California MLPA Master Plan Science Advisory Team
Digestible Modeling Work Group
Spatially Explicit Models to Support Evaluation and Revision of Marine Protected Area Proposals
Revised May 27, 2008

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 MPAs, and (2) capture 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* (master plan) support general evaluation of the efficacy of MPAs as refugia[1] and connectivity within the network[2], but do so without calculating potential population effects or accounting for conditions outside the MPA network, the actual spatial structure of the seascape, and variability of fishing pressure on different species.

Spatially explicit population models may support further evaluation of the consequences of MPA design on a proposed network's ability to satisfy various goals of the MLPA. These models go beyond the scope of the master plan guidelines to calculate whether populations will persist and how the MPAs will affect fishery yield. They include, for example, potential contributions from MPAs that do not satisfy the guidelines, the status of the portions 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.

This document is intended to provide the MLPA Blue Ribbon Task Force and regional stakeholder group with a general synthesis of insights and results from application of two models to recently revised MPA proposals in the MLPA North Central Coast Study Region (NCCSR) and offer advice on how the models could be used to complement evaluation based solely on the master plan guidelines.

Description of Models

Members of the MLPA Master Plan Science Advisory Team (SAT) developed two models to quantify the effects of an MPA network over a simplified representation of the habitat landscape along the California Coast. Both models utilize spatial data on habitat and proposed MPA locations and regulations to simulate the population dynamics of fished species and generate predicted spatial distributions of species abundances and fisheries yields for each MPA proposal. The UC Davis Spatial Sustainability and Yield Model (UCD model) considers each fished species separately, while the Equilibrium Delay Difference Optimization Model

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[1] For an objective of protecting adult populations, based on adult neighborhood sizes and movement patterns, MPAs should have an alongshore span of 5-10 km (3-6 m or 2.5-5.4 nm) of coastline, and preferably 10-20 km (6-12.5 m or 5.4-11 nm).

[2] For an objective of facilitating dispersal and connectedness of important bottom-dwelling fish and invertebrate groups among MPAs, based on currently known scales of larval dispersal, MPAs should be placed within 50-100 km (31-62 m or 27-54 nm) of each other.

(EDOM) considers a fishing fleet that targets multiple fish species. Importantly, both models incorporate the population consequences of spatial fishing regulations.

The two models differ in details regarding, for example, how specific 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 are “equilibrium models”, in that they predict the state of the system over the long term rather than its dynamics over time[3]. Each model includes more or less the same structural elements and necessarily make assumptions regarding each of the following (see Appendix 1):

- larval dispersal distances
- larval settlement regulated by species density in available habitat
- growth and survival dynamics of the resident (adult) population
- reproductive output increasing with adult size
- adult movement (e.g., home ranges)
- harvest in areas outside of MPAs

As with any model, certain factors either cannot be addressed or have not been addressed to date. For example, the models do not consider all species likely to benefit from MPAs because they are designed only to represent fished species, and neither model explicitly accounts for potential mortality from incidental catch of the modeled species in other fisheries. Both models also require assumptions regarding future fishery management success, which is difficult to predict. The UC Davis model presents a “variable success” scenario based on a critical scientific reading of currently available information, but it is only one possible interpretation among many. The EDOM model includes measures of the behavior of the fishing fleet, but has not yet been parameterized using the fishing ground and effort information derived from the interviews conducted during the MLPA process. Both modeling groups are developing better, more realistic representations of oceanography, larval dispersal, and fisherperson behavior. These features are not available in the models at present, but could be explored further in other study regions.

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

Changes to Models Based on Public Review

Habitat inputs

Habitat maps for both models have been revised based on suggestions emerging from a review of the models by an MLPA North Central Coast Regional Stakeholder Group (NCCRSG) member. These revisions were of two varieties:

- Improving the process for making one-dimensional representations of the two-dimensional GIS habitat map; and
- Dealing with regions coded as 'unknown' in the GIS habitat maps.

Both models use an idealized, one-dimensional (straight line) representation of the NCCSR coastline. In general, this one-dimensional map is obtained by dividing the two-dimensional map into 1 km wide latitudinal strips and allowing each one-dimensional model cell to represent the habitat within one latitudinal strip. This process requires some special adjustments where the coastline is highly nonlinear, such as in the vicinity of Point Reyes and Drakes Bay. The review identified mistakes that both models had made in translating the habitat near Point Reyes into one-dimensional form; these errors have been corrected.

The second type of revision has to do with the large amount of shallow, nearshore habitat labeled as 'unknown' in the GIS habitat maps. Both models require an assumption about whether the habitat in a spatial cell is suitable for a particular species (e.g., hard rocky reef). Originally, regions of 'unknown' habitat were assumed to be unsuitable habitat in both models. Results from the EDOM model are potentially sensitive to violations of this assumption because The EDOM model quantifies habitat quality in terms of the total amount of hard habitat in a latitudinal strip. This calculation can be biased downward if much of the nearshore rocky habitat is (mis)classified as unknown. Based on the NCCRSG member’s suggestion, the EDOM model now assumes that unknown habitat regions are 50% rocky habitat, which presumably reduces any bias associated with the previous 0% allocation to rocky habitat. In contrast, the UC Davis model counts a strip as rocky habitat based simply on whether any hard habitat is present in that strip. Because the UC Davis model does not attempt to quantify the total amount of habitat within each latitudinal strip, the results from the UC Davis model results are less sensitive to how unknown habitat is treated in producing the one-dimensional habitat maps. Consequently, no additional habitat adjustments were necessary for the UC Davis model.

Both models are still potentially affected by one additional bias: areas of steep relief appear smaller on a two-dimensional map relative to areas of shallow relief, which can cause the models to overestimate the contribution of the latter. As a consequence of how habitat maps are translated into model inputs, results from EDOM model are expected to be more sensitive to this bias than are results of the UC Davis model. At this time neither modeling group has developed a reliable framework for addressing this issue and it is noted as a potential source of bias.

Accounting for fishing outside of MPAs

The SAT recognizes that the effects of fishery management on the portion of stocks *outside* MPAs strongly influence the consequences for that stock of implementing an MPA network. As noted in a comment on the models evaluation of MPA packages should account for the context of future fishery management. To this end, the SAT recommends the use of spatially explicit models that incorporate the effects of fishing outside of MPAs to inform the MLPA process.

The EDOM and UC Davis models predict the status of a stock at a future steady state, and therefore require an assumption regarding the fishery management policy that affects that stock and that will be in effect as the MPA network approaches equilibrium. Predicting future policy is difficult. As a general approach, model results have been presented for analysis of MPA packages under three possible future fishery management scenarios [“conservative”, “maximum sustainable yield (MSY)-type”, and “unsuccessful”] to bracket a broad range of possible consequences of implementing MPA networks. In each scenario, the definition of future management is based on either a fraction of lifetime egg production (FLEP) for the stock (used in the UC Davis model) or fishing mortality (F) used in the EDOM model.

One modeling group (UC Davis) has demonstrated how to include stock-specific predictions of future fishery management in evaluating MPA proposals, by (1) developing predictions for the likelihood of each of the three modeled future fishery management scenarios based on interpretation of available information for the modeled stocks (e.g., stock assessments, rebuilding plans, etc.), and (2) applying these distributions to produce weighted conservation and economic metrics for each package. (see below for further discussion of this example in the context of MPA package evaluations). Other predictions of future fishery management can also be used to synthesize model results in this manner.

Although current exploitation rates provide a concrete basis for one prediction of future management conditions, these predictions must recognize that current status is a result of past actions. Conditions are expected to respond over time as changes in management policies and current actions take effect, and as such, might provide only limited insight to future management scenarios. Rigorous, robust, and realistic predictions of the likelihood future fishery management scenarios ranging from ‘best-case’ to ‘worst-case’ could be very useful for informing stakeholders and the MLPA Blue Ribbon Task Force (BRTF) about the potential performance of proposed MPA packages.

Accounting for responses of non-modeled species to MPAs

Models have been run for a common set of broadly, but not comprehensively, representative species, with a focus on species subject to harvest, yet MPAs are expected to affect a much more diverse suite of species. Both models have examined the consequences of variation in larval dispersal and adult home range for performance of proposed MPA packages across a range of future fishery management scenarios. These results, which are presented in more detail below, are intended to support cautious extrapolation of model insights to non-modeled species that have life histories similar to those of the modeled species, but that differ in dispersal behavior and exposure to harvest.

Model Outputs

The two models produce similar outputs that can be described by two basic concepts: 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). Conservation value is essentially a measure of MLPA goals 1, 2, and 6[4] while economic return is a potential cost of implementing MPAs. Because the models differ in various details of their structure, the exact forms of the measures produced by each model also differ. Nevertheless, both models yield some common insights on MPA proposals. Generally, the models found the following:

1. Increasing the size or decreasing the spacing of MPAs generally leads to an increase in the conservation value of the network. (The converse is also generally true).

2. The relationship between how measures of conservation value and economic return respond to changes in MPA configuration depends critically on what is happening outside of MPAs.

   If fishing effort outside MPAs is so high that populations become unsustainable, MPAs can produce a situation in which both conservation value and economic return are increased. In contrast, if fishing effort outside of MPAs is maintained to achieve sustainable levels of harvest, a trade-off emerges between conservation value and economic return, increasing one reduces the other. Optimizing effort outside MPAs, through other fisheries management actions, may substantially reduce the potential economic consequences of MPAs.

   Evaluating MPA proposals therefore requires information regarding the future state of the populations outside of the MPAs (i.e., How much fishing is allowed outside MPAs?). This requires an assumption regarding the future fishery management success, a projection that includes substantial uncertainty.

3. The effect of MPAs on species-specific conservation value and economic return depends strongly on larval dispersal distance and adult home range size (or other movement behavior).

   Whether proposed MPAs can convey any conservation value to individual species depends on whether the proposed MPAs satisfy the requirements of providing adequate refuge and allowing sufficient connectivity for populations to persist and for the marine ecosystems to function as naturally as possible. Networks with small MPAs can fail to sustain species with large home ranges (by exposing adults to harvest) or long larval dispersal ranges (by failing to retain sufficient offspring within protected areas). The fate of such species is also affected by management outside of MPAs.

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

Likewise, the economic return associated with proposed MPAs depends on movement of individual species, as this determines whether the proposed MPAs sustain populations, and the degree to which proposed MPAs effectively augment the harvestable portion of the populations.

Evaluation of North Central Coast MPA Proposals (April 2008 versions)

Proposals' impacts on conservation value and economic return

When looking at fin-fish species[5], the models show similar results. Figures 1 and 2 below are sets of graphs from the UC Davis and EDOM models respectively. In each, the upper left graphs represent the relative level of conservation value of each draft proposal for various levels of FUTURE fishery management scenarios ("conservative", "MSY-type", and "unsuccessful"). Conservation value is measured as either sustainability - in terms of the proportion of habitat in which production exceeds a critical fraction of lifetime egg production - or biomass. Higher conservation values are farther to the right hand side of the graph.

The lower right graphs represent the relative economic return of each draft proposal for the same levels of future stock status. Economic return is measured as either fisheries yield or total catch with respect to maximum sustainable yield. Higher economic returns are towards the top of this graph.

The lower left graphs combine conservation value and economic return from the other two graphs. Thus they represent the "tradeoffs", if any, between conservation value and economic return. In all of the figures the changes in conservation value or economic return that can be expected for each proposal can be determined by comparing the value within the same future fishery management scenario (i.e., within the same color).

Results in these graphs tend to group by level of future management scenario. For example, the orange marks (unsuccessful future management) tend to group together, the blue marks (MSY-type future management) tend to group together, and the purple marks (conservative future management) tend to be together. For each model, in an unsuccessful future management scenario, all proposals allow for both increased biological and economic success.

To examine the consequences of variability among stocks with respect to future management and resultant stock status, an additional analysis has been conducted using stock-specific results from the UC Davis model and predictions by the Davis modeling group of current stock status based on critical readings of recent stock assessments and other relevant publications. In this analysis, the probability that each stock is in one of the three modeled fishery management scenarios is used to weight the predicted consequences of an MPA package for that stock, and subsequent results are combined across species to yield weighted conservation and economic metrics for the assemblage (hollow symbols in Figure 1).

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[5] Mean results for cabezon, black rockfish, lingcod, canary rockfish, and California halibut, as these are the five species for which both models were run.

In contrast to the UC Davis model, the EDOM model explicitly assumes that all modeled stocks experience the same fishing intensity as part of a mixed-stock assemblage. The model supports optimization of effort over space to maximize yield (profit) for this fishery. The hollow symbols in Figure 2 represent these results.

The two models both clearly indicate that potential increases in both Conservation Value and Economic Return depend on the future fishery management scenario for populations outside MPAs.

Figure 1. Results of UC Davis Model for each proposal in respect to conservation value measured as the proposals' resulting change in sustainability compared to no-action (upper left), economic return measured as the proposals' resulting change in yield compared to no-action (lower right), and tradeoffs between the two (lower left) when run for finfish species. Each proposal is compared at a variety of fraction of lifetime egg production (FLEP) values representing potential future fishery management results.

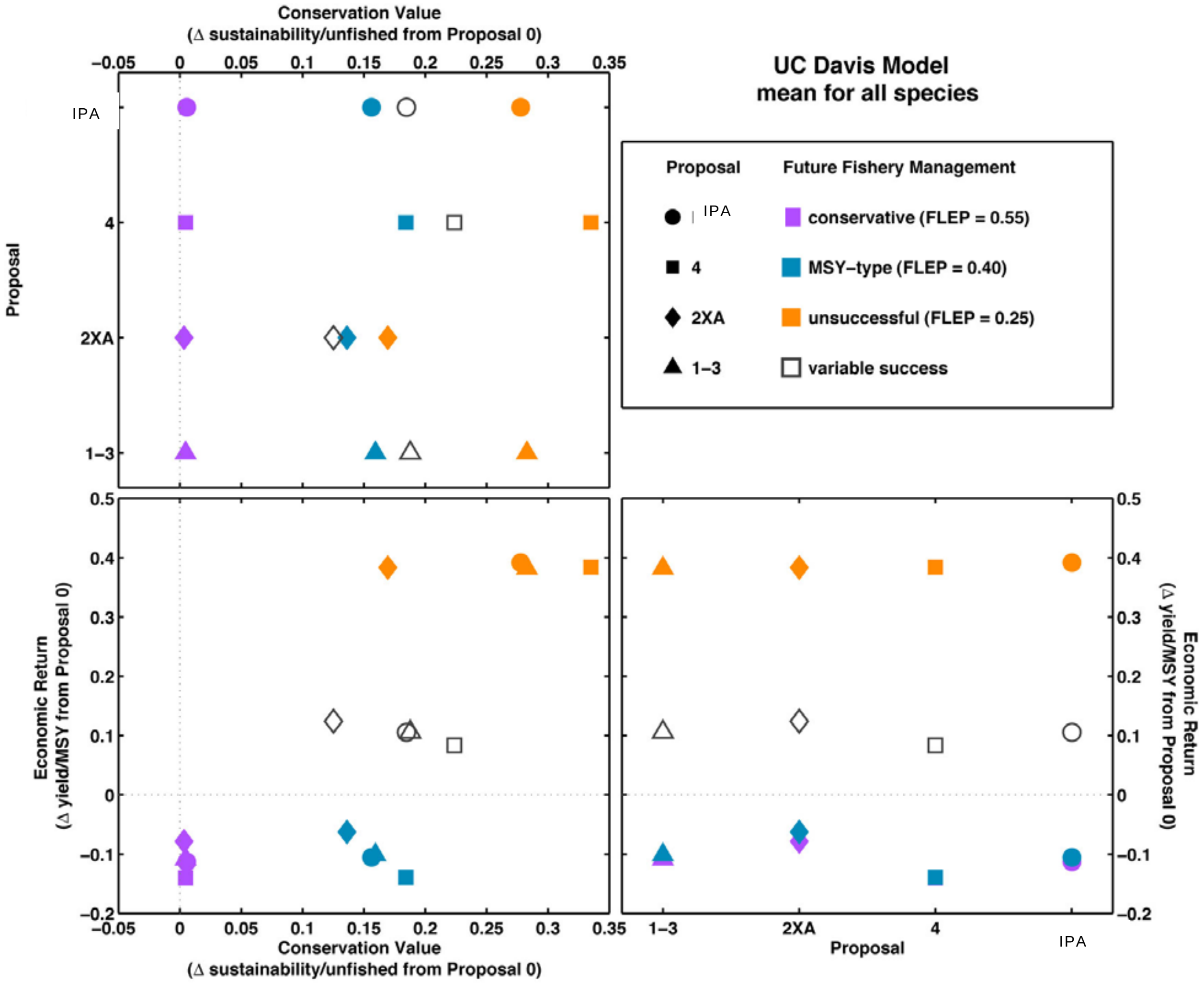
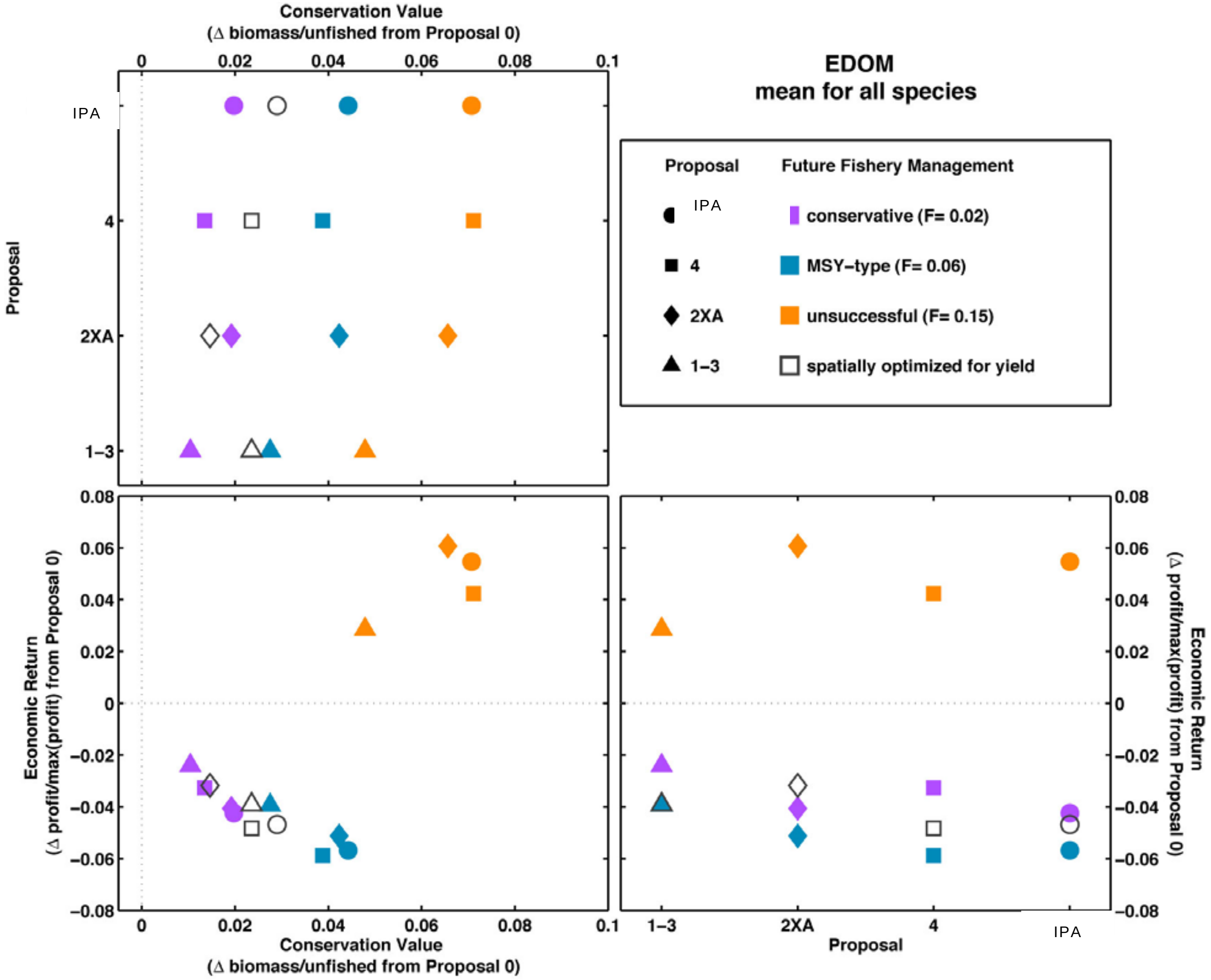


Figure 2. Results of EDOM Model for each proposal in respect to conservation value measured as the proposals' resulting change in biomass compared to no-action (upper left), economic return measured as the proposals' resulting change in profit compared to no-action (lower right), and tradeoffs between the two (lower left) when run for finfish species. Each proposal is compared at a variety of fishing removal (F) values representing potential future fishery management results.

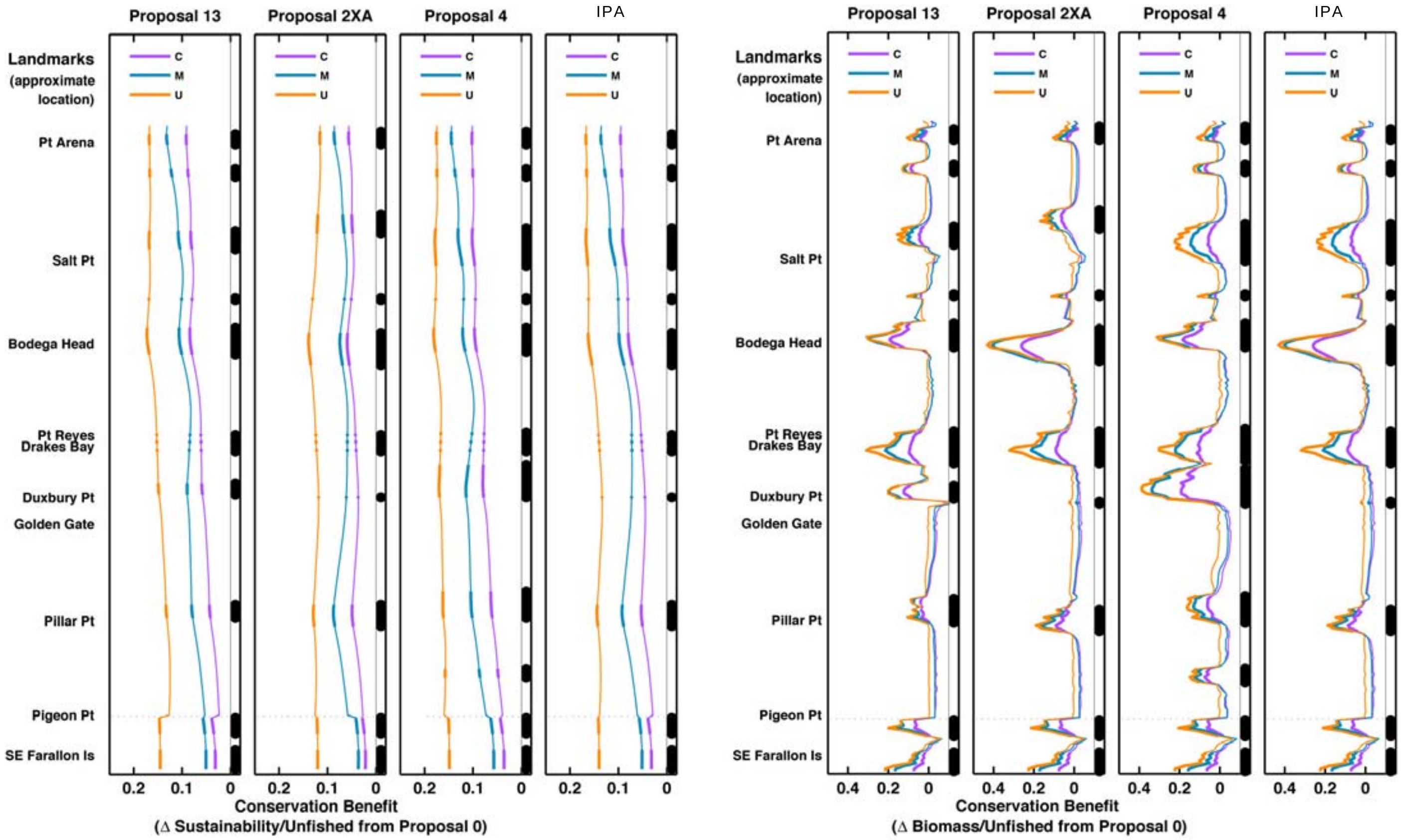


Proposals' impacts on sustainability across the region

One question regarding MPA proposals that these models can help answer is that of the impact of the MPAs on conservation outside their boundaries. MPA size and placement interacts with habitat, larval dispersal, and adult home ranges to create complex spatial consequences. In other words, the proposed size and specific placement of MPAs change their potential to provide adults and larvae to areas outside their borders. The two models can help predict the resulting supply of larvae to outside areas (UC Davis) and the resulting adult biomass of modeled fish species across space (EDOM).

The UC Davis model shows that larval supply tends to increase with new MPAs as compared to no-action (Proposal 0). This effect is similar across proposals, but there are some spatial differences (Figure 3). As with other factors, the largest change (relative to no-action) occurs when future fishery management is “unsuccessful”. The EDOM model shows that adult biomass also increases with new MPAs as compared to no-action. This effect is greatest within MPAs and, as with larval supply, the largest change occurs in an “unsuccessful” future management scenario (Figure 3). These modeled changes in biomass are consistent with empirical data from MPAs in California and elsewhere and could be used to develop predictions for monitoring success of MPAs.

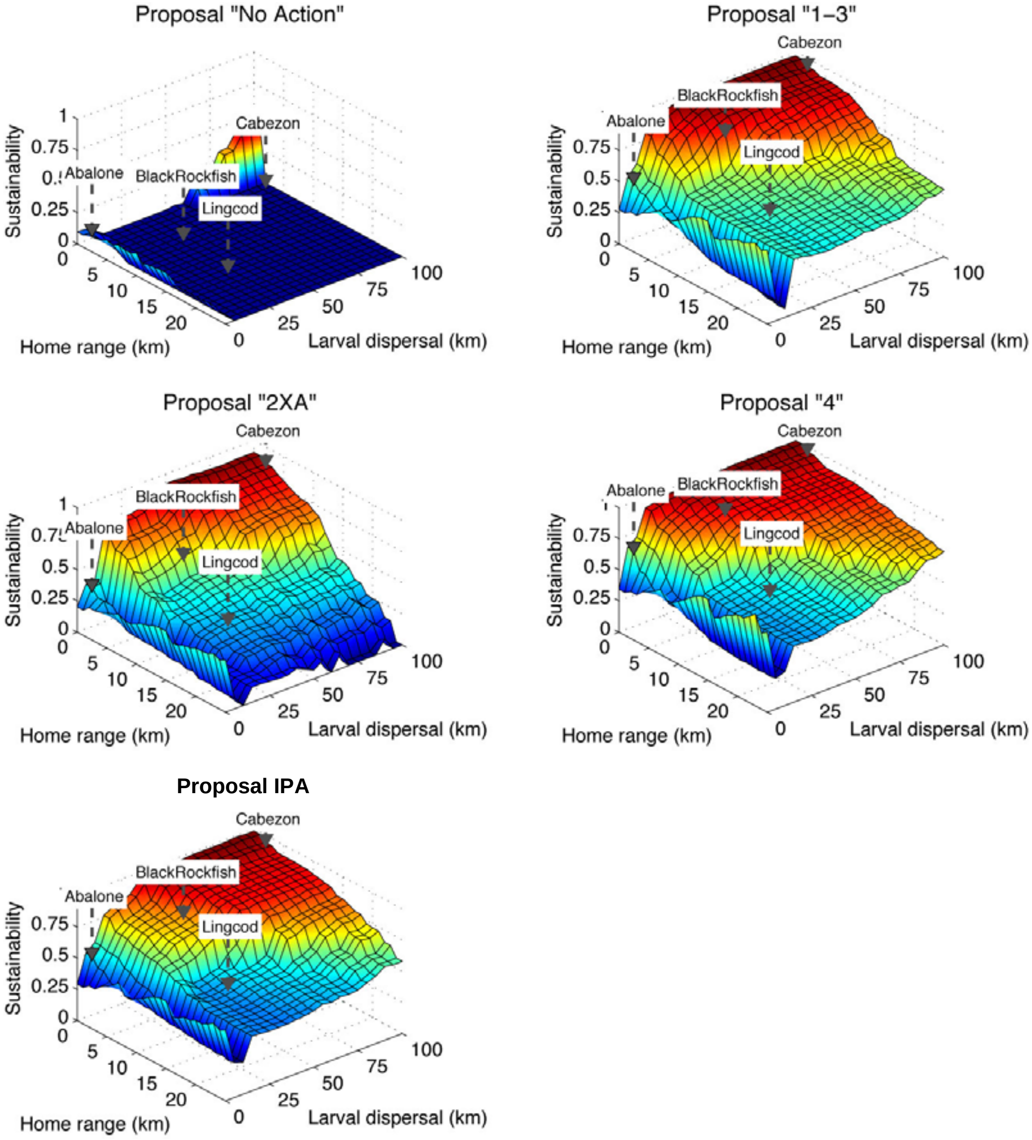
Figure 3. Spatial conservation benefit of proposed MPAs across the north central coast study region. Benefit is compared for larval supply (left graph, UC Davis Model) and adult biomass (right graph, EDOM Model). In each, dotted lines indicate non-MPA areas and solid lines MPA areas. Purple lines represent conservative future management (C), blue lines represent MSY-type (M), and orange lines represent unsuccessful (U).



Applicability of models to non-modeled species

It was not possible to model all species that may be affected by proposed MPAs, but the models can provide insight on potential effects on species not modeled. Figure 4 compares the conservation value from the three proposals and no-action across a variety of species adult home ranges and larval dispersal distances, with some modeled species identified. Figure 4 demonstrates that different species will receive different conservation values from any given proposal and that, while not all species are modeled, the modeled species represent a range of potential life history combinations. Figure 4 also indicates that the proposals with the highest conservation value in Figure 1 have high conservation value across a greater range of species' life histories.

Figure 4. Comparison of relative conservation value of each MPA proposal for rocky reef species with different combinations of parameters describing two types of movement: larval dispersal distance and adult home range size. The height of each point on the surface represents the modeled conservation value for a different hypothetical species. The results for four of the modeled species are indicated with arrows. The surface between these points provides an indication of how species with different larval dispersal or adult home range would be affected by the proposed MPAs.


Proposal "No Action"

Proposal "1–3"

Proposal "2XA"

Proposal "4"

Proposal IPA

Overall proposal rankings in the EDOM model do not change in response to either home range or larval dispersal changes. As either of these life history traits changes, the relative biological and economic success of any individual proposal does not (figures 5 and 6). This remains true regardless of whether individual species are compared or whether they are grouped together as in figures 1 and 2.

Figure 5. Relative ranking of stakeholder proposals for conservation value (biomass index) and economic return (catch index) at varying home range sizes in the MSY-type future management scenario. The home range multiplier is factor by which known home range is multiplied to determine sensitivity of the model to changes in this parameter. A multiplier of 2 doubles the modeled home range of a species.

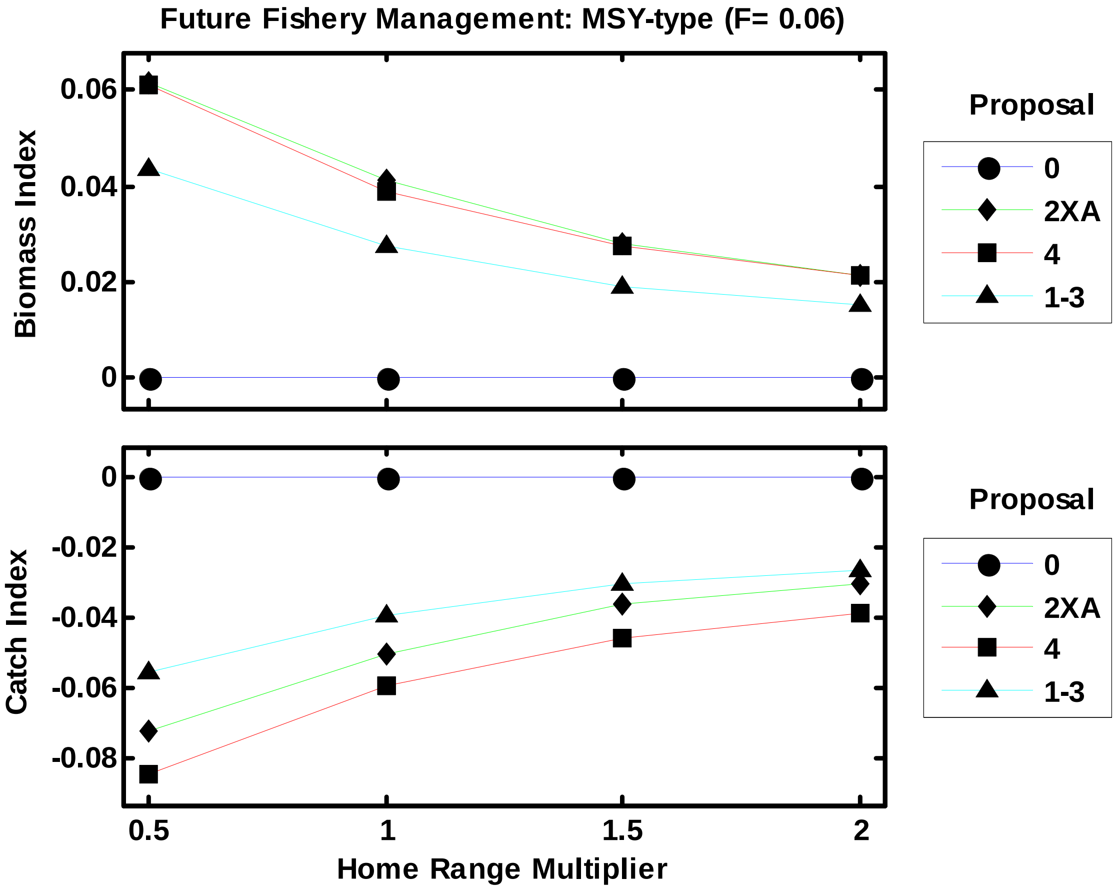
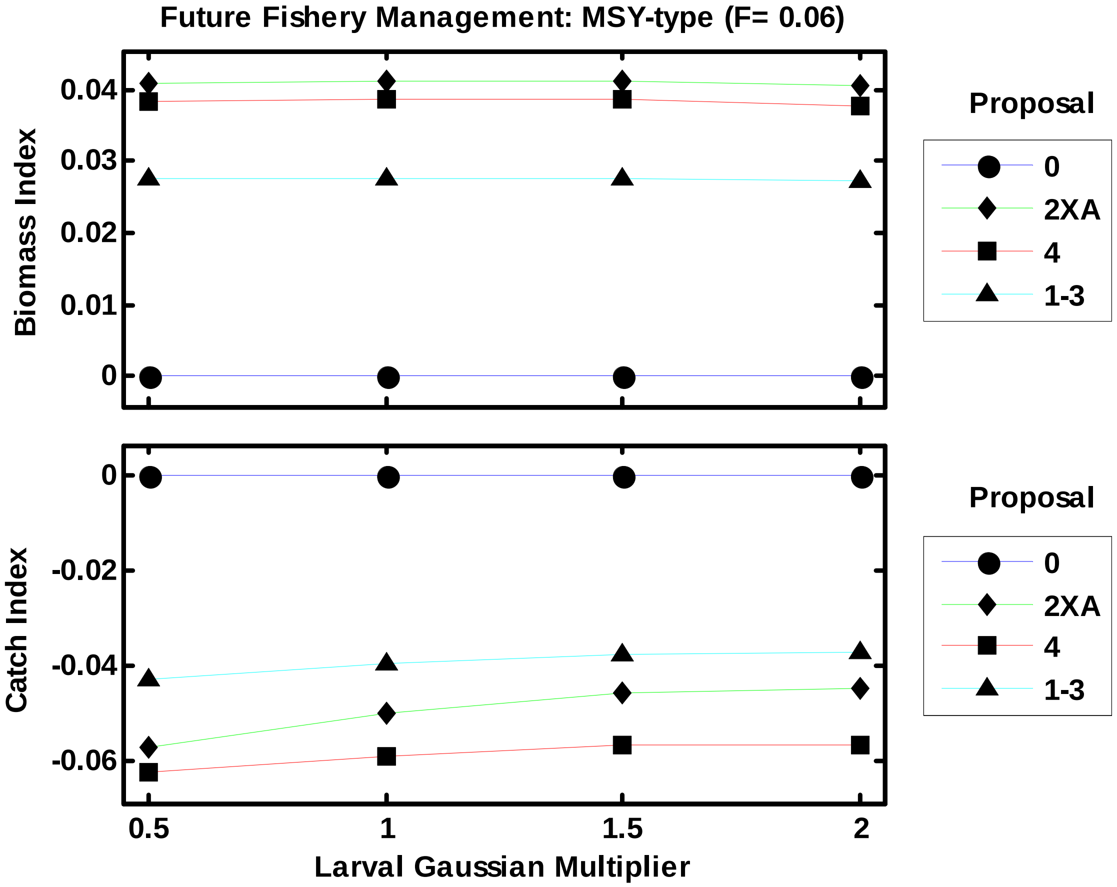


Figure 6. Relative ranking of stakeholder proposals for conservation value (biomass index) and economic return (catch index) at varying larval dispersal distances in the MSY-type future management scenario. Larval Gaussian multiplier is a factor by which the bell shaped dispersal curve (most larvae settling near the source and less at greater distances) is multiplied to determine sensitivity to changes in this parameter. The greater the multiplier, the farther larvae will disperse in the model.



Summary of Evaluations - Integrated Preferred Alternative and NCCRSG Proposals

- If conservation value is the only objective, regardless of economic return, there is a difference in results depending upon the model:
    - In the UC Davis model, Proposal 4 is projected to be more successful under all modeled possibilities of future fishery management.
    - In the EDOM model, Proposal 4 is projected to be more successful under unsuccessful fisheries management, followed closely by the Integrated Preferred Alternative. The Integrated Preferred Alternative is projected to be more successful under MSY-type, conservative, or spatially optimized future fishery management.
- Economic losses (in terms of lower economic return than no-action) found in conservative or MSY-type management may turn to gains if future management is unsuccessful at sustaining stocks:
    - Conservative or MSY-type Management: All proposals result in some degree of economic loss (lower economic return than no-action), consistent with predictions from other methods (e.g., Ecotrust evaluations). This is also true of spatially optimized management in the EDOM model.
    - Unsuccessful Management: In the UC Davis model, all proposals increase yield with little difference among them. In the EDOM model, increases in economic return result from all proposals with Proposal 2-XA showing the greatest increase followed by the Integrated Preferred Alternative, Proposal 4 and Proposal 1-3.
- If tradeoffs are considered, the two models have different results:
    - In the UC Davis model, Proposal 4 ranks highest in an unsuccessful future management scenario for both conservation value economic return. For both MSY-type and variable future management, the proposals vary in success with Proposal 2-XA ranking highest for economic return and Proposal 4 highest in conservation value.
    - In the EDOM model, no proposal ranks highest in both conservation value and economic return in any management scenario and results change depending on which scenario is modeled. In an unsuccessful scenario, Proposal 2XA has the highest economic return and Proposal 4 highest conservation value. In MSY-type and conservative future management scenarios, proposal 3 ranks highest for economic return and the Integrated Preferred Alternative highest for conservation value. In an optimized yield scenario, proposal 2-XA has the top rank for economic return, and the Integrated Preferred Alternative remains the highest rank for conservation value.
- The ordering of proposals with respect to sustainability in the UC Davis model remains the same when species with a wider range of life histories are considered.
- Ranking of proposals (by individual species or composite) in the EDOM model is generally insensitive to home range and larval dispersal. While exact values may change, the overall rank of each proposal generally remains the same regardless of how these traits are modeled.

SAT Recommendations for Spatial Modeling to Guide Creation, Evaluation and Revision of MPA Proposals

Regarding the use of spatially explicit models to support the MLPA process, the SAT recommends that such models be integrated more completely into current and, especially, future efforts to design and evaluate MPA networks. Specifically, the SAT recommends:

1. Models such as EDOM and UCD and others that have been reviewed by the SAT (such as Marxan/Marzone) should be introduced early in the planning process and, where feasible, should be made available as tools for use in the stakeholder process; and
2. Models should become an integral part of the evaluation process to supplement the process outlined in the master plan.

Two models (EDOM and UC Davis) have been extensively reviewed by the SAT for evaluation purposes and should be carried forward. Future refinements of these two and other models will be evaluated by the SAT as appropriate. Areas of potential future development include:

1. Better representation of the two-dimensional aspects of population dynamics (both in larval and benthic stages);
2. More realistic representation of larval dispersal; and
3. Better representation of the redistribution of fishing effort in response to MPAs (i.e., economic -based).

In making this recommendation, the SAT emphasizes that the models' conceptual principles are consistent with those upon which existing 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 an MPA network. In doing so, it complements the evaluation of MPA proposals 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 alone (i.e., that specific sizes and spacing (or ranges of these) are adequate, but others are not). Rather the models estimate the potential conservation and economic consequences of each proposed spatial configuration of MPAs, so that they can be evaluated directly. The SAT recommends that integration of spatially explicit models continue in order to support direct examination of the consequences of management outside MPAs and simultaneous evaluation of conservation and economic performance measures.

Appendix 1. Model assumptions for key structural elements in the UC Davis and EDOM models

UCD Model Assumptions	EDOM Assumptions
Larval Dispersal: Larvae disperse over a range of distances, but settlement declines the farther an individual is from its parent. Only larvae that find suitable habitat survive. A maximum number of larvae settling in any location survive to enter the adult population.	**Larval Dispersal:** For each species, larvae are distributed along the coast using a bell-shaped settlement curve. Successful survival of these larvae may be limited by larval settlement or availability of nursery habitat.
Spillover: 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.	**Spillover:** Two types of movement are modeled: irreversible movement of fish to seek new home ranges, and movement within home ranges. Irreversible movements are assumed to be relatively rare, but home ranges can be quite large (10-20km alongshore). Movement within home ranges creates an “exploitable biomass” that is a sum of contributions from surrounding nursery or spawning areas, hence representing “spillover” effects near MPA boundaries.
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.	**Growth and Reproduction:** Growth and survival follow a previously published growth curve and survival is independent of fish age. Egg production is assumed proportional to total weight of older fish.
Fishing Pressure: Harvest of each species is modeled separately. Fishing regulations follow those set forth in each draft proposal, and both recreational and commercial fishing are considered. Fishing effort can be modeled in any of several ways: 1) effort is equal across space and implementing MPAs does not change effort outside MPAs, 2) effort is equal across space but total effort is redistributed and increases outside of MPAs, and 3) effort is proportional to fish biomass (the ‘gravity model’ in which fishing is concentrated where there are more fish).	**Fishing Pressure:** Effort for each gear type is assumed to take all species in each cell. When effort distributions are predicted (rather than optimized) using gravity model, effort is proportional to total fish biomass outside MPAs (summed over species and ages) and weighted by relative fish prices.