

California Marine Life Protection Act Initiative
Draft Methods Used to Evaluate Marine Protected Area Proposals in the
MLPA South Coast Study Region
Chapter 10 – Bio-Economic Modeling
Draft revised February 23, 2009

BIO-ECONOMIC MODELING

Introduction

For marine protected areas (MPAs) to function effectively as a network that satisfies various goals of the Marine Life Protection Act (MLPA), they must (1) provide adequate protection from harvest to the portion of a species' (adult) population resident in the MPA, and (2) include a sufficient fraction of the populations' total larval production for populations to persist. The scientific guidelines for MPA design in the *California Marine Life Protection Act Master Plan for Marine Protected Areas* support general evaluation of the efficacy of MPAs as refugia and connectivity within the proposed MPA networks, but do not evaluate potential population effects or account for several variables, including conditions outside the MPA network (i.e., harvest), spatial structure of the seascape, realistic connectivity across space, and fishing pressure on different species.

Spatially explicit population models account for these factors and facilitate more comprehensive and spatially explicit evaluation of the consequences of MPA design for a proposed network's ability to satisfy various goals of the MLPA. Spatially explicit models developed for evaluation of proposed MPA networks go beyond the current scope of the master plan guidelines to calculate whether populations will persist and how the proposed MPAs will affect fishery yield and profit. The models include, for example, potential contributions from MPAs that do not satisfy all scientific guidelines, the status of populations outside of MPAs (which depends on fishery management), and the potential costs, in terms of fishery yield, associated with achieving a desired conservation outcome. Further, the models allow us to detect potential situations in which MPAs are sited efficiently, so conservation comes at minimal cost (or perhaps even a benefit) to consumptive users.

This document briefly describes the key inputs and outputs of two models well-suited for analysis of proposed MPA networks. We also describe the evaluations that will be performed by these models.

Description of Models

In the MLPA North Central Coast Study Region process of the MLPA Initiative, two models were developed, vetted, and utilized to evaluate MPA proposals. Those models are currently being extended for use in the MLPA South Coast Study Region. Both models utilize spatial data on habitat, fishery effort, and proposed MPA locations and regulations to simulate the population dynamics of fished species and generate predicted spatial distributions of species abundances, yields, and (in one case) profits for each MPA network proposal. The UC Davis "Spatial Sustainability and Yield" model (UCD model) considers each fished species separately, and focuses on sustainability of fished populations under each MPA proposal, using current estimates of fishery stock status to help predict future management success. The

UC Santa Barbara “Flow, Fish, and Fishing” model (UCSB model) focuses on the tradeoffs between fisheries performance (profits) and fish abundance.¹ Importantly, both models incorporate the population dynamic consequences of spatially explicit fishing regulations.

The two models differ in details regarding, for example, how specifically populations' dynamics are modeled, how the steady-state impacts of fisheries outside of protected areas are parameterized, and what units are used to express conservation and economic values. Although they differ in these details, the two models are structurally similar. Both models have the ability to be run dynamically or to equilibrium, though running dynamically requires data on the starting stock, across space, of multiple species. In equilibrium mode, they predict the state of the system over the long term rather than its dynamics over time².

Each model includes more or less the same structural elements: (a) larval connectivity across patches driven by ocean currents, pelagic larval duration, and spawning season, (b) larval settlement regulated by species density in available habitat, (c) growth and survival dynamics of the resident (adult) population, (d) reproductive output increasing with adult size, (e) adult movement (e.g., home ranges), and (f) harvest in areas outside of MPAs.

Key Changes to Models

Both models have been enhanced since they were used in the north central coast. Some of these enhancements are driven by differences in biogeography between the two regions (e.g., more heterogeneous flow patterns in Southern California), and some are driven by new methods or data (e.g., the desire to integrate data on fisherman behavior into the models). The key changes in the models are:

1. Larval dispersal kernel – we now use output from Regional Ocean Modeling System (ROMS)-based oceanographic models³ to predict connectivity, rather than assuming homogeneous Gaussian kernels along the coastline.
2. Spatial dimension – we represent the coastline as a two-dimensional map (in contrast to the previous one-dimensional representation). This permits more realistic modeling of complex habitat patterns and offshore islands in the Southern California Bight. We will use a 1 kilometer x 1 kilometer grid for our patches.
3. Fleet dynamics – we will parameterize our fleet model with data from Ecotrust’s surveys of commercial fisheries in Southern California, rather than assuming the fleet responds only to changes in fish density. The details of the fleet model are given in Appendix 2.

¹ The UCSB model adopts many of the key assumptions of the Equilibrium Delay Difference Optimization Model (EDOM), developed by Walters, Hilborn, and Costello in the North Central Coast Study Region. Both the UCSB and UCD models contain important advances over the versions used in the NCCSR to accommodate a more complex biogeography and spatial data on fishing effort in Southern California.

² Note that equilibrium models do not account for the costs incurred during the time required to reach steady state.

³ The ROMS model has been developed by oceanographic investigators at UCLA and UCSB who have provided model outputs for use by the spatially explicit population models described in this document. See Section 8 – Spacing for additional information on the ROMS model.

4. Species – with help from the MLPA Master Plan Science Advisory Team (SAT), we have assembled a list of species that cover a wide range of life history and fishery traits that are relevant in Southern California (Appendix 3).
5. Variability in larval dispersal – we will evaluate MPA networks in a variable (rather than static) environment. Larval dispersal matrices will vary among larval years to reflect the interannual variability present in the existing set of ROMS model outputs (years 1996-2002).

Caveats Associated with Model Interpretation

All models necessarily make simplifying assumptions about the nature of real-world processes. Both the UCD and UCSB models rely upon a series of key assumptions about the structural elements (a-f) listed above (Appendix 1). As such, model results should be interpreted with awareness of the assumptions, although these actually are less restrictive than those required by the verbal and mathematical models that form the basis of the size and spacing guidelines in the master plan. For example, the ROMS model used to estimate larval dispersal patterns in the models has limitations in its ability to resolve nearshore circulation, yet is more realistic than the spatially homogenous pattern of connectivity implicitly (see Chapter 8 - Spacing for more information on the ROMS model).

Model outputs also depend on the particular parameter values chosen for each species, so the predictions of the models will be most accurate when appropriate parameter values are known. Both modeling teams have undertaken a search of the biological literature for the best estimates of the necessary life history parameters for each model species. In Appendix 3, both modeling teams have detailed the parameter values and literature source for each estimate. This document will be circulated among SAT members and outside experts to ensure that the best parameter estimates have been used, and these consensus parameter values will be standardized between the two models.

The spatial distributions of larval settlement and adult biomass predicted by the model are driven by two sets of assumptions: larval dispersal is driven by oceanography as predicted by the ROMS model, and the suitability of a particular location for the settlement and growth of a species is determined by the presence of habitat appropriate for that species. Habitat is derived from the regional habitat map developed by the California Department of Fish and Game (DFG) and Rikk Kvitek, and is represented in a binary fashion; that is, habitat is either hard- or soft-bottom. Using these maps, the UCD model categorizes each 1 km² cell in the model as habitat or not, depending on whether it meets a critical value of hard substrate within a specified depth range, and the UCSB model uses the fraction of the 1 km² cell which is hard substrate within the appropriate depth, and treats this as a continuous measure of habitat availability in the cell.

A limitation to this approach is that it assumes that all locations with the appropriate substrate can support each species, whereas many species in the MLPA South Coast Study Region, including some of those being modeled, have range limits within the study region, and therefore are not found on suitable substrates outside those limits. For example, kelp bass are

not found in great numbers, if at all, in the westernmost Channel Islands, despite the abundance of suitable substrate there. The precise mechanisms creating these boundaries are generally unknown and likely reflect a complex combination of factors (e.g., temperature, habitat quality, and the abundance of prey, among others) that are beyond the scope of the current modeling effort. As a consequence, the models sometimes misrepresent abundances outside of these range limits (e.g., the ocean circulation model predicts that kelp bass larvae will settle on San Miguel Island, where no adult kelp bass are actually found). To handle this potential artifact, the models assume that there is no suitable habitat for larval settlement outside of the known range of the species. Larvae arriving in those excluded locations are assumed to die, regardless of the substrate type. At present, range limits are estimated using existing survey data on species abundances around the study region to estimate range limits primarily the 2004 CRANE survey data. Additional range limit data could be incorporated if provided by the SAT. Note that with this approach, the representation of suitable habitat remains binary: either a location is suitable habitat for a species, or not. Survey data are used to characterize the presence or absence of a species in a location, not actual population densities, which would not be well represented by a single year of survey data.

A final caveat is that model results are highly sensitive to the level of fishing outside of MPAs. Because the models are intended to predict a future equilibrium state, it is necessary to predict future fishing levels, an area of high uncertainty. Moreover, the performance of a species under a certain level of fishing is also highly sensitive to the shape of the settler-recruitment relationship (see Appendix 1), which is itself highly uncertain. The precise relationship between fishing effort and the shape of the settler-recruit curve is complex and not perfectly understood, especially in models such as these with considerable spatial complexity. In general, however, it is possible to represent the joint uncertainty in the shape of the settler-recruit curve (biological uncertainty) and in future harvest scenarios (management uncertainty) relative to each other. Specifically, the models describe the shape of the settler-recruit curve in terms of a *compensation ratio* or *critical replacement threshold* (CRT), and harvest can be described in terms of its effect on the *lifetime egg production* (LEP) of a species.

For a given value of the CRT, the model results depend roughly on the relative values of CRT and LEP rather than on the particular CRT chosen. In general, the management scenario depends on whether harvest causes lifetime egg production to exceed or fall short of the critical replacement threshold set by the settler-recruit relationship. Expressing the effects of harvest in terms of lifetime egg production also reduces some of the dependence of model results on uncertainty about adult life-history parameters. Therefore, it is possible to represent both biological and management uncertainty by choosing a particular value for the CRT for each species and then simulating population dynamics under several different harvest regimes relative to that CRT. The models will simulate harvest regimes that will approximate *poorly managed*, *MSY-like management*, and *conservatively managed* scenarios, given that CRT. Thus the model results can illustrate a range of possible performance for each species. For concise interpretation (i.e., coming up with several summary results for each MPA proposal) it may be desirable to weight results across species or possibly weight the probability of different future management outcomes.

SAT Recommendations for Using Models to Compare Alternative MPA Proposals

Because the models are built on the best available science, the SAT recommends that these models be among the principal modes of evaluation for each alternative MPA proposal in the MLPA South Coast Study Region. In making this recommendation, the SAT emphasizes that the models' conceptual principles are consistent with those upon which existing MPA size and spacing guidelines are based, and yield similar general conclusions: MPA size relative to adult movement strongly determines MPA effectiveness, and MPA spacing relative to larval dispersal distance strongly determines the ability of MPAs to function as a network. Spatially explicit modeling is more comprehensive in that it integrates the effects of MPA size and spacing, habitat distribution, level of fishing, and adult and larval movement to quantify the effectiveness of alternative MPA proposals. In doing so, the models extend the scope of the evaluation of MPA proposals currently addressed by the size and spacing guidelines. Moreover, spatially explicit models are not susceptible to threshold-related sensitivity that can arise from evaluation based on the size and spacing guidelines (i.e., that specific sizes and spacing (or ranges of these) are adequate, but others are not). Rather they estimate the conservation and economic consequences of each proposed spatial configuration of MPAs, so that they can be evaluated directly.

The UCD and UCSB models produce similar outputs that can be used to evaluate these conservation and economic consequences. Both models produce a measure of *conservation value* (e.g., increases in biomass or population sustainability), and a measure of *economic return* (e.g., yield or fishery profitability). Both conservation value and economic return can be described study-region wide or can be made spatially explicit. The models calculate each output at three spatial scales: individual 1x1 km cells, the entire study region, and four sub-areas (the mainland south of Long Beach Harbor, the mainland north of Long Beach Harbor, the northern islands [San Miguel, Santa Rosa, Santa Cruz, Anacapa, Santa Barbara] and the southern islands [San Nicolas, San Clemente, Santa Catalina]).

Conservation value is essentially a measure of the effectiveness of a proposed network of MPAs at meeting MLPA goals 1, 2, and 6⁴ while economic return reflects the expected changes to fishing yields of implementing MPAs. Specifically, each model will output:

1. Conservation Value
 - a. [UCD] Biomass and larval supply (a proxy measure of population sustainability) of 10 or so representative species, across space, under each MPA proposal (including "No Action").
 - b. [UCSB] Biomass of 10 or so representative species, across space, under each MPA proposal (including "No Action").
 - c. If A=Conservation Value under Proposal X, and B=Biomass under No Action, then the quotient: (A-B)/B provides a measure of the percentage increase in conservation value compared with No Action.
2. Economic Return

⁴ Subsections 2853(b)(1), (b)(2), and (b)(6), California Fish and Game Code.

- a. [UCD] Fish yield of 10 or so representative species, across space, for each MPA proposal.
- b. [UCSB] Fish yield and Fisheries Profit for the 10 or so representative species, across space, for each MPA proposal
- c. Again, by comparing to “No Action”, one can generate a measure of the percentage increase or decrease in economic return from the proposal.

The SAT proposes that each alternative MPA proposal be evaluated by compiling the following outputs:

1. Spatial effects on Conservation Value (as percentage changes versus No Action, presented as a spatial map and averages for each sub-area)
 - a. For each model species
 - b. For a weighted average of all model species (SAT to determine weights)
2. Region-Wide effects on Conservation Value
 - a. For each model species
 - b. For a weighted average of all model species (SAT to determine weights)
3. Spatial effects on Economic Return (presented as a spatial map and averages for each sub-area)
 - a. For each model species
 - b. For a weighted average of all model species (SAT to determine weights)
4. Region-Wide effects on Economic Return
 - a. For each model species
 - b. For a weighted average of all model species (SAT to determine weights)
5. Spatial effects on Recruitment (presented as a spatial map and averages for each sub-area)
 - a. For each model species
 - b. For a weighted average of all model species (SAT to determine weights)
6. Spatial fishing intensity (presented as a spatial map and averages for each sub-area)
 - a. For each model species
 - b. For a weighted average of all model species (SAT to determine weights)
7. Connectivity diagrams – the larval dispersal kernel that shows the intensity of connections from all source to all destination locations.
8. Tradeoff Curves – plot Conservation Value against Economic Return for each MPA proposal

This suite of eight model outputs will be generated for each species in each MPA proposal under the three different future management scenarios (*poor, MSY-like, and conservative* management).

Using Model Outputs to Improve each Alternative MPA Proposal

In addition to the outputs being used to compare alternative MPA proposals, both models also produce outputs which can be used to evaluate the strengths and weaknesses of each design. These outputs are intended provide feedback during the iterative process so that proposals can be adjusted to improve their performance in terms of conservation value and (if desired) economic value.

Three kinds of feedback are provided for each species:

1. The models calculate changes in conservation and economic value on sub-area scales. These data can be used to evaluate how the effects of proposed reserves vary over space, and if necessary to revise proposals to correct spatial imbalances in effects. The sub-areas used are the southern mainland (Long Beach harbor south to the Mexican border), northern mainland (Long Beach harbor north to Point Conception) northern islands (San Miguel, Santa Rosa, Santa Cruz, Anacapa, and Santa Barbara) and southern islands (San Nicolas, Santa Catalina, and San Clemente). In each sub-area, conservation value is calculated by comparing biomass in the sub-area with the alternative MPA proposal to biomass in the sub-area without fishing. In each sub-area, economic value is calculated by comparing profit (or yield) in the sub-area with the MPA proposal to profit (or yield) in the sub-area with no new reserves. Examples of these outputs as produced by the UCSB model are given in figures 1 and 2 of Appendix 4
2. The models calculate how much biomass is in each MPA, what fraction of the larvae arriving in that MPA were produced within the reserve (self-recruitment), and to what degree the MPA is self-sustaining (self-persistence). The first metric will allow an evaluation of which MPAs are in locations that support large populations of the target species and which are poorly placed to protect that species. The second metric (self-recruitment) allows a determination of to what extent each MPA is seeded with larvae originating elsewhere, as opposed to being replenished primarily by larvae spawned within that MPA. The third metric (self-persistence) is related and determines whether the MPA would persist in isolation. This is subtly different from self-recruitment, in that an MPA may receive a huge influx of larvae from other sources (low fraction of self-recruitment) but might nonetheless persist on its own. Conversely, an MPA may be highly self-recruiting, but if the total number of self-produced larvae is very low, the population in the MPA may not be persistent. Examples of these outputs as produced by the UCSB model are given in figures 3 and 4 of Appendix 4
3. The models also calculate how conservation value and economic value would vary for an alternative MPA proposal if one of the proposed MPAs was not implemented. That is, the model is run for a particular MPA proposal, which contains m individual MPAs. Then m additional model runs are made; in each one, one of the MPAs is 'deleted' from the proposal. The outcome of these deletion runs is then compared to the run with the full proposal. By comparing the performance of the proposal with and without each individual MPA, the relative importance of each MPA can be determined. If the proposal with a particular MPA removed performs similarly to the whole, intact proposal, that

indicates that the given MPA is not currently contributing greatly to MLPA goals, and could be altered to improve its effectiveness. Alternatively, if removing an MPA causes a sharp decrease in overall performance, that MPA is performing well and should probably not be reduced in size or repositioned. Examples of these outputs as produced by the UCSB model are given in figures 5 and 6 of Appendix 4

In interpreting these feedback outputs, it is important to recognize that the performance of an alternative MPA proposal or a particular MPA within that proposal is determined by the interplay of multiple factors, often in nonlinear ways. Therefore “improving” the performance of a particular MPA could be accomplished by varying any one of a number of factors (including size, shape, coverage of habitat in the vicinity, distance to neighboring MPAs, position relative to oceanographic retention zones, etc.). However, lessons drawn from simpler models of population dynamics within MPAs (e.g, Crowder et al. 2000, Botsford et al. 2001, Gaines et al. 2003, Moffitt et al. *in press*) do suggest the consequences of adjusting different MPA features. In general, MPAs will afford better protection to a species if it is made larger relative to the home range radius of that species. An MPA is more likely to be self-sustaining and independently persistent if it is larger (so that a greater fraction of larvae produced within that MPA return to replenish the population within the MPA) and if it is positioned in a location with higher oceanographic retention (larger values on the diagonal of the larval connectivity matrix). MPAs may also support large populations if they are situated such that they receive large inputs of larvae from ‘upstream’ locations, although then the performance of the ‘downstream’ MPA is tied to the persistence of the population in the ‘upstream’ location. Similarly, it may be advantageous to locate MPAs such that they export many larvae to ‘downstream’ locations (determined by looking at the off-diagonal elements of the connectivity matrix in the horizontal rows corresponding to that MPA as a larval origin). However, the successful export of larvae will still depend on whether the ‘source’ MPA maintains a large, persistent population.

Figure 1. Example of spatial map of Conservation Value generated by UCD model. The map shows the equilibrium biomass for one species (kelp bass) in each model cell.

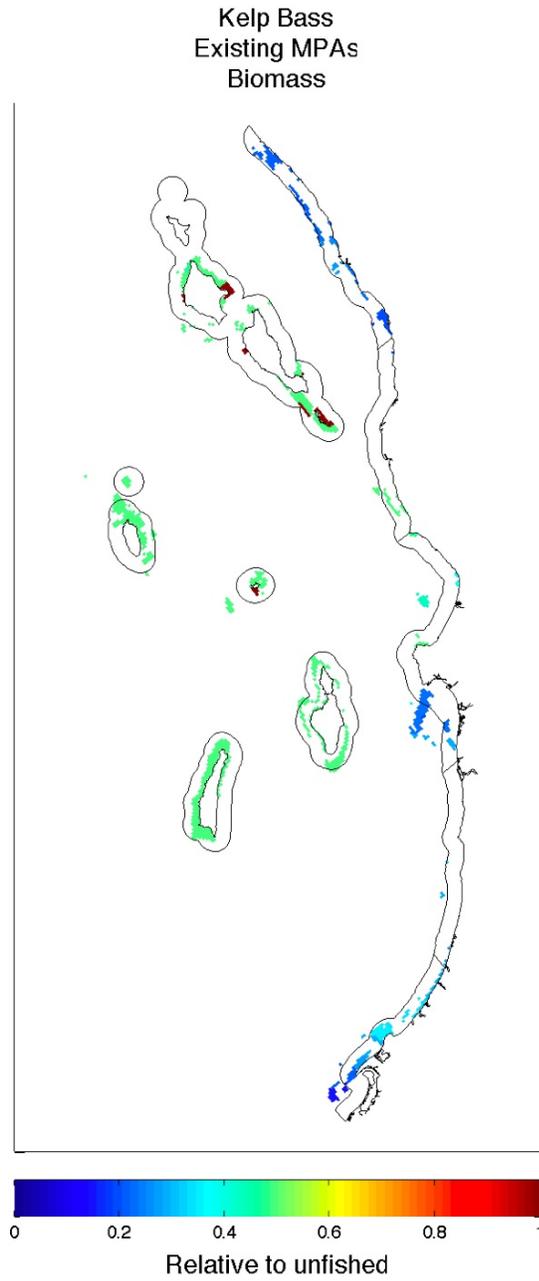


Figure 2. Example of spatial map of Economic Return generated by UCD model. The map shows the equilibrium yield for one species (kelp bass) in each model cell. [This map is a draft and may be altered for the final document.]

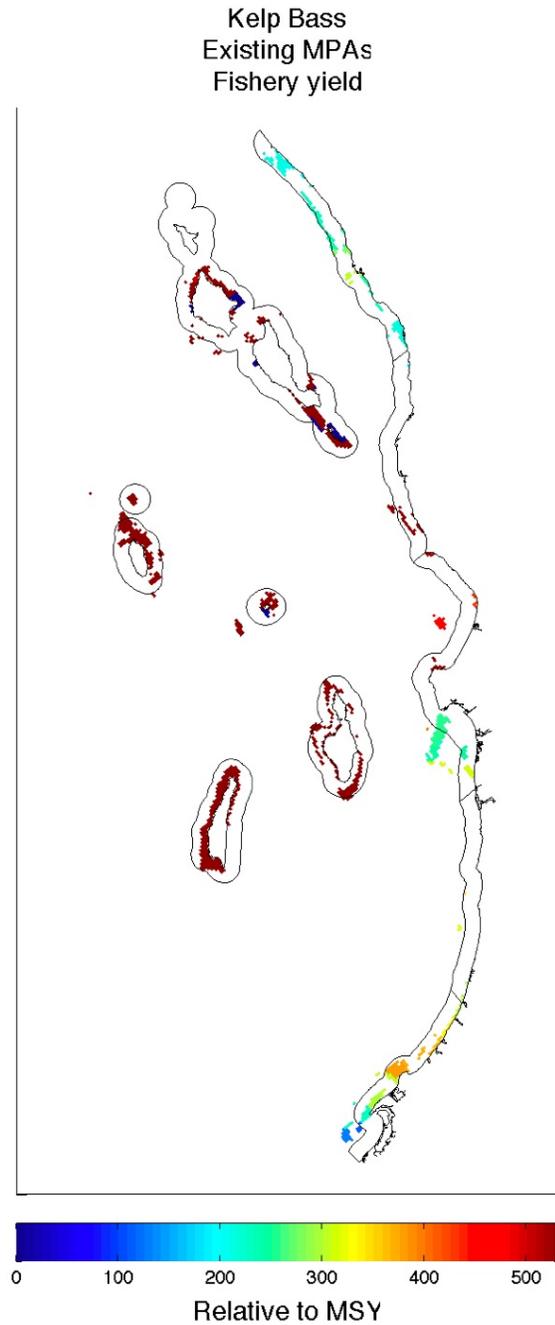


Figure 3. Example of spatial map of Recruitment generated by UCD model. The map shows the equilibrium larval recruitment for one species (kelp bass) in each model cell.

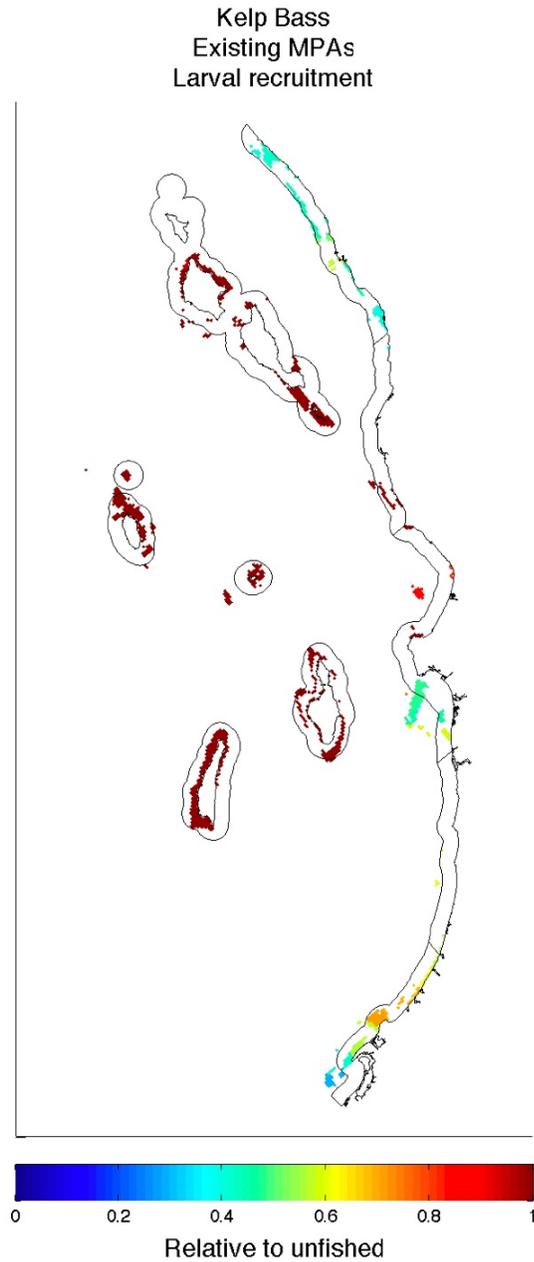


Figure 4. Example of spatial map of Fishing generated by UCD model. The map shows the equilibrium fishing rate for one species (kelp bass) in each model cell.

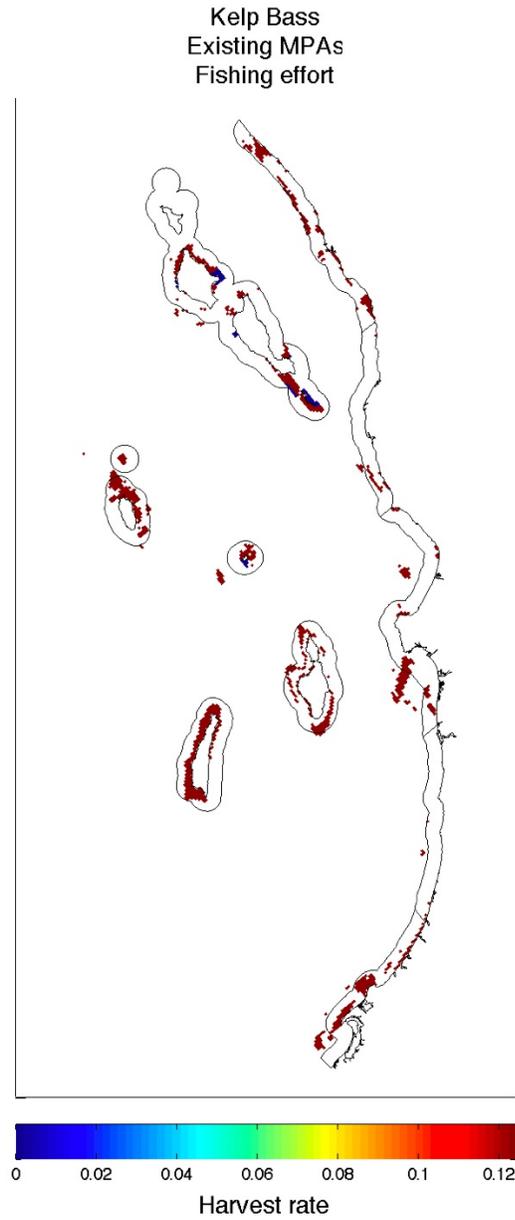


Figure 5. Example of Connectivity Matrix used by models. Color intensity at each point shows the probability of dispersal of kelp bass larvae from an origin patch (along vertical axis) to a destination patch (along horizontal axis). Points are grouped by geographical region (see Chapter 8 for description). [This is a draft; a revised version with more geographical landmarks denoted is forthcoming.]

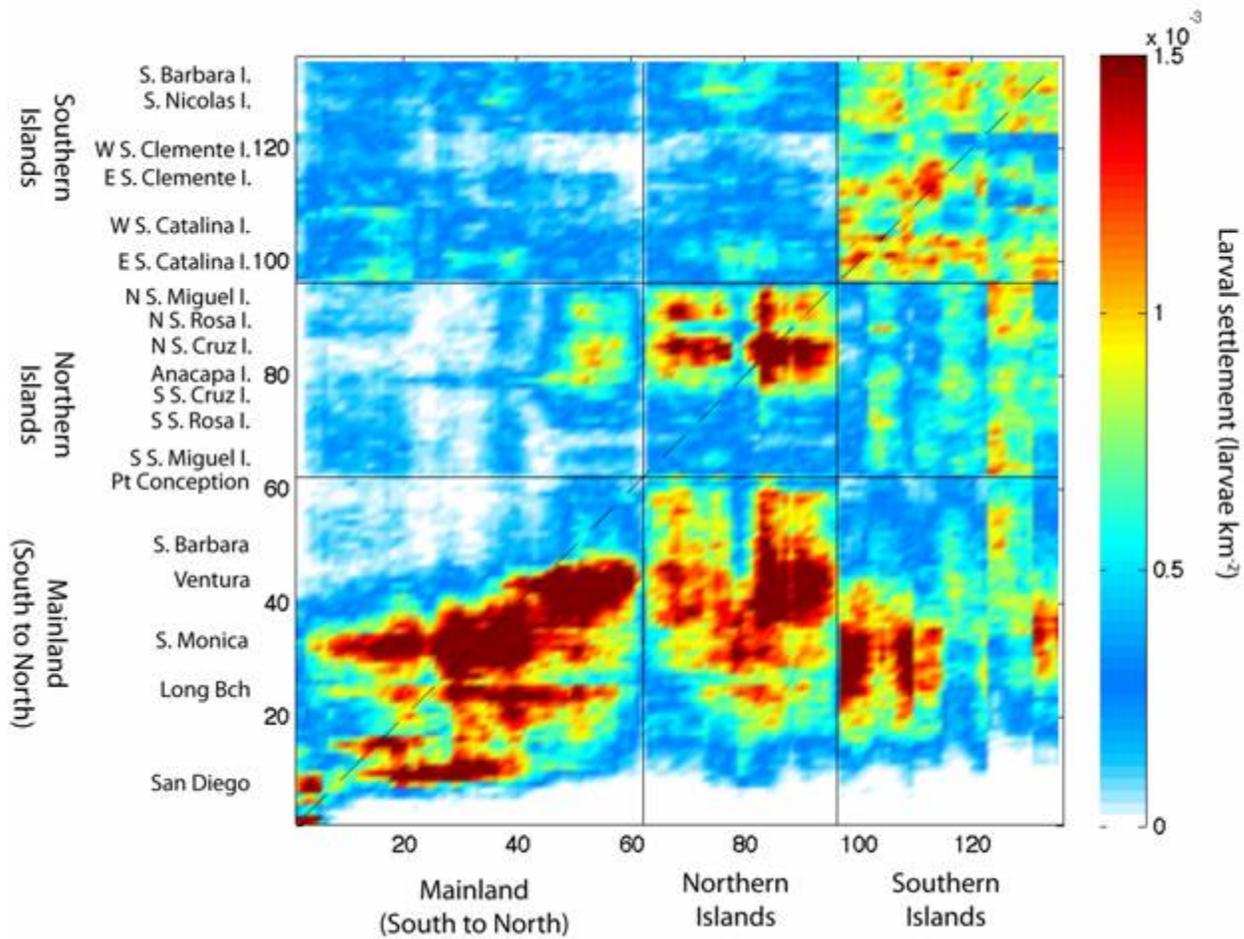
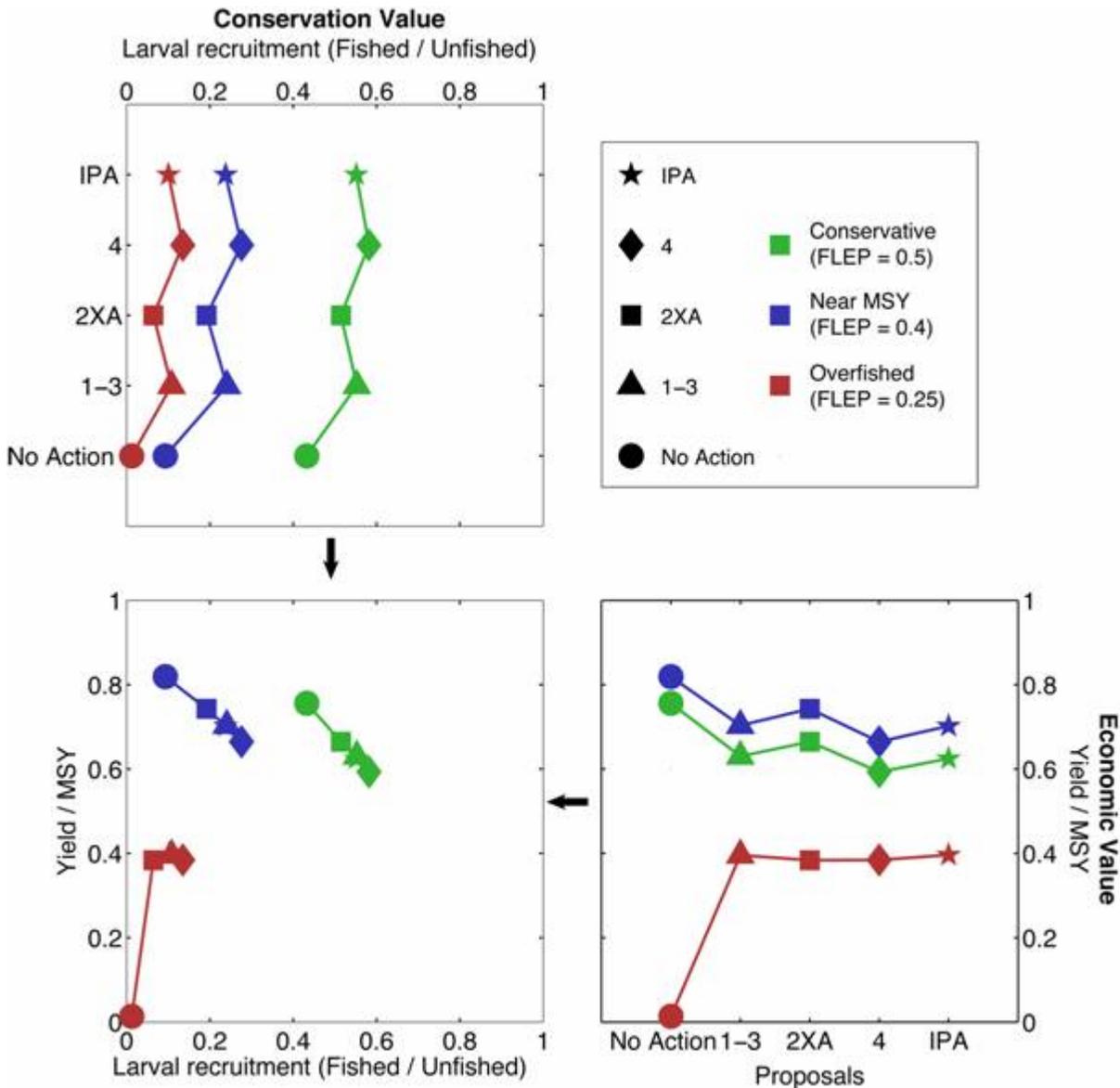


Figure 6. Example of tradeoff curve produced by models. This example shows a comparison of four MPA proposals and the No Action alternative from the MLPA North Central Coast Study Region (NCCSR). [An example using data from the MLPA South Coast Study Region is forthcoming.] The top left panel shows the Conservation Value metric ('spatial sustainability,' a measure of population persistence estimated by the NCCSR UCD model) for each proposal; the bottom right panel shows the Economic Value metric (yield as a proportion of maximum sustainable yield) for each proposal, and the bottom left panel shows the tradeoff curve for both metrics for each proposal. Model results were generated using 3 different assumptions about the future success of fishery management outside of MPAs and 1 scenario in which past management success was used to predict future success ('best estimate'), these different scenarios are indicated by different colors in the figure.



Appendix 1. Model Assumptions for Key Structural Elements in the UCD and UCSB Models

UCD Model Assumptions	UCSB Model Assumptions
<p>Larval Dispersal: Adults of representative species in each 1 km x 1 km habitat cell throughout the study region spawn larvae that are randomly distributed within that cell. The probability of larvae moving from that cell to any other in the study region is calculated using output from the ROMS model, for which larvae are assumed to behave as passive, neutrally buoyant particles. Dispersal pathways are calculated by averaging across 7 years of ROMS circulation output (1996-2002). This is may be modified, as needed, pending analysis of the sensitivity of model results to time-varying dispersal kernels. For each species, dispersal pathways are calculated using known spawning seasons and pelagic larval durations for the species. ROMS dispersal probabilities are calculated for 5 km radius circles distributed along the coastline of the study region; these data are mapped onto the 1 km x 1 km habitat grid used in the population models. Successful settlement for larvae 'arriving' at each model cell is contingent on the presence of suitable habitat in that cell.</p>	<p>Larval Dispersal: Same as UCD model.</p>
<p>Larval Settlement: Settling larvae experience intra-cohort density-dependent mortality. That is, the mortality rate of settlers depends on the density (fish per square meter) of other settlers arriving at that location, reflecting competition for habitat and predator refuges that is typical of the species being modeled.</p>	<p>Larval Settlement: Settling larvae experience intra-cohort density-dependent mortality as in the UCD model. Because this density-dependence represents competition for habitat and refuges, its strength depends on the proportion of the cell that is suitable habitat. For a given number of settling larvae, more will survive to adulthood in a cell with abundant suitable habitat than will survive in a cell with mostly poor habitat.</p>
<p>Adult Growth and Reproduction: Growth, survival, and egg production are based on published data. In general, individuals grow to a maximum length, their weight is proportional to length cubed, and egg production is proportional to weight. Thus old, large individuals produce more eggs than young small individuals. Survival is constant with age except for species for which more precise data are available.</p>	<p>Adult Growth and Reproduction: Growth for each species is based on previously published growth curves. Survival is independent of fish age and is based on published estimates of mortality in the absence of fishing. Egg production is assumed to be proportional to the total weight of adult fish.</p>
<p>Adult Movement: Adults move within home ranges. Individuals with home ranges spanning MPA boundaries experience fishing pressure in proportion to the amount of their home range that is outside the MPA. This creates a spillover effect for adults with home ranges centered just inside MPAs.</p>	<p>Adult Movement: Two types of movement are modeled: irreversible movement of fish into a new home range and movement within a fixed home range. Irreversible movements are assumed to be relatively rare, but sometimes quite large (10-20 km alongshore). Movement within home ranges means that the "exploitable biomass" within a cell is a sum of contributions from fish with home ranges centered in the cell and in surrounding areas.</p>
<p>Fishing Pressure: Fishing regulations follow those set forth in each draft proposal, and both recreational</p>	<p>Fishing Pressure: We assume that fishers are acting to maximize their own profits. Assuming a large</p>

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<p>and commercial fishing are considered. Initially, in the absence of better information, fishing effort will be modeled assuming that effort is equal across space but total effort is redistributed and increases outside of MPAs after MPA implementation. Pending collaboration with UCSB and EcoTrust, fishing effort will vary over space depending on fish abundance and travel costs (distance from port) using a fleet model that is parameterized based on data from the southern California commercial fishing fleet.</p>	<p>number of fishers acting independently, this means that fishing effort will be distributed such that at the end of each season marginal profits are the same in all patches. The current calculation of profits accounts for the “stock effect” in which fish are cheaper to extract from large than from small populations. We are working on incorporating costs of travel and weather into the model, which will reduce profits in more distant and less sheltered locations. We are collaborating with UCD and EcoTrust to parameterize the fleet model using data on fishing effort and profit, by location.</p>
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Appendix 2. Methods Used for Parameterizing FleetMmodel Using Ecotrust Fishery Data

[these methods are currently under development]

Both the economic and conservation outcomes of implementing an MPA network will depend on how areas outside of the MPA's are fished. The UCSB and UCD models therefore predict not only how MPA's will change fish populations but also how fishing effort will be distributed throughout the region. Because of the broad spatial scale and the large number of fishers involved, the models do not seek to predict decisions made by individual fishers but instead to predict the aggregate distribution of fishing effort for each species.

The description of the spatial distribution of fishing effort in the bioeconomic models can take on several forms, of increasing complexity. The simplest description is a uniform distribution of effort (except in MPAs, where effort is restricted or prohibited). A somewhat more realistic description is to allow fishing effort to be redistributed across space as a function of profit. This approach is based on the expectation that effort on each species will be distributed across patches so that marginal profits from fishing the species are the same in all fished patches. If this were not the case, and one patch had higher marginal profits than another, fishers would be expected to reduce effort in the less profitable patch and allocate more effort to the more profitable patch. To calculate the level of fishing effort that equalizes marginal profits in each patch, the models need to know how profit in each patch varies as a function of fishing effort.

Profit in each patch is calculated as revenue less costs, where revenue is a function of fishing effort and fish biomass in the patch, and costs are a function of fishing effort in the patch, distance of the patch from the nearest port and typical weather conditions in the patch. We assume a simple form for this relationship:

$$\text{Profit in patch } i = \alpha_1 f(E_i, B_{i0}) - [\alpha_2 D_i + \alpha_3 W_i + \alpha_4] E_i$$

Where $f(E_i, B_{i0})$ gives yield as a function of effort and biomass in patch i , D_i is the distance of the patch from port, W_i reflects typical weather conditions in the patch, and the α terms are unknown parameters giving the relative importance of the different factors.

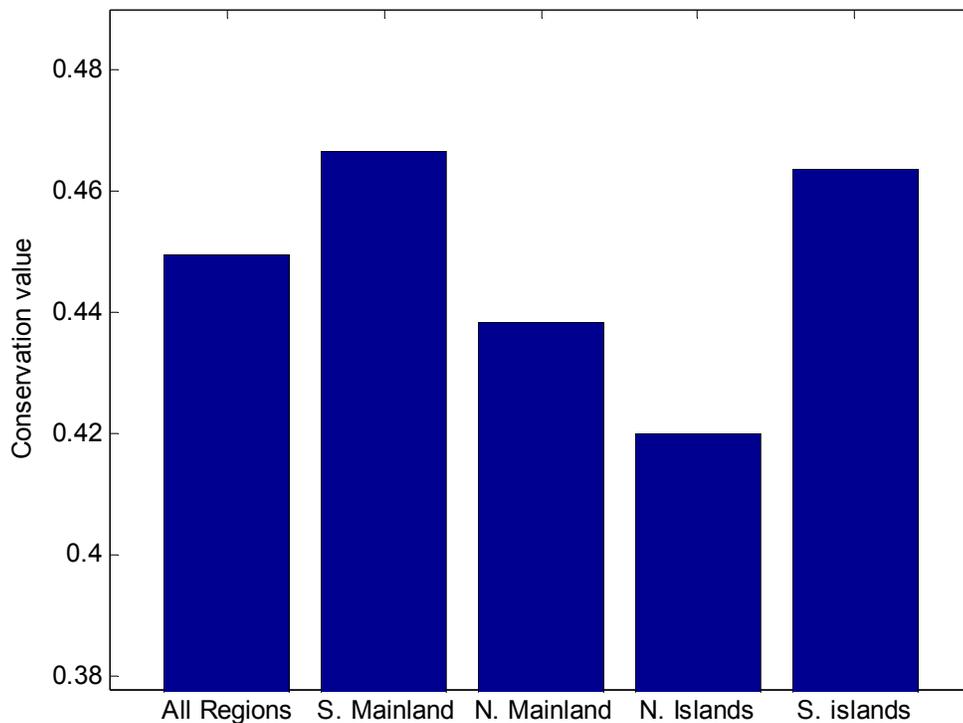
The modeling team is collaborating with Ecotrust to determine the values of these α parameters. For each species, the α parameters are tuned to obtain the best match between the spatial distribution of fishing effort predicted by the model (assuming the current suite of existing MPAs) and the actual current distribution of fishing, documented by Ecotrust. These best parameter values will then be used in evaluating alternative MPA proposals, and will allow the models to predict how fishing effort will be distributed under that proposal, and thus how fishing outside of MPAs will effect conservation and economic outcomes of the proposal.

Note that while 'profit' implies the sale of harvested resources, it is possible to calculate the relative benefit of recreational fishing in each location in an analogous manner because recreational fishermen place a value, though not necessarily monetary, on the fish they catch.

Appendix 4: Feedback on an Individual MPA Proposal

Examples of model outputs which will be provided to help improve alternative MPA proposals. These example results were produced by the UCSB model based on a proposed network of 3 MPAs: MPA A - near San Diego, MPA B - near Santa Barbara and MPA C – at San Nicholas Island

Figure 1. Conservation value (biomass as a fraction of unfished biomass) for all regions (Point Conception to the California/Mexico border, including all island) and for each sub-region



separately.

Figure 2. Economic value (profit with reserves as a fraction maximum sustainable profit without reserves) for all regions (Point Conception to the California/Mexico border, including all islands) and for each sub-region separately.

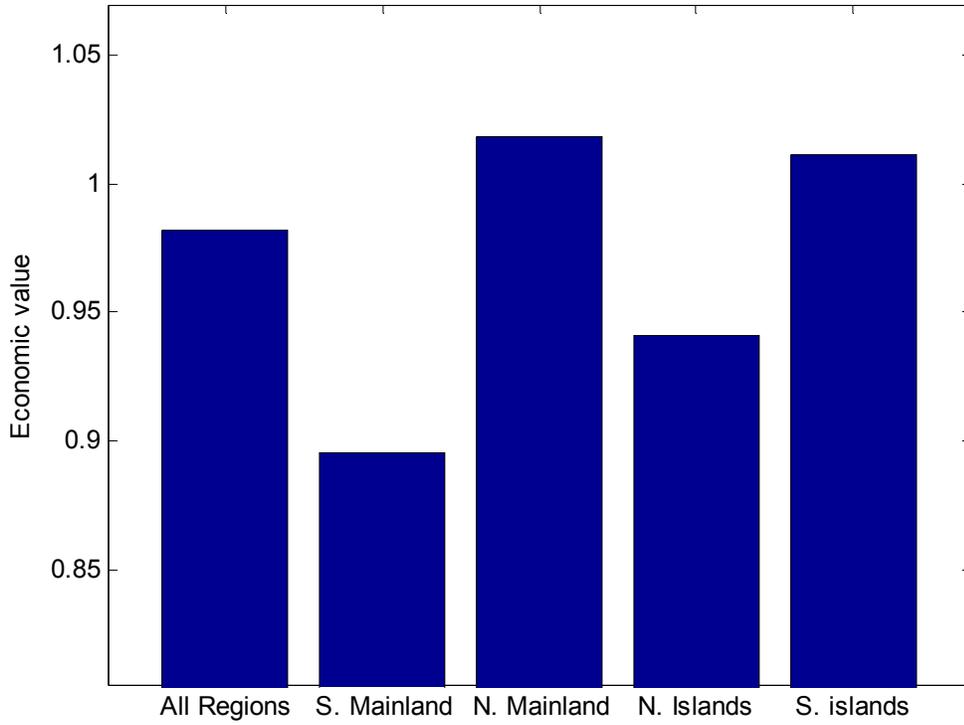


Figure 3. The mass of fish in each reserve, as a fraction of the total mass of fish in the whole system.

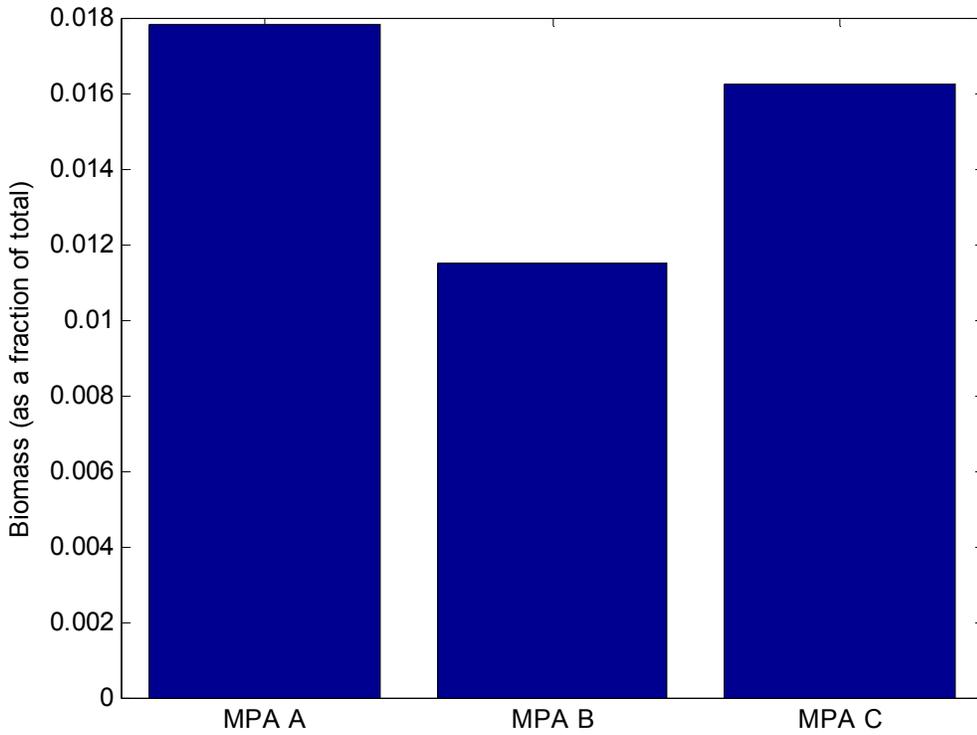


Figure 4. The fraction of larvae arriving in each reserve which were produced within the reserve.

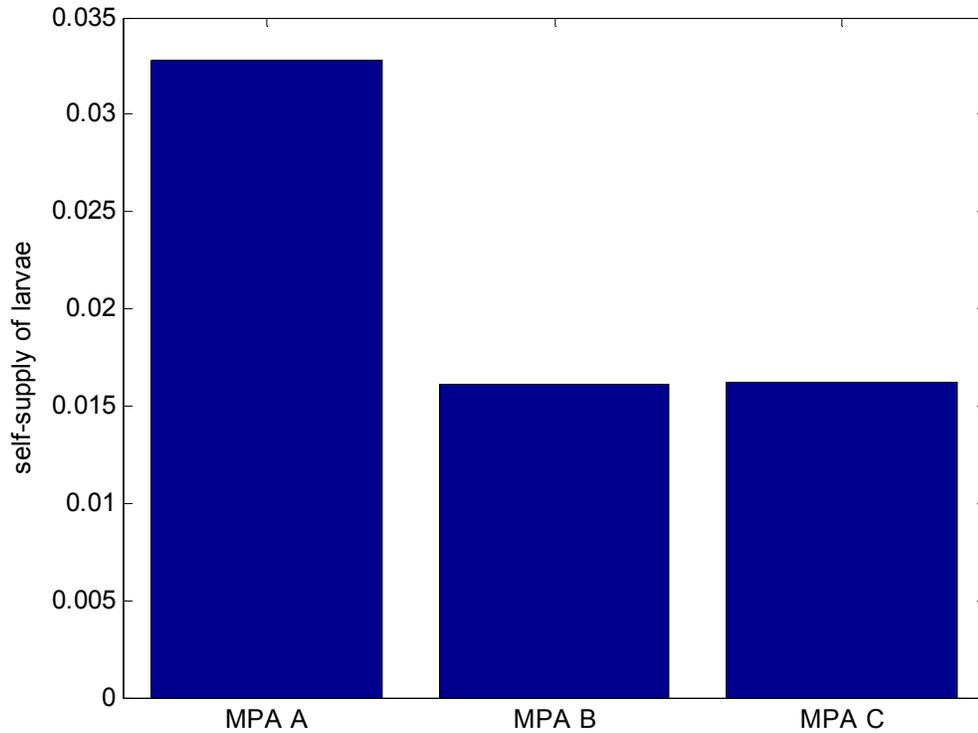


Figure 5. Conservation value (biomass as a fraction of unfished biomass) for the whole system, with all reserves (i.e. the whole MPA proposal), as well as with all reserves except reserve A, all except reserve B, all except reserve C and no MPAs.

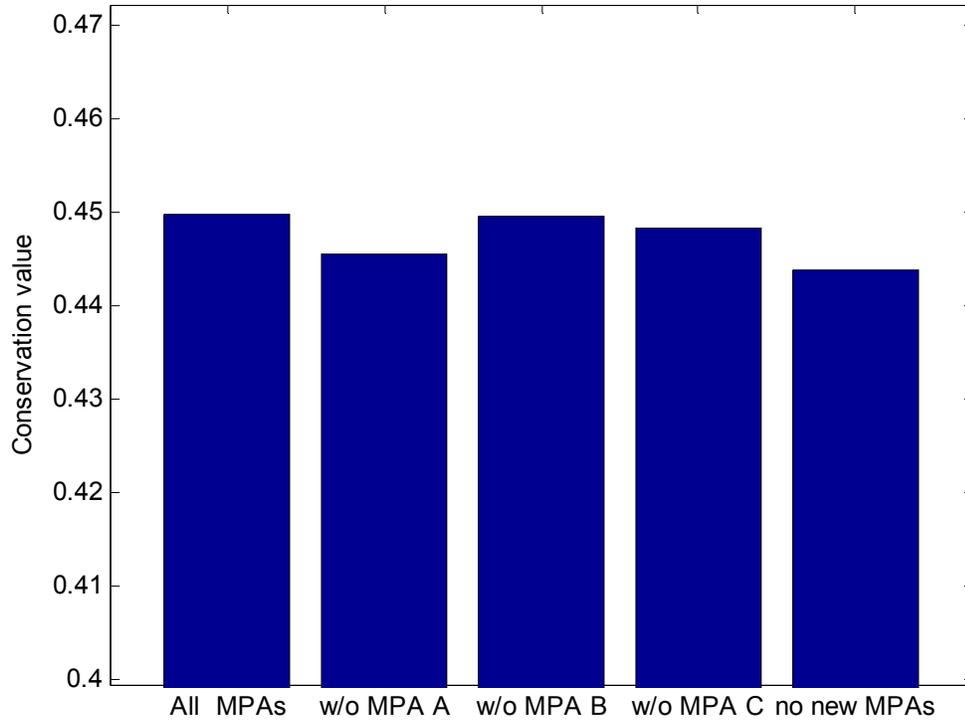


Figure 6. Economic value (profit with reserves as a fraction maximum sustainable profit without reserves) for the whole system, with all reserves (i.e. the whole MPA proposal), as well as with all reserves except reserve A, all except reserve B, all except reserve C and no MPAs.

