow (Crozier and Zabel 2006), and population models of Snake River and Snohomish River Chinook have been linked to downscaled global circulation models that include climate change (Battin *et al.* 2007; Crozier *et al.* 2008). Additional downscaling of climate models to predict hydrology for broad regions, and applications to multiple salmon populations may allow an analysis of climate change at a larger scale. Climate change effects will not occur in isolation from other drivers such as population growth: streamflow will also be influenced by land use change (Battin *et al.* 2007) and human demand for water, due to predicted 50% increases in population growth over 50 years (Bierwagen 2009).

The groundfish management system is likely to influence the vulnerability of fisheries profits to energy prices (**Figure MS11**). Modeling of the groundfish fleet under the new individual quota system predicts substantial reductions in effort as compared to the previous cumulative landings limit system (Appendix MS6). Gross revenue declines only slightly under individual quotas as compared to landings limits, and net revenues (after variable costs such as fuel, and fixed costs) are typically higher under individual quotas. Our simulations assumed fuel to be $3/gallon; diesel fuel prices for West Coast states averaged $3.64-$3.72 in August 2012 (http://www.psmfc.org/efin). Assuming $6/gallon fuel heavily penalizes the scenario with high fishing effort (cumulative trip limits): for some years fuel costs erase all profits under cumulative landings limits. In our 30 year model projections, individual quota systems have higher revenue per unit effort and therefore fuel costs have only moderate 10-14% impacts on net revenue (profits).

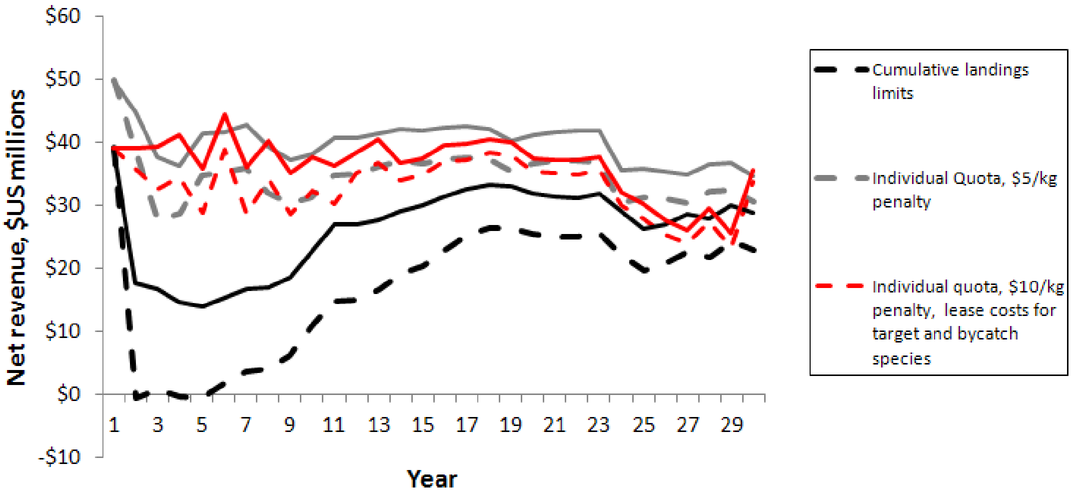

Figure MS11. Net revenue for West Coast groundfish fleets over 30 years. Solid lines denote fuel at $3/gallon, dashed lines at $6/gallon. This simple metric of net revenue is gross revenue minus fixed costs (excluding capital costs) and variable costs (fuel, ice, and food, but not labor or quota costs). Details as in Appendix MS6, except that annual net revenue calculation includes adjusted variable costs to include $6 fuel. Colors denote options for the management system: black = cumulative landings limits in place prior to 2011; grey = individual quotas with no lease price and low penalties for exceeding quota; red = individual quotas with higher lease costs and penalties.

CONSERVATION DEMAND

The Conservation Demand scenario envisions increased public and political desire for species recovery and ecosystem health. Here we evaluate two facets of that: effects of dam removal, and effects of restricting harvest of forage fish.

We evaluated the impact of **Klamath River dam removal on Chinook salmon (Appendix MS2),** projecting population dynamics for the period from 2012 to 2061. Median escapements and harvest were higher under dam removal than with no action (**Table MS1**), though there was a high degree of overlap in 95% confidence intervals due to uncertainty in stock-recruitment dynamics. Still, there was a 0.75 probability of higher annual escapement and a 0.7 probability of higher annual harvest by performing dam removal relative to no action, despite uncertainty in the abundance forecasts. The median increase in escapement in the absence of fishing was 81%, the median increase in ocean harvest was 47%, and the median increase in tribal harvest was 55% under dam removal relative to no action.

Table MS1. Percent increase in abundance and harvest due to performing dam removal versus no action, for two time periods: 1) prior to dam removal (2012 – 2019); and after removal of dams and cessation of active reintroduction and production of the Iron Gate Hatchery production (2030-2061). "95% CrI" is 95% credibility interval.

	2012 – 2020		2033-2061	
Metric	**Median**	**95% CrI**	**Median**	**95% CrI**
Escapement in the Absence of Fishing	11%	-80%, 493%	81%	-60%, 881%
Lower Basin Escapement	0%	-72%, 386%	9%	-76%, 490%
Ocean Commercial Harvest	9%	-87%, 836%	47%	-69%, 1495%
Ocean Recreational Harvest	9%	-87%, 836%	47%	-69%, 1495%
River Harvest	0%	-92%, 1520%	9%	-77%, 2754%
Tribal Harvest	10%	-89%, 1010%	55%	-71%, 1841%

Based on these projections for Chinook salmon harvest, we estimated annual changes in fishery revenue likely to derive from **Klamath dam removal, and applied an input-out model to estimate effects on income and employment (Appendix MS7**). Higher abundance of Klamath River Chinook due to dam removal would allow more fishing on all Chinook stocks south of Cape Falcon Oregon, since harvest of all stocks in this broader region has been limited by low abundance of Klamath Chinook. We estimated $17.1 million in annual troll fishery revenue without dam removal, and a 43% increase to $24.4 million with dam removal. Impacts in the broader economy include an additional $8.9 million annually in gross revenue, distributed across five management regions. For San Francisco, Fort Bragg and Central Oregon, annual impacts (depending on the area) include an additional 69 to 218 jobs, an additional $1.05 million to $2.56 million in labor income, and an additional $2.41 million to $6.6 million in output. For the Klamath Management Zones in California and Oregon, the annual impacts include an additional 11 to 19 jobs, an additional $0.06 million to $0.07 million in labor income, and an additional $0.13 million to $0.19 million in output.

Conservation demands may lead to reductions in existing harvest of forage groups. As mentioned above, we applied food web and ecosystem models to identify ecosystem-level impacts due to **a range of potential harvest rates for lower-trophic level forage species (Appendix MS3)**. Though higher trophic level species such as groundfish are often managed on the basis of reference points that can reduce biomass to 40% of unfished levels, we found that depleting forage groups to this level could have large effects on other species in the food web, with up to half of all species responding by >20%. These responses were strongest for euphausiids and forage fish, which are highly abundant and are common diet items for predators. Conservation demand scenarios to restrict harvest of these forage groups would primary benefit their direct predators, including target fish species. Caveats include the simulation of coast-wide harvests, the aggregation of multiple species into functional groups, and the testing of a broad range of harvest rates, including rates that exceed current levels and legal limits. Other ongoing efforts (**Box MS2**) will have finer taxonomic and spatial resolution, and will also link to climate and oceanography models.

Box MS2.

An extensive collaboration between multiple researchers* has been developing a new type of model that may capture the dynamics and climate response of forage species such as California Current sardine and anchovy. For such species, managers are increasingly being asked to quantify fishing effects at the ecosystem level, present fishing impacts relative to other factors such as environmental conditions, and to project fishing effects under future, previously unobserved, conditions such as climate change. These activities require models that represent ocean circulation, lower trophic levels, a fish food web, and fishing dynamics in sufficient detail to allow for fishing to respond to changing conditions and to account for both direct and indirect effects of fishing.

Recently, advances in physics and biology have made possible end-to-end (climate-to-fish-to-fishers) ecosystem models, including fishing (humans) as a dynamical component. Our group has been developing one such end-to-end model within the widely-used ROMS (Regional Ocean Modeling System) circulation model. The concentration-based NEMURO (Nutrient-Phytoplankton-Zooplankton-type) submodel provides lower trophic level dynamics, including multiple nutrients, two phytoplankton and three zooplankton fields. A multi-species, individual-based, full life cycle submodel simulates fish population and community dynamics, including fishing fleets as one of the predator species. Our preliminary version focuses on anchovies and sardines in the California Current System. Using a 10-km resolution ROMS model, we have demonstrated proof-of-concept, how the multiple submodels can be integrated simultaneously for a multi-decadal historical simulation (1958-2006).

***Contributors**
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Pacific sardine photo courtesy of Tewey, Monterey Bay Aquarium

STATUS QUO

In our Status Quo scenario, we assume that drivers and pressures will continue at current rates or trends. However, even assuming that most other aspects of the system do not change, we expect rapid human responses to individual quotas (catch shares), the current management framework for groundfish fleets. The Pacific Fisheries Management Council implemented this individual transferrable quota (ITQ) system in 2011 for the West Coast groundfish trawl fleet. Under the ITQ system, each vessel now receives transferable annual allocations of quota for 29 groundfish species, including target and bycatch species.

Individual quotas and the new incentives they present are likely to cap most bycatch, while leading to increases in catch of target species (particularly flatfish) through changes in gear, location and timing of fishing. As part of previous work, Pacific Fishery Management Council staff developed several projections for fishery catch under varying assumptions about improvements in targeting accuracy under an **individual quota sytem. In Appendix MS5, we apply these catch projections** in 25 year simulations and find that target species in the California current responded directly to the imposed fishing mortality rates. Indirect (trophic) effects were minor and typically involved response of less than 10%. Relative to pre-catch share conditions, the scenarios suggest improved targeting by the groundfish fleet could yield $27-44 million more in revenue to the fishery sectors (dockside value). At the scale of the broader West Coast economy, the IO-PAC input/output model suggests this may translate into $22-36 million more in total income, which includes employee compensation and earnings of business owners (**Figure MS12**).

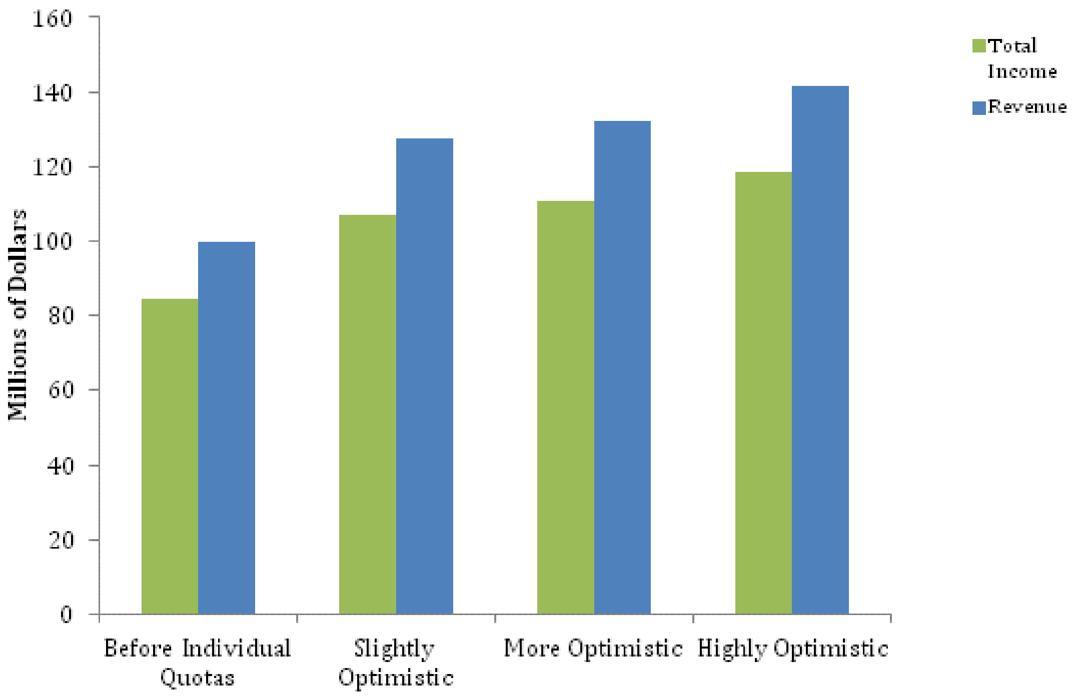


Figure MS12. Revenue in fishery sectors, and income effects in the broader West Coast economy. Year 1 predictions. Total income and revenue are represented by bars in millions of dollars (left axis). "Slightly optimistic" scenarios for individual quotas assume moderate increases in target species catch and little change in rockfish bycatch, while "Highly optimistic" scenarios for individual quotas assume large increases in target species catch with little change in rockfish bycatch.

Fishermen's response to individual quotas is likely to evolve as a function of quota costs, enforcement, penalties for exceeding quota, initial quota allocation, and captains' ability to target particular species. We simulated **fleet dynamics under an individual quota system (Appendix MS6**)and found that in the absence of penalties for discarding over-quota fish, removing constraints related to the previous management system (per-vessel landings limits) led to large increases in fishing effort and bycatch. The penalties fishermen expected for exceeding quota had the largest effect on fleet behavior, capping effort and total bycatch. Quota prices for target or bycatch species had lesser impacts on fishing dynamics, even up to bycatch quota prices of $50/kg. Ports that overlapped less with bycatch species could increase effort under individual quotas, while other ports decrease effort. Relative to a prior management system, ITQs with penalties for exceeding quota led to increased target species landings and lower bycatch, but with strong variation among species. In addition to providing insights into how alternative fishery management policies affect profitability and sustainability, the model illustrates the wider ecosystem impacts of fishery management policies.

Combining some aspects of the Energy Crunch and Status Quo scenarios, we considered the potential impacts of spatial closures due to wave energy facilities in Oregon (**Appendix MS1**) on groundfish fleet dynamics (**Appendix MS6**). Resulting fleet effort and catch were predicted to vary by less than 1% due to these simulated closures. The four model regions off the Oregon coast are large relative to the size of these facilities (only 72 km^2 total), and closures would not exceed 2% of each region (**Table MS2**). Note that this fleet dynamics modeling is indicative of overall patterns at a fairly coarse spatial scale, and the finer scale GIS analysis (**Appendix MS1**) indicates potential conflicts for particular ports and gears.

Table MS2. Percent of each model polygon closed to groundfish fleets, assuming establishment of three wave energy facilities per cost scenario, with each facility closing fishing in an area 12km N-S and 2km E-W . Each model polygon spans most of the Oregon coast in the N-S direction, and is defined by depth contours indicated in the column headings.

	Oregon coast, from Columbia River to Cape Blanco Region:			
Cost scenario	**50-100m**	**100-150m**	**150-200m**	**200-550m**
Low	0.0%	1.0%	1.0%	0.2%
Medium	0.0%	0.8%	1.7%	0.0%
High	1.3%	0.6%	0.0%	0.0%

“NATURAL” ECOSYSTEM COMPONENTS ACROSS SCENARIOS

SUMMARY OF NATURAL COMPONENTS: PROTECTED SPECIES AND ECOSYSTEM INTEGRITY

The quantitative analyses do not predict how all attributes of the California Current system might respond to our scenarios, but they do make the following predictions regarding natural components:

- **Human Population Growth scenario:** Wave energy facilities built in response to increased demand for power could impact green sturgeon habitat. Increased consumer demand for trawl-caught species could lead to increased take of Steller sea lions and California sea lions. Models predict only modest indirect changes on the food web and ecosystem structure in response to three potential new fisheries. Large increases in harvest of forage species (above current levels) may restructure energy pathways related to alternate forage groups, such as copepods.
- **Climate Change and Energy Crunch scenario:** As above, wave energy facilities built to produce low-carbon power or to meet increased energy demand may impact green sturgeon habitat.
- **Conservation Demand scenario:** Dam removal on the Klamath River could increase Chinook salmon abundance. In future research, this model prediction can be compared to ongoing monitoring in the Elwha River basin, where 2 large dams have almost entirely removed. A separate food web model analysis of the California Current predicts that limiting harvest of forage species (e.g. sardine and euphausiids) to low catch levels may benefit some protected species such as seabirds and mammals; however, an ecosystem model predicts little response of protected species at the coast-wide level.
- **Status Quo:** The groundfish individual quota system includes mechanisms to reduce bycatch of rockfish and encourage their recovery; enforcement of target species quotas are the strongest such mechanism. Increased harvests of groundfish under the individual quota system could lead to increased take of Steller sea lions and California sea lions. Models predicted that at a coast-wide level, strong impacts on the food web and ecosystem typically occur at high benchmark fishing mortality rates, which exceed both current harvest rates and legal limits on catch.

PROTECTED SPECIES

In the **Human Population Growth**, **Energy Crunch**, and **Climate Change** scenarios, wave energy facilities are likely to overlap critical habitat for green sturgeon (**Appendix MS1**). The severity of the impact on sturgeon habitat is not known, but the spatial modeling suggests that if high electricity transmission costs force wave energy to be sited near shore, there is potential for overlap between sturgeon habitat and wave energy arrays.

Conservation Demand scenarios leading to dam removal on the Klamath River would increase abundance of Chinook salmon (**Appendix MS2**). Were the Klamath River dams removed, the adult salmon returned would increase by around 80% for the period 2030-2061. Lower Klamath basin escapement (returns after fishing) would be 9% higher. The analysis does not consider the effects on other anadromous species that might benefit from dam removal.

Restoring access of anadromous species such as salmon to historical spawning grounds, as discussed here for the Klamath River system, will become more common in the future. This is because many dams that block anadromous access are aging and removing them is often a more cost effective and straightforward solution than trying to repair or refurbish them. Actual dam removal in the Klamath River system will likely require years due to such issues as funding and permitting. Thus, being able to compare model predictions of the response of anadromous species with monitoring data will require decades. However, model predictions for the Klamath can be compared to results of ongoing monitoring from the Elwha River basin, where two large dams have almost entirely been removed. Predictions of the abundance, species composition, spatial distribution, and diversity of anadromous species at various intervals following dam removal have been made and will be compared to the actual response of anadromous species, ultimately improving predictions for other rivers such as the Klamath.

The **Human Population Growth** and **Conservation Demand scenarios** considered indirect (food web) effects that would result from depleting forage groups (**Appendix MS3**). However, the impacts on protected species are equivocal, with Ecosim predicting more dynamic responses (as was typical in these model comparisons). Ecosim food web modeling predicted that depletion of forage fish would negatively impact some seabirds and marine mammals. However, the Atlantis ecosystem model did not predict strong declines in marine mammals or birds due to forage fish depletion. The Ecosim food web modeling predicted that depletion of euphausiids would lead to a shift in production towards copepods and micro-zooplankton, with subsequent increases in bird groups. The Atlantis model similarly predicted that euphausiid depletion would shift production toward copepods, but two protected groups groups (baleen whales and surface seabirds) that depend heavily on ephausiids had only slight declines (10% or less).

Direct impacts on protected species would also result from changes in groundfish landings. The **Status Quo scenario** included increases in landings of flatfish (**Appendix MS5**), which are likely to be associated with increased fishing effort by the groundfish trawl fleet. In the **Human Population Growth scenario**, increased harvest of grenadier (**Appendix MS4**) would also most likely involve groundfish trawl gear, with its associated bycatch of protected species. Jannot et al. (2011) estimated bycatch of marine mammals, seabirds, and sea turtles by groundfish gears for the years 2002-2009. Of all the species in these groups, California sea lions had the highest estimated bycatch, with estimated coastwide totals between 10 and 116 animals per year, with the majority of observations occurring in groundfish trawl fisheries. Steller sea lions were caught in smaller numbers, with estimated bycatch totals of 0-17 animals per year. Very few seabirds and turtles have been observed as bycatch in groundfish trawl fisheries.

Estimating the change in bycatch levels associated with increased landings depends on the spatial and temporal distribution of fishing effort and the specific fishing method. Furthermore, changes in bycatch rates that may have occurred after the implementation of the catch share system in 2011 are not reflected in the data analyzed by Jannot et al. (2011). Thus, specific estimates of increases in bycatch of sea lions or any other protected species are difficult. In the projections considered here to represent harvests under an individual quota system (**Appendix MS5**), the multipliers on fishing mortality were in the range 1-4. These values probably represent upper bounds on the increase in bycatch of protected species under these catch projections. However, the coastwide effort for many fully exploited species is not expected to increase under these scenarios, so the maximum increase in coastwide bycatch of any species is likely to be much smaller than four-fold.

The **Human Population Growth scenario** led to investigation of the impacts of new fisheries and their potential ecosystem-level effects (**Appendix MS4**). Generally, the potential fisheries considered – grenadier, croaker, and shortbelly rockfish – would harvest low amounts of biomass, and the trophic effects of these were minimal at the coastwide scale. Food web response tended to involve plankton species such as copepods, microzooplantkon, dinoflagellates, and phytoplankton, and to be concentrated in Central California.

The **Human Population Growth** and **Conservation Demand scenarios also** considered the effect on food web structure of depleting more abundant forage groups such as euphausiids (krill), mackerel, myctophids (lantern fish), and small pelagic fish (**Appendix MS3**). Two contrasting modeling approaches, Atlantis and Ecosim, both found that harvest of these forage species can have positive as well as negative effects on other species in the California Current. The most common impacts were on predators of forage groups, some of which showed declines of >20% under the scenarios that involved depletion of forage groups to typical single-species management targets. Depletion of euphausiids and forage fish, which each comprise > 10% of system biomass, had the largest impact on other species, restructuring the food web to follow energy pathways related to alternate lower-trophic level groups.

Ecosim food web modeling predicted that predators, including large piscivores (salmon, sharks, sablefish *Anoplopoma fimbria*), seabirds and marine mammals would decline in response to the depletion of forage fish. However, the model also predicted a restructuring of food web energy flow towards zooplankton: depletion of forage fish released euphausiids and copepods from predation pressure, resulting in increased abundance of those groups. This in turn provided more prey for higher trophic levels, many of which increased in abundance. The Atlantis model also predicted an increase in abundance of euphausiids in response to forage fish depletion. Unlike the Ecosim predictions, the Atlantis modeling did not predict strong declines in marine mammals or birds due to forage fish depletion.

The Ecosim food web modeling predicted that depletion of euphausiids would lead to a shift in production towards copepods and micro-zooplankton, with subsequent increases in forage fish and their predators, including several flatfish and bird groups and black rockfish (*Sebastes melanops*). The Atlantis model predicted that euphausiid depletion would cause a shift in production toward copepods, but that euphausiid removal would cause moderate declines (>20%) in many mid-trophic level groups, primarily predators on euphausiids. Euphausiid depletion also led to declines of 10% or less for two protected groups (baleen whales and surface seabirds), an overfished rockfish functional group (yelloweye and cowcod), as well as small demersal sharks and midwater rockfish.

The **Status Quo scenario** related to individual quotas for groundfish fleets caused extensive effects on the ecosystem (food web structure) only when fishing effort was allowed to rise to very high levels. In hypothetical benchmark simulations that lacked caps on effort and bycatch (**Appendix MS6**), abundance of targets species such as sablefish and large flatfish and bycatch species such as Pacific Ocean Perch and darkblotched rockfish declined. In these same benchmark simulations, over-fishing of piscivores led to a release of forage groups (small planktivores, deep vertically migrating fish, cephalopods, and nearshore fish). Thirty to sixty percent increases in these forage groups led to 10-50% increases in bird and pinniped abundance under these scenarios, since birds and mammals also consume forage species such as sardines and squid. Two highly productive invertebrate groups, shrimp and meiobenthos (flagellates, ciliates, nematodes) also responded indirectly to these benchmark ITQ cases. These benchmark high fishing mortality rates were required for two ecosystem models (Brand *et al.* 2007b; Horne *et al.* 2010) to predict strong indirect (trophic) effects on the food web. Applying projections of catch under individual quotas, we found that functional groups that were not subject to increased fishing pressure in the catch share scenarios did not deviate more than 10% from status quo (**Appendix MS5**). Increases in groundfish catch caused slight increases (<6%) of three invertebrate prey groups, which ultimately led to minor increases (<10%) for some pelagic predators such as sharks and mackerel.

HUMAN WELL-BEING ACROSS SCENARIOS

SUMMARY

We have identified which ports and communities are most likely to gain or lose economic activity under these scenarios, and where possible have translated these to revenue, income, and employment both in fishery sectors and in the broader economy:

- Scenarios that involve wave energy development involve increases in non-fishery revenue near electrical substations (**e.g. Tillamook and Toledo**), but potential fishery losses for communities such as **Newport and Astoria.**
- Scenarios that vary the harvest of small pelagic fish have the strongest effects on revenue in **Central and Southern California ports.**
- Potential increase in demand for new species can lead to small but concentrated increases in fisheries revenue. For instance, increased landings of shortbelly rockfish could provide a boost **($~1 million in revenue**) to the relatively small fishing communities of **Central California**.
- Klamath River dam removal would cause a **42-44% increase in fishery revenue and resulting employment and income** in the broader economy. For San **Francisco, Fort Bragg and Central Oregon**, annual impacts (depending on the area) include an additional **69 to 218 jobs**, an additional **$1.05 million to $2.56 million in labor income,** and an additional **$2.41 million to $6.6 million in output.**
- The groundfish trawl fleet and associated processors and wholesalers, which are most concentrated in **Oregon and Northern California**, are projected to see long-run increases in revenues of **$27-44 million**. At the scale of the broader West Coast economy, the economic model suggests this may translate into **$22-36 million more in total income.**
- **Under individual quotas for groundfish, fleets that cannot stay below quotas are likely to reduce fishing effort and revenue**. In these simulations, Moss Landing, Fort Bragg, Eureka, and Coos Bay increase effort and landings, while northern fleets are more likely to cut effort. **Individual quotas have high revenue per unit effort**, and have fishery profits that are less vulnerable to increased **fuel costs**.

HUMAN WELL-BEING

Though detailed predictions related to human well-being are still in development, we can begin to identify which ports and communities are most likely to gain or lose economic activity under these scenarios. Future analyses for the IEA will build on this to predict two aspects of human well-being, resilience and vulnerability, in response to changes in port-level fishery activity and income (Jacob et al. (2012), see **Box MS3**).

Under **Human Population Growth**, **Climate Change** and **Energy Crunch** scenarios, non-fishery economic activity in Oregon is expected to increase near the Tillamook, Toledo, and Tahkentich (near Reedsport) power substations. The wave energy facility siting exercise **(Appendix MS1)** considered relatively small-scale arrays, but noted that any future wave energy sites must be near these existing substations to connect to the electrical grid. Potential fishery losses might occur for the Newport fleet, based on spatial overlap with wave energy sites, and based on the large proportion of Newport revenue from groundfish fleets (**Tables MS2-MS3**). Other Oregon fleets, such as Astoria (**Tables MS2-MS3**), that harvest groundfish may also lose revenue depending on spatial overlap of fishing areas with wave energy sites.

Table MS2: For 2006-2010, the proportion of each portgroup's revenue derived from each species or species group. From PacFIN landings database.

PORTGROUP NAME	PACIFIC WHITING	GROUNDFISH TRAWL	GROUNDFISH NONTRAWL	SALMON	CRAB	SHRIMP	SHELLFISH	PELAGICS	HIGHLY MIGRATORY	OTHER	PORTGROUP AVG. ANNUAL REVENUE ($1000s)
BELLINGHAM	0%	4%	7%	21%	35%	3%	14%	0%	1%	14%	$ 54,977
SEATTLE	0%	0%	0%	25%	4%	1%	67%	1%	0%	2%	$ 33,995
WESTPORT	10%	2%	4%	8%	51%	5%	1%	2%	15%	2%	$ 48,185
ILWACO	3%	0%	7%	14%	32%	2%	0%	1%	37%	2%	$ 18,823
OTHER WASHINGTON	0%	0%	0%	29%	29%	0%	37%	0%	0%	5%	$ 796
ASTORIA	7%	22%	2%	10%	24%	6%	0%	15%	11%	2%	$ 33,901
GARIBALDI	0%	1%	5%	7%	72%	6%	2%	0%	8%	0%	$ 3,274
NEWPORT	10%	12%	8%	2%	44%	9%	0%	0%	13%	2%	$ 31,541
CHARLESTON	2%	18%	7%	2%	43%	16%	0%	0%	10%	3%	$ 22,907
BROOKINGS	0%	16%	23%	2%	52%	4%	0%	0%	1%	2%	$ 9,599
CRESCENT CITY	2%	6%	5%	0%	80%	5%	0%	0%	1%	0%	$ 14,542
EUREKA	2%	26%	5%	1%	58%	1%	0%	0%	3%	3%	$ 13,297
FORT BRAGG	0%	30%	17%	12%	17%	0%	0%	0%	1%	22%	$ 7,037
BODEGA BAY	0%	2%	3%	18%	73%	0%	0%	0%	0%	3%	$ 4,949
SAN FRANCISCO	0%	9%	4%	5%	64%	2%	0%	4%	4%	8%	$ 12,726
MOSS LANDING	0%	7%	10%	3%	6%	5%	0%	64%	2%	3%	$ 8,791
AVILA	0%	4%	65%	1%	7%	6%	0%	1%	8%	8%	$ 3,784
SANTA BARBARA	0%	0%	2%	0%	4%	4%	0%	62%	1%	27%	$ 35,356
TERMINAL ISLAND	0%	0%	3%	0%	1%	3%	0%	75%	3%	15%	$ 30,623
OCEANSIDE	0%	0%	11%	0%	2%	7%	0%	0%	19%	60%	$ 6,480
OTHER CALIFORNIA	0%	0%	0%	0%	1%	5%	0%	0%	0%	93%	$ 53
OFFSHORE	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	$ 23,046
SPECIES GROUP SHARE OF ANNUAL REVENUE	8%	7%	6%	8%	30%	4%	8%	14%	7%	8%	$ 418,683

Table MS3: For 2006-2010, the proportion of revenue derived from each species or species group that is landed in each portgroup. From PacFIN landings database.

PORTGROUP NAME	PACIFIC WHITING	GROUNDFISH TRAWL	GROUNDFISH NONTRAWL	SALMON	CRAB	SHRIMP	SHELLFISH	PELAGICS	HIGHLY MIGRATORY	OTHER	PORTGROUP SHARE OF TOTAL REVENUES
BELLINGHAM	0%	8%	17%	34%	16%	8%	25%	0%	2%	23%	13%
SEATTLE	0%	0%	0%	25%	1%	1%	73%	0%	0%	2%	8%
WESTPORT	14%	3%	9%	11%	19%	12%	1%	2%	25%	3%	12%
ILWACO	2%	0%	6%	8%	5%	2%	0%	0%	24%	1%	4%
OTHER WASHINGTON	0%	0%	0%	1%	0%	0%	1%	0%	0%	0%	0%
ASTORIA	7%	26%	3%	10%	6%	12%	0%	9%	12%	2%	8%
GARIBALDI	0%	0%	1%	1%	2%	1%	0%	0%	1%	0%	1%
NEWPORT	9%	13%	11%	2%	11%	15%	0%	0%	14%	2%	8%
CHARLESTON	1%	14%	7%	1%	8%	20%	0%	0%	7%	2%	5%
BROOKINGS	0%	5%	9%	1%	4%	2%	0%	0%	0%	1%	2%
CRESCENT CITY	1%	3%	3%	0%	9%	4%	0%	0%	1%	0%	3%
EUREKA	1%	12%	3%	0%	6%	1%	0%	0%	1%	1%	3%
FORT BRAGG	0%	7%	5%	2%	1%	0%	0%	0%	0%	5%	2%
BODEGA BAY	0%	0%	1%	3%	3%	0%	0%	0%	0%	0%	1%
SAN FRANCISCO	0%	4%	2%	2%	7%	1%	0%	1%	2%	3%	3%
MOSS LANDING	0%	2%	4%	1%	0%	2%	0%	10%	1%	1%	2%
AVILA	0%	0%	10%	0%	0%	1%	0%	0%	1%	1%	1%
SANTA BARBARA	0%	0%	3%	0%	1%	8%	0%	38%	2%	28%	8%
TERMINAL ISLAND	0%	0%	4%	0%	0%	5%	0%	40%	4%	14%	7%
OCEANSIDE	0%	0%	3%	0%	0%	3%	0%	0%	4%	12%	2%
OTHER CALIFORNIA	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
OFFSHORE	65%	0%	0%	0%	0%	0%	0%	0%	0%	0%	6%
TOTAL AVG. ANNUAL REVENUE ($1000s)	$ 35,310	$ 28,577	$ 24,017	$ 34,482	$ 125,570	$ 18,685	$ 31,614	$ 57,663	$ 29,502	$ 33,262	$ 418,683

Our ability to quantify fishery economic effects on communities varies across modeling approaches due to differences in the spatial resolution of predicted landings. In some cases the quantitative analyses are at the port or local level; in other cases the analyses provide a rough idea of what gears harvest the catches but we do not attempt to explicitly model fleet dynamics and landings spatially. When we couple these catch projections with recent price data and information about the recent magnitude and distribution of revenues across species groups and port groups (**Tables MS2 and MS3,** taken from PacFIN landings database**),** we can, in some cases, draw at least qualitative conclusions about relative economic impacts on groups of fishing communities (grouped by port groups) along the coast.

Human Population Growth scenarios are likely to shift the regional flow of fishery revenues to particular ports. The analysis of development of new fisheries for grenadier (Macrouridae), white croaker (*Genyonemus lineatus*), and shortbelly rockfish (*Sebastes jordani*) (**Appendix MS4**) predicts sustainable yield coastwide yields and suggests a potential distribution of catches based on the distribution of the respective fish stocks. If catches rose to sustainable yield predictions of 2055, 2000 and 675 metric tons respectively for grenadier, white croaker and shortbelly rockfish this would translate into gross revenues of $720 thousand, $2.4 million and $965 thousand respectively, based on average prices for these species between 2006 and 2010. Grenadier and white croaker are widely distributed along the coast, so we might expect landings and revenues to be spread widely as well, and the economic impacts on any specific community are unlikely to be large. Shortbelly rockfish are more concentrated in central California, and, were new landings to also concentrate there, they might provide a boost to the relatively small fishing communities there. While $965 thousand is only a small fraction of overall fishery revenues for central California, it represents a significant increase in groundfish revenues (e.g. groundfish revenues for the Bodega Bay, San Francisco and Moss Landing port groups average less than $6 million a year, **Tables MS2-3**). Increased revenue and catches of forage species (**Appendix MS3**) such as Pacific sardine and mackerel would be expected to accrue mainly to fleets operating out of central and southern California that dominate landings for small pelagics (**Tables MS2-MS3**).

Aspects of the **Conservation Demand scenario** identify ports and regions that could be affected by alterations to salmon harvest and purse seine fisheries. As noted above, central and southern California ports would experience changes in revenue and landings due to declines in forage fish (small pelagic species) harvest. Increased abundance of Chinook salmon associated with removal of the Klamath River dams **(Appendix MS2)** would cause a 42-44% increase in fishery revenue and resulting employment and income in the broader economy of San Francisco, Fort Bragg, Central Oregon, and the Klamath Management Zone (Humboldt and Del Norte Counties in California and Curry County Oregon**, Appendix MS7**). The additional $8.9 million in gross revenue in these areas generates regional impacts that vary widely by area. For San Francisco, Fort Bragg and Central Oregon, annual impacts (depending on the area) include an additional 69 to 218 jobs, an additional $1.05 million to $2.56 million in labor income, and an additional $2.41 million to $6.6 million in output. For the Klamath Management Zones, the annual impacts include an additional 11 to 19 jobs, an additional $0.06 million to $0.07 million in labor income, and an additional $0.13 million to $0.19 million in output. The size of these communities and reliance on fishing might influence the effect on human wellbeing; for instance, after dam removal the largest employment effect was 218 jobs related to the San Francisco fishery, but this may have lower effect on human wellbeing than smaller employment gains in communities more reliant on fishing (e,g, 69 jobs in Fort Bragg).

Explorations of **Status Quo** management related to the evolution of fishery individual quotas point to potential benefits to groundfish fleets, but with an uneven spatial distribution. Catch projections similar to what may be expected under the new individual quota system (**Appendix MS5**) could result in up to $44 million more in fishery sector revenue. The projections assume constant harvests and would require development of markets that can absorb higher landings, particularly of Dover sole. The projections of revenues and income from this analysis are not spatially specific. However, assuming they accrue to different port group regions in proportion to revenues from the respective gear groups (**Tables 2 and 3**), we can gain a rough idea of how impacts might be distributed. The groundfish trawl fleet, for which revenues are most concentrated in Oregon and Northern California, is projected to see long-run increases in revenues of 34-46%. The fixed gear groundfish fleets which are more broadly dispersed along the West coast see smaller gains of 6-8%. No changes are projected for the shoreside hake fleets as no direct changes in exploitation rate of hake was modeled. Changes in income effects modeled with IO-PAC are proportional to these changes in revenue.

More detailed port-level fleet dynamics under the **Status Quo** scenario's individual quotas (**Appendix MS6**) suggests that fleets (based in particular ports) that have low spatial overlap with bycatch species are most likely to increase effort and landings under an individual quota system. Other fleets that cannot avoid bycatch and cannot stay below quotas are predicted to reduce fishing effort. In these simulations, Moss Landing, Fort Bragg, Eureka, and Coos Bay increase effort and landings, while northern fleets are more likely to cut effort.

Box MS3.

Jacob and colleagues (2012) developed an approach to quantify the resilience and vulnerability of human communities in the Gulf of Mexico. Following Jacob et al. (2012), vulnerability and resilience may be related to:

- Population composition
- Poverty
- Housing characteristics
- Labor force structure
- Natural and technological disaster risk
- Labor force disruptions
- Housing disruptions
- Personal disruptions

Such an approach could be developed for the US West Coast to predict how changes in the marine and coastal economy and social conditions will influence wellbeing. Norman and colleagues' (2007) profiles of 123 fishing communities on the West Coast may be a starting point, detailing each community's demographics, history, housing, infrastructure, and involvement in fisheries.

Photo: Robert K. Brigham, NOAA Photo Library

TRADE-OFFS AMONG ECOSYSTEM COMPONENTS, INCLUDING HUMAN WELL-BEING

Here we focus on trade-offs between ecosystem components of interest for the IEA (**Figure MS1**): ecosystem integrity, protected species, human communities, habitat, and fisheries.

Our narratives related to energy illustrate potential conflicts between the need for electricity generation and other goals related to protected species, fisheries, habitat, and some metrics of human communities. Continued operation of Klamath dams (including hydropower facilities) could have negative impacts on Chinook salmon abundance and fishery economics (**Appendices MS2, MS7**), while development of wave energy sites could negatively impact sturgeon habitat, groundfish fisheries, and shipping (**Appendix MS1**). The spatial analysis illustrates areas of potential tradeoffs, but does not attempt to quantify the magnitude of these.

Most of our quantitative results do not point to stark coast-wide trade-offs between fisheries and conservation goals related to protected species and ecosystem integrity. Fishery catches similar to those currently occurring did not cause large changes in fish food webs, nor did additional harvesting of new low-biomass species (**Appendices MS4, MS5, MS6**). When these trade-offs did occur, for instance when bird and mammal abundance declined due to depletion of forage species (**Appendix MS3**), they were triggered by fishery effort much greater than current levels; such levels of depletion would be illegal under current law or harvest guidelines. Fishery and conservation goals were aligned in the case of Klamath Dam removal (**Appendices MS2, MS7**), albeit with costs incurred by other sectors. Fishery and conservation goals are also aligned in relation to groundfish catch shares, as the modeling predicts increased catches as some target stocks, with concurrent recovery of rockfish (**Appendices MS5, MS6**). Potential conflicts can arise for individual species (e.g. California and Steller sea lions), but this will be highly dependent on whether future fisheries diverge in effort, location, and gear from current practices.

Our spatial ecosystem modeling suggests that when they occur, trade-offs between fisheries and conservation goals (ecosystem integrity and protected species) are likely to be at the local scale and only in particular regions. For instance, individual quota designs that led to coast-wide increases in stocks led to local declines in fishing effort for some northern fleets (**Appendix MS6**). Similarly, harvest of new fishery targets that are sustainable when measured on a stock-wide basis can cause reconfiguration of plankton communities in Central California (**Appendix MS4**).

SYNTHESIS: LESSONS LEARNED

- The scenarios and modeling here illustrate the benefits of identifying the **"leverage points" for management actions.** This means identifying what the full response to a policy decision will be, as it plays through the human and economic portions of the system. Consideration of such leverage points is one strength of the modeling efforts here.
    a. For instance, quantitative analyses suggest that moderate increases in one "weak stock", Klamath River Chinook, can lead to large increases in harvest and economic benefits at the broader regional level.
    b. On the other hand, low quotas of "weak stock" rockfish may not constrain groundfish catches. Instead, enforcement and monitoring of target species quota is more important to overall fleet behavior, revenues, bycatch, and the biological response.
- Models suggested that under most cases, harvests near current levels would not drive extreme trade-offs between fishing and conservation goals. In contrast, we illustrate **other potential trade-offs between electricity demand and shipping, fishing, and conservation of sturgeon**, based on population modeling of Chinook salmon and spatial analysis related to wave energy illustrate potential trade-offs. **Such conflicts between multiple uses in the California Current are likely to**

continue in the future, and scenario planning should therefore consider the full array of drivers and pressures.

- **A full toolbox of modeling approaches was necessary to connect drivers, pressures, and ecosystem response** in the California Current. Approaches included GIS mapping; single-species, food web, and ecosystem models; and economic input/output models. **Gaps exist in our modeling capability related to climate change, protected species, and human wellbeing**. Ongoing efforts will address some of these topics.

DETAILED ANALYSIS OF LESSONS LEARNED

Through preliminary engagement with experts and narrative scenarios we have identified drivers, pressures, and policy considerations that may shape future conditions of the California Current ecosystem. Where possible, we have applied quantitative models that evaluate management options and predict impacts of particular pressures, with the goal of demonstrating the potential to inform future management decisions. Here we present some of the key lessons learned, and surprises, regarding the following: What management actions appear to have large effects, and why? What are key trade-offs, and what modeling approaches reveal them? And what are vulnerabilities of the system that need to be considered further?

"LEVERAGE POINTS" FOR MANAGEMENT ACTIONS

Two analyses related to dam removal and groundfish individual quotas illustrate the need to identify the "leverage points" for management actions. This means identifying what the full response to a policy decision will be, as it plays through the human and economic portions of the system. With dam removal, the economic effects of moderate increases in Klamath River Chinook populations are amplified through much of Oregon and California, as Klamath Chinook are a "weak stock" and constrain fishing for other salmon runs. For groundfish fleets, our modeling argues against the *a priori* assumption that low quotas of "weak stock" rockfish would constrain catches. Instead, enforcement and monitoring of target species quota is more important to overall fleet behavior, revenues, bycatch, and the biological response. Moreover, fleets at times choose to exceed "weak stock" quotas, paying penalties or risking fines to maximize total revenue. Decision making requires understanding which management actions or policies have the largest effect on the human and economic response, and this is one strength of the modeling efforts here.

REVEALING TRADE-OFFS

Given an emphasis on models focused on fishing, we had expected to illustrate strong trade-offs between fishing and conservation goals. However, models suggested that under most cases, harvests near current levels would not drive extreme trade-offs. On the other hand, as discussed above, we illustrate other potential trade-offs between electricity demand and shipping, fishing, and conservation of sturgeon, based on population modeling of Chinook salmon and spatial analysis related to wave energy illustrate potential trade-offs. Such conflicts between multiple uses and pressures in the California Current are likely to continue in the future, and scenario planning should therefore consider the full array of drivers and pressures.

ADVANTAGES OF MODELING APPROACHES

Though scenarios exercises like those here may seem to lend themselves to complicated dynamic models, we found that simple maps were a highly effective tool for identifying trade-offs and conflicts related to wave energy. Though these analyses do not quantify such trade-offs in detail, they are a first step toward informed decisions. The analysis identified a key axis of uncertainty, the cost of underwater transmission lines, which is likely to dictate the proximity of wave energy facilities to shore. This subsequently determines spatial overlap with gears and species, which are typically confined to certain depth zones. Additionally, the analysis points to the need for comprehensive data sets for each sector – for instance, shipping involves not just the primary shipping lanes but also specific lanes negotiated by tugs and crabbing vessels. Similar map-based analyses have had an immense impact on conservation decisions, for instance allowing tradeoffs between costs and objectives for marine reserves (Leslie et al. 2003) and terrestrial conservation (Carwardine et al. 2008).

We found that each level of model complexity was appropriate for particular questions and scenarios. We applied only one single-species model here (for Chinook salmon), in addition to comparing predictions from published stock assessments (single-species models) to ecosystem model predictions related to groundfish. Where management questions are focused on single species such as Chinook salmon, single-species models allow statistical estimation and capture the uncertainty in predictions. For higher trophic level species for which fishing causes a large portion of total mortality, our ecosystem modeling generally predicted simple, direct responses caused by harvest and bycatch, as would single-species models. The full complexity of the ecosystem and food web models was useful primarily to investigate scenarios involving lower trophic levels, spatial fishery effects, and more drastic increases in fishing rates. Additionally, spatially-explicit ecosystem modeling provided a unified view of fleet dynamics for mixed-species fleets; unlike salmon trollers groundfish fleets base their decisions on harvesting opportunities across many species, and their catches influence population dynamics of many unassessed stocks.

Predictions from the ecosystem model (Atlantis) and food web model (Ecosim) suggest distinct hypotheses regarding energy flow. Both models predict that harvest of one lower trophic level species (e.g. forage fish) will lead to increased abundance of others (e.g. euphausiids or copepods). The two models' predicted effects on predators of these species are consistent in some cases but not others; the divergent predictions are alternate hypotheses that illustrate the uncertainty in system structure and model assumptions. This paired application of modeling approaches illustrates the strength of such comparison: the ability to identify predictions that are robust to model assumptions, to highlight uncertainty in models, and to suggest alternate hypotheses that can be investigated with field data.

Overall, we found that a full toolbox of modeling approaches was necessary to begin to connect drivers, pressures, and ecosystem response in the California Current. We expect that such an approach will be necessary in the future, bringing existing tools and expertise to investigate potential scenarios.

FUTURE DIRECTIONS INDICATED BY PRELIMINARY ENGAGEMENT WITH MANAGERS, SCENARIOS, AND MODELING

The seven modeling analyses above are a first step toward linking pressures to the response of ecosystem attributes in the California Current (**Figure MS1**). However, many key species and processes were identified in the preliminary engagement with managers and other experts (**Section1**) and scenario narratives, but are not included in the quantitative analyses here. In these cases the preliminary engagement with managers and narratives are useful to at least conceptually identify potential drivers, pressures, and management options. At a minimum, this conceptual approach is informative in identifying areas of potential conflict and trade-offs and guiding future quantitative modeling. Below we discuss gaps in our existing modeling capability and avenues for future work related to climate change, protected species, and human wellbeing.

Climate change and ocean acidification were included in the conversations with experts and managers, as well as in our narrative scenarios, but were not the focus of our modeling. Wave energy development could be one response to climate change, but direct impacts might translate into shifts in river and ocean temperatures, rainfall, and freshwater volume and timing. Ocean acidification may cause declines in shelled plankton and benthic species, with indirect effects on predators. In the 2011 IEA Ainsworth and colleagues (2011) projected some aspects of climate change for marine species North Pacific, and Kaplan et al. (2010) considered effects of ocean acidification on food webs. We have not added to these capabilities here, but there are several relevant avenues of research.

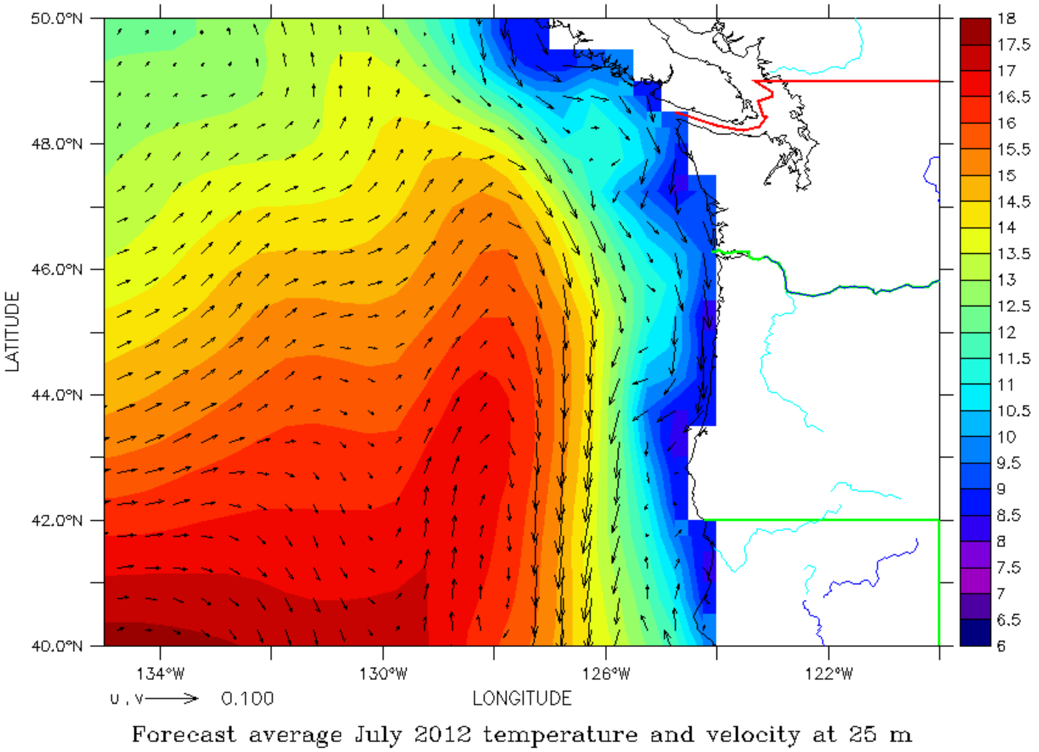
Projections of climate change can be linked to oceanographic models, and this can then be used to predict ecosystem and fishery responses. For instance, the end-to-end modeling framework being developed by Rose and colleagues **(Box MS2)** can link climate models to oceanography, plankton, small pelagic fish, and fishing fleet dynamics. Similarly, Kaplan and colleagues have begun developing the ability to link oceanographic models (Hermann *et al.* 2009) to atmospheric models forced by IPCC scenarios for carbon dioxide emissions. The oceanographic models will be linked to an Atlantis ecosystem model to yield spatial and temporal projections of the effects of global change. Such efforts may reveal local impacts of climate change, for instance at the scale of particular ports, rookeries, or National Marine Sanctuaries. In a related effort that will inform the 2013 IEA, short term climate forecasts are being used to predict metrics of ecological integrity, such as northern copepod abundance (**Ecological Integrity section**) that is positively related to salmon survival rates (Peterson and Schwing 2003) (**Box MS4**) .

Conversations with experts suggest that salmon and other anadromous species are likely to be directly influenced by climate change, due in part to shifting patterns in timing, volume, and temperature of fresh water. Preliminary engagement with experts and managers identified specific runs of salmon hypothesized to be most vulnerable to such shifts. Analyses already exist that predict the response of particular runs of Chinook salmon to climate (**Box MS1**), and these approaches can be applied to additional populations and regions.

Analysis of pressures including shipping, fishing, and energy infrastructure will necessitate additional consideration of protected species, including marine mammals and birds. The food web and ecosystem models typically require very strong, coast-wide impacts on aggregated prey groups to predict large changes in abundance of marine mammals, birds, and other protected species. We have only qualitatively identified the gears that are involved in particular scenarios and that have relatively high bycatch rates of protected species (Jannot et al. 2011). More detailed spatial consideration of hotspots of fishing and protected species (Bertrand et al. 2012) would better illustrate fishing effects on the prey base of these species. Models that predict abundance of protected species as a function of habitat (Redfern *et al.* 2006) could be used to predict current spatial distributions as well as distributions under climate change. These could be combined with dynamic projections of fishing effort to predict entanglement or take. Similarly, more refined scenarios regarding changes in shipping traffic (e.g. related to oil and gas exports or widening of the Panama Canal) could be combined with spatial abundance modeling to inform projections for ship strikes or disturbance.

Box MS4.

Work is underway to provide short term (six to nine month) forecasts of ocean conditions that are testable and relevant to annual management decisions for protected species, fisheries, and ecosystem health. The bottom-up forcing of the California Current ecosystem is predicted using the Climate Forecasting System linked to a ROMS (Regional Ocean Modeling System) with a Nutrient –Phytoplankton-Zooplankton component. The modeling predicts coastal upwelling, currents, mixed layer depths, water temperature, nitrate and oxygen concentrations, pH, and plankton distributions. A recent forecast from the CFS for the region of interest is shown below. Modeling tools and statistical relationships are available to then predict the effects of ocean condition on each of the biological components of the IEA such as protected species (salmon), fisheries (groundfish and coastal pelagic fishes), and ecosystem heath.



Forecast of temperature (deg C) and velocity (m/s) at 25m depth, from the Climate Forecast System. This forecast of average July 2012 conditions was produced during October 2011.

Our analyses here use modeling approaches to translate scenarios into revenue and economic impacts due to fisheries. We consider port-level or regional impacts on revenue, employment, and income. However, we do not consider the distribution of revenue and income among individuals, nor do we consider non-monetary factors related to human wellbeing. Norman and colleagues (2007) have profiled fishing communities on the west coast, detailing not only fisheries income and involvement but also each community’s demographics, history, housing, and infrastructure. These data are useful for considering narrative scenarios of future change in the California Current, and could be combined with factor analysis similar to Jacob et al. (2012) for quantitative predictions or rankings of resilience and vulnerability of human communities (**Box MS3**).

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Integrated Ecosystem Assessment of the California Current

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Chapter (example):

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Appendix, example for MS5:

Gray, I.A., I.C. Kaplan, I.G. Taylor, D.S. Holland, and J. Leonard. 2013. Biological and economic effects of catch changes due to the Pacific Coast Groundfish individual quota system, Appendix MS5, Appendix to: Management testing and scenarios in the California Current, In: Levin, P.S., Wells, B.K., and M.B. Sheer (Eds.). California Current Integrated Ecosystem Assessment: Phase II Report. Available from ***http://www.noaa.gov/iea/CCIEA-Report/index***.