FINAL REPORT NARRATIVE:

Maximizing the Value of Offshore Aquaculture Development in the Context of Multiple Ocean Uses (PI: Lester)

Background

Demand for seafood in the United States and around the world continues to rise, driven by population growth and escalating per capita consumption. As a result, aquaculture is increasingly proposed as a potentially sustainable option to meet this demand. Given intense competition for space on land and in coastal bays and estuaries, many are looking to open water or offshore aquaculture as an innovative solution. Offshore aquaculture represents an opportunity to bring economic development to coastal communities, decrease our reliance on foreign imports and overharvested wild stocks, overcome potential downsides of other types of aquaculture, and ensure that high quality seafood products reach American consumers.

Offshore aquaculture is not without its own challenges, and there is a strong need for scientifically-informed marine spatial planning (MSP) to minimize undesirable interactions and maximize benefits. Because aquaculture interacts with many ocean uses, single sector planning is likely to result in negative environmental impacts, unnecessary tradeoffs with other uses, and unintended consequences. We have developed a new quantitative spatial planning framework that informs offshore aquaculture siting by minimizing the economic and environmental tradeoffs between offshore aquaculture development and other existing and planned marine uses. We applied this framework to a case study of aquaculture development (for finfish, shellfish and seaweed culture) for the Southern California Bight. There is growing interest in developing offshore aquaculture in the region; there is strong potential for development due to relatively consistent ocean conditions, weak prevailing winds, low frequency of storms, and proximity to processing facilities and high value markets in Los Angeles and San Diego. We hope that our research will facilitate the development of offshore aquaculture in California, providing a robust analytical framework for siting offshore aquaculture within the context of a diversity of other uses and environmental impacts.

Project Goals and Objectives

The overarching goal of this project was to develop a framework to inform marine spatial planning for offshore or open ocean aquaculture such that the value and success of aquaculture development is optimized in the context of a suite of ocean uses and environmental impacts.

The specific objectives of the project were to:
1) Assess the full suite of potential conflicts and environmental impacts associated with the development of open ocean aquaculture.
2) Employ the Southern California Bight as a case region to develop spatial bioeconomic models (that are dynamic to the extent that spatial dynamics are relevant and/or feasible to model) and a tradeoff analysis to examine aquaculture development and other ocean uses and benefits.
3) Apply our model to aquaculture planning and regulation development in California to inform multi-sector planning that maximizes sustainable production across multiple uses.
4) Develop a modeling framework that is sufficiently general so that it can be adapted to inform aquaculture siting across the US.
5) Advance the dialogue about offshore aquaculture development in the US from a place of uncertainty regarding impacts and conflicts towards a point where regulatory decisions can be made in a way that provides compatibility with other uses and environmental regulations.

Project Methodology

Our project approach centers on three key steps:

1) Identify potential impacts, conflicts, and planning/permitting needs for offshore aquaculture in southern California through an extensive literature review and scoping process to determine the interactions to include in our models and key model parameters.

We conducted an extensive literature review about offshore aquaculture, including promising species and technologies, potential conflicts, environmental impacts, regulatory challenges, and spatial planning considerations. We also participated in meetings and/or phone calls with California Department of Fish and Wildlife, California Ocean Science Trust, Sea Grant Extension Officer Paul Olin, the Aquarium of the Pacific, Sea World Hubbs, NOAA, and California legislators to determine key regulatory issues and likely sources of conflict with offshore aquaculture. We also observed stakeholder surveys conducted by project collaborator Rachel Tiller to evaluate perceptions and concerns about offshore aquaculture among fishermen, conservationists, and scientists in central and southern California.

Furthermore, we held meetings and/or phone calls with aquaculture industry representatives to identify the most promising species and technologies for offshore aquaculture development, spatial planning constraints and challenges for these aquaculture types, and parameter values for our models. We focused our modeling on the following aquaculture scenarios, which are intended to be broadly representative of the range of types (species and structures) of aquaculture being considered in an open ocean context, but parameterized based on real species: finfish in netpen cages (based on striped bass); shellfish on longlines (based on Mediterranean mussels), and kelp on longlines (based on sugar kelp). Our primary industry contacts, which provided us with operations and cost data, included:

- Santa Barbara mariculture, a small-scale shellfish mariculture operation
- Catalina Sea Ranch, a planned larger-scale shellfish mariculture operation near Long Beach, CA
- Hubbs Sea World Research Institute, a private research institute working on researching and developing finfish open ocean aquaculture in CA and beyond
- Ocean Approved, the only commercial seaweed mariculture operation in the US, located on the east coast

An additional key part of this step was identifying fixed spatial constraints to aquaculture development, which represent locations where aquaculture cannot feasibly be sited. For our California case study, this includes shipping lanes, military use zones, state and federal Marine Protected Areas that explicitly prohibit aquaculture (or prohibit alteration of the seafloor), active oil platforms, locations with hard bottom habitat, sewage outfalls and major river mouths, and depths less than 20 meters or greater than 80 meters for mussel and kelp culture and depths less than 30 meters or greater than 100 meters for finfish. We compiled the best available data layers to represent these constraints for our case study region and then determined what areas are potentially suitable for aquaculture development. This involved major data compilation and processing efforts, and resulted in a map of the Southern California Bight (gridded into 1 km^2 cells) that identifies feasible locations for aquaculture development; based on these constraints, we identified 914 (fish) and 1011 (mussels and kelp) 1-km^2 grid cells where aquaculture could be developed (1134 cells total) (Fig. 1).

2) Develop spatial bioeconomic models for the Southern California Bight, simulating different types of offshore or open ocean aquaculture development (shellfish, kelp, and finfish) and capturing key existing uses that may conflict with aquaculture (e.g., fisheries) and impacts from aquaculture (e.g., altered viewshed, environmental impacts).

Modeling ocean currents

Three-dimensional ocean current dynamics were estimated using an Eulerian ocean circulation model comprised of flow field solutions from a high-resolution Regional Ocean Modeling System (ROMS) applied and calibrated to the Southern California Bight (SCB) [1]. The model domain covered the SCB coastline from north of Point Conception to San Diego and included all eight Channel islands. The model grid was 258 km by 386 km with 1 km horizontal resolution and 40 vertical levels. For estimating transport patterns of organic material from the aquaculture farms to the benthos, viruses from farms to neighboring patches, and halibut larvae among populations, the ocean circulation model was combined with a Lagrangian particle tracking "biophysical" model. Each of the three types of particles (organic material, viruses, and larvae) were independently "seeded" into the biophysical model along with their physical and life history (if applicable) properties, and then tracked in the model to generated a two-dimensional particle density distribution function of patch-to-patch transport probability, following methods by Simons et al. [2].

Aquaculture models

For each of the three aquaculture types (finfish, shellfish, kelp), we have developed spatially explicit production and cost models. Aquaculture yields (production) will be impacted by spatially variable environmental conditions (e.g. water temperature, currents, productivity, etc.), and costs of production (economics) will vary based on environmental conditions (e.g., wave height, depth) and geographic location (e.g., distance from port). By putting together a revenue model (based on production and prices) and a cost model, we are able to evaluate the value of each developable cell to the aquaculture industry (represented as a 10 year net present value) (e.g., see Fig. 2). The production models for each type of aquaculture were developed using different approaches (see below), and were developed assuming a standard farm design, based on information from industry contacts, that did not vary spatially.

Finfish aquaculture model: The cage design for our model finfish farm was based on an offshore aquaculture farm proposed by Hubbs SeaWorld in 2009. We used AquaModel, a proprietary GIS modeling software developed by System Science Applications to model the growth of striped bass in offshore net pen cages. AquaModel is a complex, dynamic model of finfish aquaculture that is well respected by our industry contacts. It combines a model of fish physiology (within the farm) with a plankton model and a benthic model to simulate a wide range of interactions between the farm and surrounding ecosystem [3]. We input growth parameters for the striped bass along with environmental parameters specific to the Southern California Bight into AquaModel. Environmental parameters included modeled current data (see above), temperature, bathymetry, and background nutrient levels. We modeled the production of a farm with 24 9,000 m^3 cages (in two rows of 12) for one and a half years and recorded the total biomass produced and the flux of organic material to the benthos. Since AquaModel is too time intensive to run in each of our potential aquaculture cells, we ran it in a subset of 70 cells that were chosen using cluster analysis. We then extrapolated the production from these 70 cells to all 914 cells that were potentially developable for aquaculture using least squares regression. For the economic component of the finfish aquaculture model, we used projected cost data provided by Hubbs SeaWorld Research Institute, and then modified the costs for each site to take into consideration the distance from port (which affected labor and fuel costs), wave height (which affected maintenance costs), and depth (which also affected maintenance costs). We combined the production potential and cost models to determine the overall value of a site for aquaculture development, characterized by its 10 year net present value.

Shellfish aquaculture model: We developed a shellfish production model based on a published model of individual mussel growth [4] that we modified to represent an entire mussel farm (consisting of 100 long lines that are each 210 meters). The model incorporated environmental parameters, such as temperature, currents, and POC, to determine the amount of time it would take mussels to grow to market size in each developable site. We created a cost model that varied in the same way as described above for fish to determine the total value of each site for aquaculture development. Our farm design and economic information was based on data provided by Bernard Friedman (Santa Barbara Mariculture) and Catalina Sea Ranch, and then combined with an economic model of price and spatially variable costs (Fig. 2).

Kelp aquaculture model: We used a published dynamical model to assess changes in individual *Saccharina lattisima* biomass [5]. We modified the model to estimate growth of an entire kelp farm (consisting of 200 long lines that are each 210 meters). The model incorporated environmental parameters, such as temperature, nitrate concentrations, current speed, and photosynthetically available radiation. We allowed each individual kelp plant to reach a maximum biomass according to literature and then harvested 50% biomass of each plant and allowed plants to regrow until the end of the growth period (Oct-01 to Mar-31), at which point the entire plant was harvested. We created a cost model that varied as described for finfish, which was coupled to the production model to determine the overall value of each site for algal aquaculture development. Our farm design and economic information was based on data provided by Ocean Approved and information published by the Irish Sea Fisheries Board [6].

Tradeoff models

We are examining tradeoffs among our three aquaculture types and: 1) wild fish populations, specifically California halibut, and the associated recreational and commercial fisheries, 2) environmental health, specifically benthic impacts (i.e., nutrient enrichment) from finfish aquaculture, 3) viewshed quality given that offshore aquaculture will interrupt the view from coastal locations, and 4) disease risk from aquaculture (both in terms of spread to other farms and to wild populations), focusing on the increased risk resulting when there is greater connectivity among farms.

Wild halibut fish population and fisheries model: For estimating effects of offshore aquaculture development on wild capture fisheries we constructed a spatially-explicit, age-structured simulation model of the California halibut (*Paralichthys californicus*) natural population and wild-capture fishery dynamics in the Southern California Bight (SCB). *P. californicus* (hereafter referred to as halibut) is a flounder (Family *Pleuronectidae*) that associates with nearshore soft and mixed-sediment benthic habitat [7,8]. It is an important sport and commercial fish species that is typically caught via hook-and-line, trawl, set gill net and trolling, and marketed as fresh fillet. Overall, the SCB halibut fishery is considered to be well-managed at a population level approximately equal to that associated with maximum sustainable yield [9].

In the population model, larval production at a site scales with biomass of reproductively mature fish at the site; larval dispersal among nearshore sites across the study region is simulated in relation to halibut larval life history and behavioral attributes and an oceanographic model of current patterns in the SCB (see above); survival and recruitment of settling larvae is mediated by intra-cohort density dependent mortality and local habitat availability and quality; and adult fish movement among sites is simulated in relation to the species' intrinsic adult movement rate and the distance and habitat gradient among neighboring sites.

We integrated the population model with a halibut fishery fleet model containing spatial, size limit and fishing effort level regulations. In the resulting coupled bioeconomic model, fishery profit is a function of revenue from harvest and market price, less the cost of fishing in relation to fishing effort and local stock density. In accordance with a limited entry fishery regulated by total allowable fishing effort (as is the case for the halibut fishery in the SCB), the spatial distribution of the fleet was estimated using Ideal Free Distribution theory in relation to fishery profit among the fishable patches. The fishery fleet model then redistributes fishing in response to aquaculture development (i.e., in our tradeoff analysis, if a cell is developed for aquaculture, the fishery is not able to harvest in that cell, creating a de facto MPA). For evaluating near-term effects of alternative aquaculture development scenarios on the fishery, we focused on the sum of the discounted annual payoffs, or Net Present Value (NPV), of the fishery over 10 annual time steps starting with the present (i.e., years 2015-2025). We considered both fishery profit and biomass yield as payoffs in order to represent commercial and recreational components of the fishery.

Environmental health/impact model: We use impact to the benthic environment (as measured by organic material flux to the seafloor) at finfish aquaculture sites as our environmental impact trade-off for several reasons: (1) benthic impact is widely cited as a key concern of aquaculture development, (2) development of deep sites with high currents can minimize or eliminate benthic impact, and (3) most of the other environmental effects of aquaculture are poorly understood (such as effects on fisheries productivity), difficult to measure or predict (such as invasive species introductions), not a concern in the Southern California Bight at the levels of development we are modeling (such as reaching a carrying capacity for filter feeders), managed by on farm practices (chemical pollution), or some combination of the above. As described for the finfish aquaculture model above, we are using AquaModel and modeled ocean currents to model finfish aquaculture; we use AquaModel output of organic material flux to the seafloor as our metric of environmental impact, as excess organic material is known to increase the risk of hypoxic and/or anoxic conditions.

Viewshed model: We developed a GIS approach, using the Viewshed Analysis tool in ArcGIS 10.2, to capture viewshed impacts and weigh the relative impact of different aquaculture development spatial plans on the view out to sea from land. The Viewshed Analysis tool allows us to map where on land a given aquaculture farm would be visible using a coastal digital elevation model. We then take into account views from state and county parks, weighted by visitation rates, and the effects on the broader viewshed, weighted by coastal population density. The model assumes that aquaculture infrastructure (buoys, lights, etc.) project ≤1m above sea surface. The model calculates views based solely on elevation and does not account for trees, buildings or infrastructure on land that may modify views. We assume that the maximum distance kelp and mussel farms would be visible is 3km, while finfish farms, which generally have more significant surface infrastructure, would be visible up to 8 km away.

Disease risk model: Disease outbreak is a major concern for marine aquaculture development – both because of its potential economic impact on the industry and effects on the ecosystem. On-farm management practices play a major role in mitigating disease, but spatial planning can also be important in reducing the risk of a large, multi-farm outbreak. Unfortunately, disease dynamics are highly complex and there is a lack of information about diseases that are likely to affect our species and study region. However, there is considerable literature showing that disease outbreaks are more likely to escalate when farms are in close proximity (due to increased likelihood of spread) and that separating aquaculture facilities that are farming the same species (by minimizing the connectivity between sites) can minimize the risk of disease transfer between farms [10-12]. We used modeled current data (see above) to assess the connectivity between farms for each development scenario, using a 1 day PLD since this is the maximum time that viruses can usually survive in the ocean. We modeled farm connectivity using a method called eigenvector centrality [13] that measures the centrality of a location to all other locations in a network. We assumed that the scenarios that had the lowest degree of connectivity between farms were the best in terms of minimizing the risk of disease outbreak.

3) <u>Conduct tradeoff analysis to quantitatively examine interactions among various types of offshore aquaculture development and other existing uses and benefits</u>.

A key component of our framework is the ability to represent multiple aquaculture farms and examine a diversity of spatial configurations in order to inform the optimal spatial plans for aquaculture development that maximize productivity while minimizing tradeoffs and negative impacts. We are conducting a tradeoff analysis examining the millions of possible permutations of developing these feasible cells (Fig. 1) with our three aquaculture scenarios.

We are using dynamic optimization, based on a branch of heuristic search algorithms known as genetic algorithms [14], to maximize a seven-dimensional objective function that explicitly considers weighted preferences for the seven sectors in our model (three types of aquaculture, halibut fishery, viewshed quality, disease risk, and environmental health). In the objective function, sector-specific weighting parameters determine the relative influence of each sector in contributing quantitatively to the overall value of the objective function. In concept, the weighting parameters in the collective reflect a societal preference for particular sectors relative to each other. For a given weighting scenario (7-parameters setting) the heuristic seeks to identify the single aquaculture farm design that maximizes the specified parameter setting and thus the overall societal objective of how to "use" the seascape. We evaluated the full range of weighting values for every sector, and in combination with the full range for all other sectors, in order to generate the most comprehensive results possible for optimal marine spatial planning of the three aquaculture types in the SCB.

Preliminary Results

Our model is currently running on computer clusters to produce the final tradeoff analysis results. Preliminary results include only a subset of optimal spatial plans for particular weighting values across the seven axes. Example preliminary two dimensional tradeoffs are shown in Figure 3 and example seven dimensional (radar) plots are show in Figure 4. Every single point on all of these plots represents a point on the seven-dimensional frontier, with preferred plans depending on how each of the seven objectives are weighted.

We will need to synthesize all of our results before reaching final conclusions based on this research. However, some tentative conclusions include:

- Even when all cells profitable for finfish aquaculture are developed (392 cells), the halibut fishery still retains 93.5% of its value.
- Even when all cells profitable for mussel aquaculture are developed (1011 cells), the halibut fishery still retains 77% of its value.
- Even when all cells profitable for kelp aquaculture are developed (392 cells), the halibut fishery still retains 91% of its value.
- There is a strong tradeoff between finfish aquaculture development and environmental health (i.e., minimized benthic impacts).
- There is only a tradeoff between viewshed value and aquaculture development at very high levels of aquaculture development, as only a small number of developable cells contribute to significant viewshed impacts.
- Our analysis showed that kelp and mussel aquaculture is most valuable to develop in the northern parts of the Bight and fish is more valuable in the south (Fig. 5). Indeed, there is no tradeoff between finfish and kelp aquaculture development in the study region because there is no overlap in profitable cells for the two aquaculture types.

Project Outreach

Although we are still synthesizing our results, we expect this project to have important impacts, facilitating the development of offshore aquaculture in California and ideally throughout the United States. Our project provides the first robust analytical framework for siting offshore aquaculture within the context of a diversity of other uses and environmental impacts. We expect it to be particularly useful in southern California, where interest in marine aquaculture has been growing significantly. A shellfish farm offshore of Long Beach, Catalina Sea Ranch, was recently given regulatory approval and is soon to be the first shellfish farm in US federal waters. SeaWorld Hubbs is currently seeking regulatory approval for a finfish farm offshore of San Diego. The Ventura Shellfish Group is seeking to pre-permit offshore mussel farms near Venture harbor. This general momentum towards offshore aquaculture in the state has brought attention and interest to our project from both industry and government. We have been cultivating these relationships in order to make our project relevant from both a scientific and management perspective. Finally, although we parameterized our model to southern California, we developed the models with the intention of building a general framework that could be applicable to aquaculture siting in any context.

We have engaged in the following outreach and communication activities for our project:

- Seafood Summit, New Orleans, February 9-11, 2015. We attended this conference and spoke with many of the participants about our project, including Michael Rubino from NOAA's Office of Aquaculture.
- Aquaculture Law Symposium, UCLA, March 13, 2015: We attended this meeting and networked with participants.
- Offshore Aquaculture in the Southern California Bight, Aquarium of the Pacific, Long Beach CA, April 28-29, 2015: We presented our project to a large audience of regulators from both the state and national level and discussed potential applications and next steps to apply this research to aquaculture development in the state.
- Provided a project brief for legislators to be distributed at tour of Sterling Caviar farm organized by DFW's State Aquaculture Coordinator (May 6, 2015).
- Discussions with key regulators, industry representatives, and aquaculture influencers in California to explain our project approach and expected results and determine how our research can best be leveraged to advance aquaculture development in California: Randy Lovell (DFW), Paul Olin (CA Sea Grant Extension), Diane Windham (NOAA), Skyli McAfee (California Ocean Science Trust), Cassidy Teufel (California Coastal Commission), Don Kent (SeaWorld Hubbs Research Institute), Doug Bush (Cultured Abalone Farm), Warner Chabot (California Shellfish Initiative), Rebecca Martone (Center for Ocean Solutions), Michael Jones (Maritime Alliance), Ken Riley (NOAA), Michael Rubino (NOAA), Phil Cruver (Catalina Sea Ranch), and Bernard Friedman (Santa Barbara Mariculture).
- Scientific conferences: We have presented our work to scientific colleagues at a number of venues, including the Western Society of Naturalists meeting (2014), the Australian Marine Science Association South Australia Symposium (2014), and to the Managing Coastal Environments Workshop hosted at UCSB (2015).
- We have met several times with Hubbs-SeaWorld Research Institute to discuss the applications of our model to their Rose Canyon project. We also provided them with benthic habitat maps specific to their proposed location.

We are planning to participate in these additional outreach and communication activities:

- Collaborating with the Ventura Shellfish Group (VSG): We are in discussions with VSG about how we can support their efforts to pre-permit 2000 acres of nearshore waters off the coast of Ventura for mussel farming, including participating in workshops they will host and providing technical guidance for the siting aspect of their strategic plan based on our modeling results.
- TNC presentation: We will be presenting the results of our research to staff at the San Francisco office of The Nature Conservancy on July 1, 2015. TNC has sought out input because they are interested in ways to engage productively in the conversation about sustainable offshore aquaculture in California and beyond.
- Scientific conferences: We intend to present project results at the Aquaculture 2015 Conference in Montpellier, France, August 23-26 2015 and at the International Congress for Conservation Biology meeting in Montpellier, France, August 2-6 2015.
- We will continue to work closely with Paul Olin (California Sea Grant) and Randy Lovell (CA DFW) on how our results can help advance sustainable open ocean aquaculture development in California.

Sea Grant Priorities

Our project addressed several priorities of the California Sea Grant Strategic Plan:
1) *Healthy coastal and marine ecosystems*: our framework can improve sustainable ocean management by accounting for aquaculture's environmental impacts and interactions with other ocean uses and benefits.
2) *Resilient coastal communities*: our framework accounts for the economic impacts of different ocean uses and can be applied by coastal communities to develop sustainable and profitable plans for aquaculture development.
3) *Safe and sustainable seafood supply*: our framework can inform the development of new sources of healthy and sustainable seafood through aquaculture development, while minimizing negative interactions with wild fisheries and reducing our dependence on seafood imports.

Our project is also aligned with the West Coast Regional Sea Grant priorities, including advancing effective ecosystem-based management (through integrated, multi-use planning), reducing impacts of offshore development (by taking into account the full suite of benefits and tradeoffs), and sustainable economic development of coastal communities (by informing the development of a new sustainable industry). Our research further accords with the National Sea Grant Strategic Plan priorities: healthy coastal ecosystems; safe and sustainable seafood supply; and sustainable coastal development. Finally, our research addresses many priorities of the NOAA Aquaculture Policy, which seeks to foster sustainable aquaculture growth using science-based decision making; engaging in marine spatial planning; and ensuring that aquaculture development is compatible with ecosystem health and other uses in the marine environment [15].

Figures

Figure 1. Developable cells for aquaculture following constraint mapping. “All” indicates cells developable for finfish, shellfish or kelp culture; “fish” indicates cells only available to finfish culture; and “NoFish” indicates cells available to shellfish or kelp culture.

Figure 2. Spatial distribution of 10 year net present value (NPV) for shellfish culture.

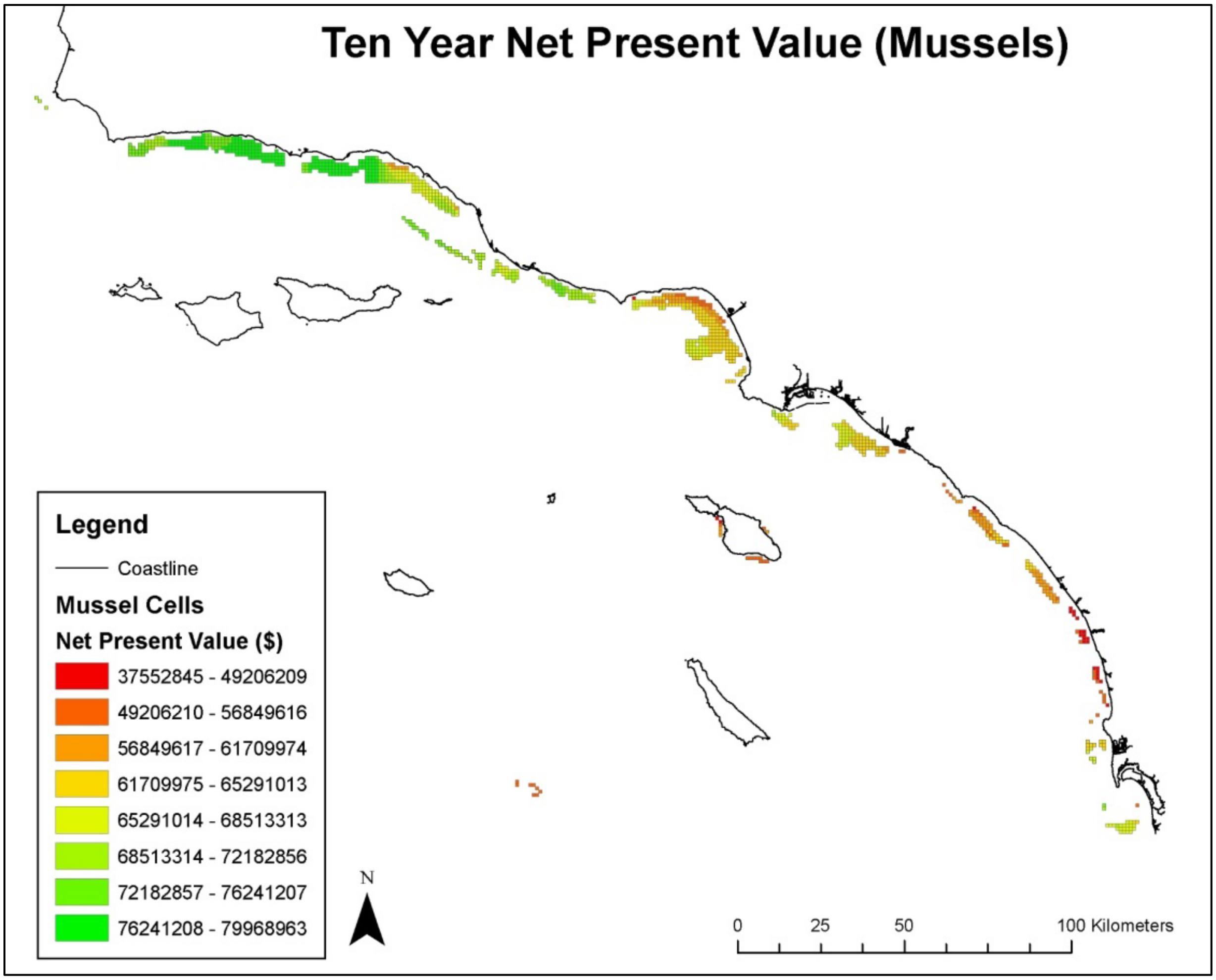


Figure 3. Example two dimensional tradeoff plots. Note that these are preliminary results and do not include output from all model runs. Viewshed, environmental, and disease impacts are minimized at 100% (higher values are preferable).

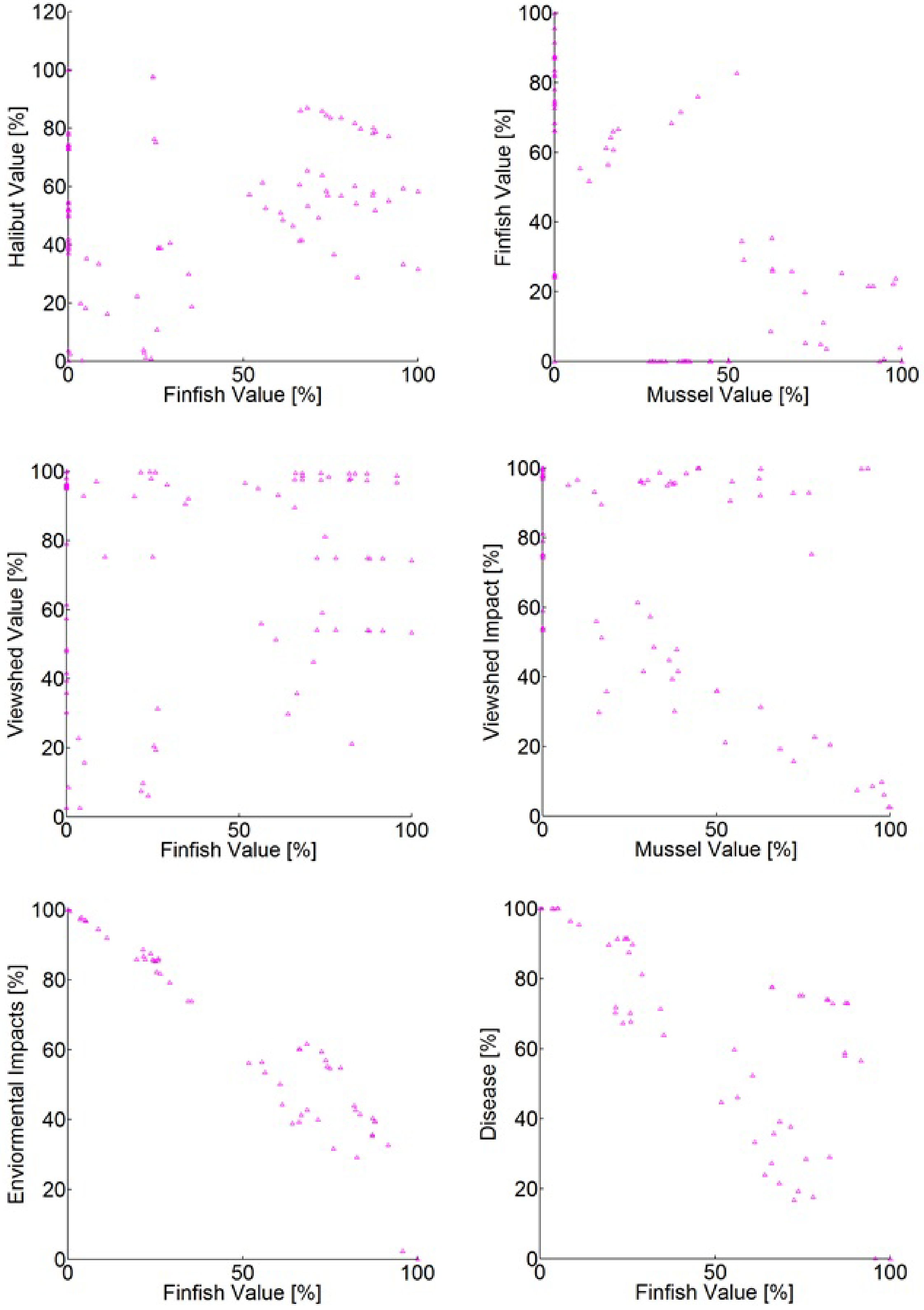
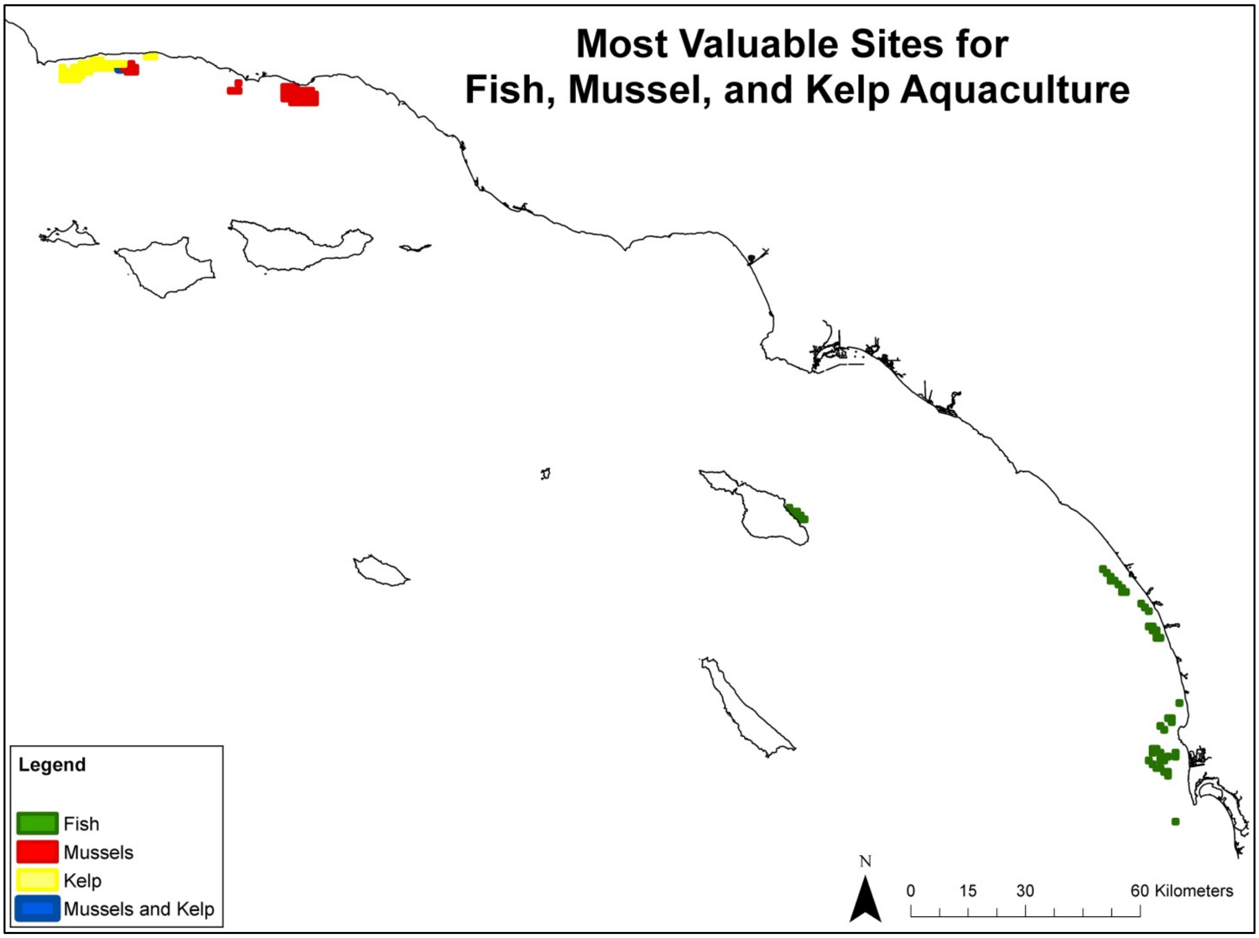


Figure 4. Example preliminary radar plots of two different scenarios (marine spatial plans) with their respective weighting values above each plot. Just as in the two-dimensional tradeoff plots, viewshed, environmental, and disease impacts are minimized at 100% (higher values are preferable).

Figure 5. Comparison of the 50 most valuable sites for each category of aquaculture.



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