California MLPA Master Plan Science Advisory Team
DRAFT: A synthesis of insights and results from spatially explicit models to support evaluation and revision of MPA proposals.

Prepared by Eric P. Bjorkstedt

Introduction

For a set of marine protected areas (MPAs) to function effectively as a network in satisfying various goals of the Marine Life Protection Act (MLPA), regardless of the level of fishing in non-MPA areas, the MPAs must (1) provide adequate protection from harvest to the portion of a species (adult) population resident in the MPA, and (2) capture a sufficient fraction of the populations' total larval production to maintain densities within the MPAs above persistence thresholds. The so-called 'size and spacing guidelines' (SSG) in the MLPA Master Plan support qualitative evaluation of the efficacy of MPAs as refugia[1] and connectivity within the network[2], but do so independent of the context of conditions outside the MPA network, the actual spatial structure of the seascape, and [… something about being consistently effective across diverse species only at large & close part of range per the Moffitt et al analysis.]

Spatially explicit population models are now available to support evaluation of the consequences of MPA size and spacing for a proposed network's ability to satisfy various goals of the MLPA. These models go beyond the scope of the SSG to include, for example, potential contributions from MPAs that do not satisfy the SSG, the status of populations outside of MPAs (which depends on fishery management), and the potential costs associated with achieving a desired conservation outcome. Here, we provide a general synthesis of insights and results from application of the models to recently revised proposals for MPA networks in the North Central California Study Region, and offer advice on how the models can be used to complement the SSG to inform evaluation of MPA network proposals. Detailed descriptions of the rationale for the SSG and of the structure and assumptions of each of the two population models are available elsewhere[3] and will not be repeated here.

What are the models?

Two models (REFS) have been developed to quantify the effects of imposing an MPA network over a simplified representation of the habitat landscape along the California Coast. Although they differ in many 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[4]. Each includes more or less the same structural elements: (a) larval dispersal, (b) density-dependent regulation of settlement to available habitat, (c) growth and survival dynamics of the resident (adult) population, (d) size-dependent fecundity, (e) adult movement (e.g., home ranges), and (f) harvest in areas outside of MPAs. Specific assumptions embodied in each model regarding how each of these processes operate and the biological parameters for each of the target species are provided in Tables X and Y.

---

[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.
[3] Walters REF, Botsford REF, SSG REF
[4] Note that equilibrium models do not account for the costs incurred during the time required to reach steady state. (draw more from Walter et al.'s discussion?).

UCD Model Assumptions	EDOM Assumptions
Larvae disperse over a range of distances, but settlement declines exponentially with distance from origin. Only larvae that disperse to suitable habitat survive. There is a maximum number of larvae settling in any location that will survive to enter the adult population (i.e., density-dependent recruitment)	For each species, larvae are distributed along the coast from each spatial cell using a bell-shaped settlement curve. Recruitment from these larval may be limited by larval settlement or availability of nursery habitat (Beverton-Holt recruitment curve with habitat-dependent maximum recruitment).
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.	Two types of movement are modeled: irreversible dispersal of fish to seek new home ranges, and movement within home ranges. Irreversible dispersive movements are assumed to be relatively rare (few percent of spawning fish), but home ranges can be quite large (10-20km longshore). Movement within home ranges creates an “exploitable biomass” for each model cell that is a sum of contributions from surrounding nursery or spawning cells, hence representing “spillover” effects near MPA boundaries.
Growth, survival, and egg production after reruitment follow published accounts for each species. In general, individuals grow asymptotically to a maximum length, their weight is proportional to length cubed (L^3), 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 survival after recruitment follow Ford-Brody growth curve and age-independent survival rate, and egg production assumed proportional to total weight of recruited (older) fish
Harvest of each species is modeled separately. Fishing regulations for each species in each spatial cell 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 in non-MPA cells (the simplest assumption), 2) effort is equal across space but total effort stays the same after MPAs are implemented (effort is redistributed and increases outside of MPAs), and 3) effort is proportional to fish biomass in a cell (the ‘gravity model’ in which fishing is concentrated where there are more fish).	Effort for each gear type is assumed to take all species in each cell, i.e. is not species-selective. When effort distributions are predicted (rather than optimized) using gravity model, effort for each cell is proportional to total vulnerable fish biomass (summed over species and ages) on that cell, weighted also by relative fish prices.

What do the models tell us?

The two models produce similar sorts of results (e.g., predictions of biomass and its distribution over space, predictions of fishery yield, etc.) that can be boiled down into two basic concepts: a measure of conservation value (e.g., biomass or sustainability), and a measure of (extractive) economic return (e.g., yield). 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, general insights to the consequences of implementing a network of MPAs. Insights from unique (but presumably replicable) analyses pursued by the two modeling groups are included in the following summary.

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 protection and measures of (extractive) economic return respond to changes in MPA configuration depends critically on what is happening *outside* of MPAs (Figure 1).

   When fishing effort outside of MPAs is unsustainable and the stock is overfished, implementing MPAs can yield a win-win situation in which both biomass and yield are increased.

   In contrast, when fishing effort outside of MPAs is maintained to achieve sustainable levels of harvest, a trade-off emerges between biomass and yield. Optimizing effort outside of MPAs can substantially reduce the economic consequences of MPAs.

   Evaluating MPA package proposals therefore requires information regarding the future state of the populations outside of the MPAs (i.e., what will the populations outside MPAs look like when the MPA network reaches a steady state corresponding to the model predictions?). This requires an assumption regarding the future consequences of current and future fishery management policies, a projection that will likely include substantial uncertainty. Indeed, stakeholders have varying beliefs regarding current conditions, and the science on this matter is also uncertain.

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

   Whether a proposed network of MPAs can convey any benefit to a species depends on whether the network satisfies the requirements of providing adequate refuge and allowing sufficient connectivity. Networks with insufficiently large MPAs can fail to protect species with large home ranges (by exposing adults to take) or long larval dispersal ranges (by failing to retain sufficient offspring within protected areas). The fate of such species is determined by management outside of MPAs.

   The economic value associated with an MPA network likewise depends on movement, as this determines the degree to which MPAs effectively augment the harvested portion of the population.

How can the models guide evaluation and revision of proposed MPA packages?

The models predict what is expected to arise (eventually) after implementing proposed MPAs, and can make such predictions for a heterogeneous habitat seascape under any of a wide range of biological and management conditions. In doing so, they can predict responses to MPA configurations that might otherwise be missed by rules (or ranges) of thumb derived from simpler models and simpler habitat distributions. The models' greater flexibility therefore allows them to strongly complement evaluations based on the SSG by reducing the potential for application of the SSG to yield erroneous conclusions, say as a consequence of applying the SSG to a case that differs substantially from the conditions for which the SSG were developed. Further, the SSG evaluate only the conservation value of an MPA package; the models integrate this analysis with predictions of the economic value as well. The models also ensure that the effects of management outside of MPAs can be considered appropriately in evaluating their potential costs and benefits.

Comparing results among different proposals can reveal the costs and benefits of a particular MPA. When the size or spacing (or presence) of an MPA differs across packages, the model reveals which configuration leads to higher sustainability and/or higher yield. Moreover, spatially explicit predictions of where biomass and yield are concentrated or lacking provide fodder for considering how to adjust MPA proposals to achieve desired conservation or economic results.

The models also offer the potential to identify MPA configurations that are clearly inferior within the set of proposed packages. Under the assumption of sustainable fisheries outside of MPAs, evaluations across a suite of MPA proposals sketch a frontier of (apparent) maximum conservation-yield combinations achievable. MPA configurations that lie closer to the origin of the 'yield-by-conservation' plot are not providing maximum benefits according to either measure for the costs incurred in the other. If it is assumed that fisheries outside of MPAs will be managed for sustainable yield, efforts to improve MPA proposals should seek configurations that move away from the origin and that move in the desired direction along the conservation-economic tradeoff.

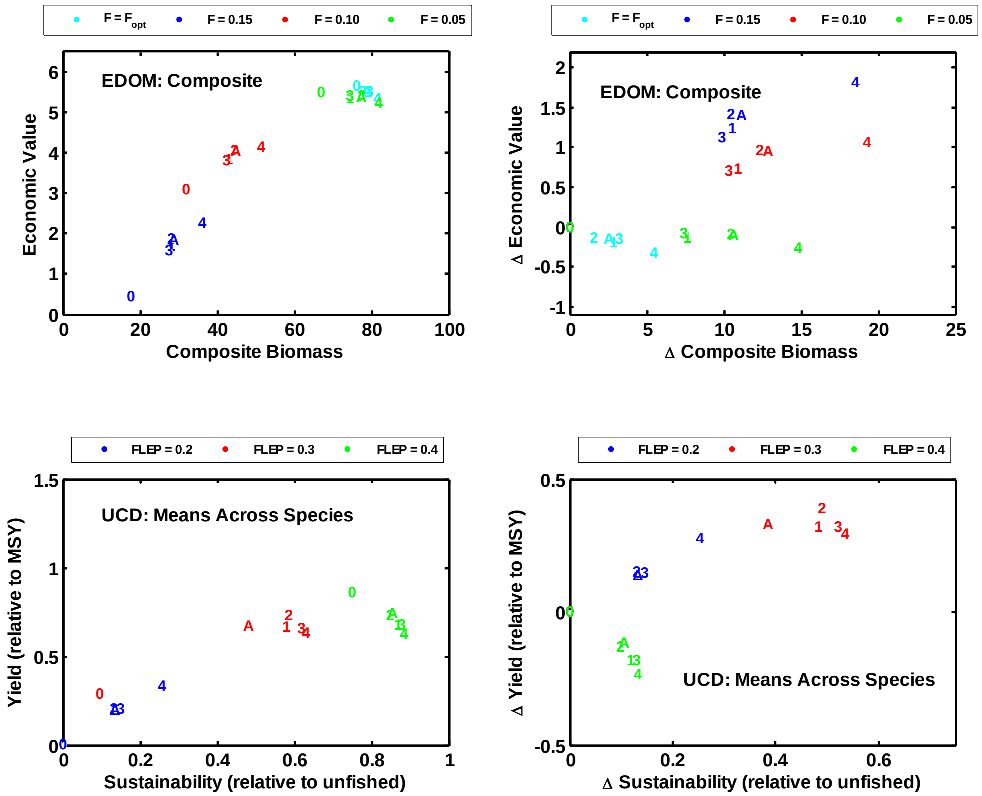
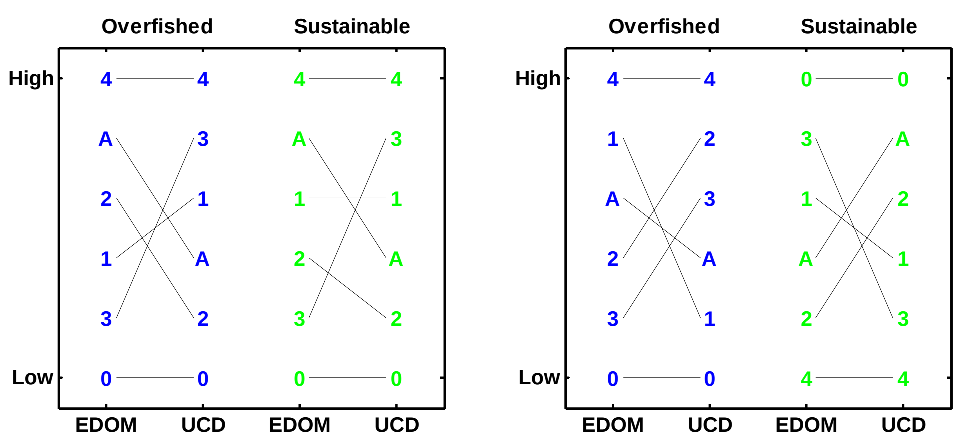


Figure 1. Left-hand plots: conservation-economics relationships for EDOM (top) and UCD (bottom) models. Colors indicate position along overfishing-sustainable yield continuum (blue = heavy overfishing; red = moderate overfishing; green = sustainable fishing). Right-hand plots: relationships between differences in conservation & economics measures relative to appropriate "no action" case for EDOM (top) and UCD (bottom) models. Colors indicate position along overfishing-sustainable yield continuum (blue = heavy overfishing; red = moderate overfishing; green = sustainable fishing).

Rankings



Ordered rankings of MPA packages for EDOM and UCD models. Rankings based on comparison to "No Action" under same conditions. "Overfished" indicates F = 0.15 (EDOM) or FLEP = 0.2 (UCD); "Sustainable" indicates F = 0.05 (EDOM) or FLEP = 0.4 (UCD).

Left hand plot: Conservation measure: Composite Biomass (EDOM) or Sustainability (mean across species) (UCD) (note: absolute differences among middle 4 and sometimes all 5 MPA packages are typically small.)
Right hand plot: Economic Measure: Economic Value (EDOM) or Yield/MSY (UCD) (note: absolute differences among middle 4 and sometimes all 5 MPA packages are typically small.)

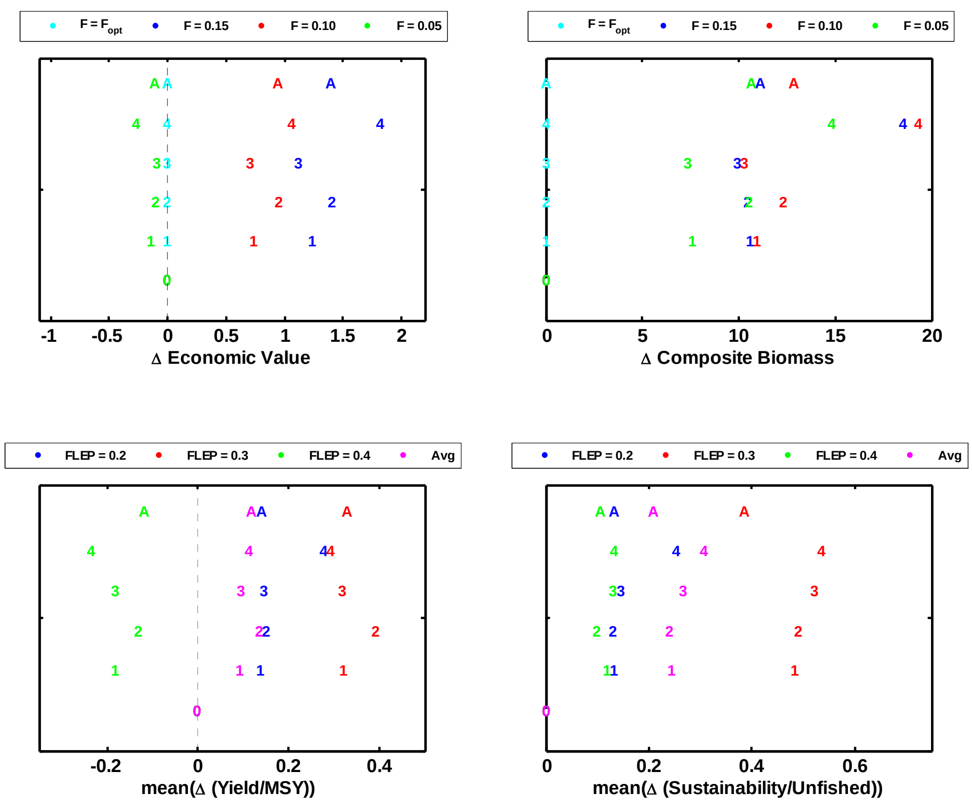


Figure X. Graphical representation of package rankings according to economic measures (Economic Value or Yield relative to MSY) and conservation measures (Composite Biomass or Sustainability relative to unfished state) for a set of future fishing scenarios ranging from heavily overfished outside of MPAs to well managed outside of MPAs (blue = heavy overfishing; red = moderate overfishing; green = sustainable fishing). Top plots: EDOM; bottom plots: UCD. Magenta values represent average rankings for UCD model, assuming equal likelihood for all three fishery scenarios.

Appendix 1 – Model Parameters

a) UCD Model – Life History Parameters

Parameter	Black rockfish	Cabezon	Canary rockfish	Lingcod	California halibut
Pelagic larval duration	n/a	n/a	n/a	n/a	n/a
Mean larval dispersal	40 km	100 km	40 km	35 km	45 km
Home range diameter	6 km	2 km	40 km	15 km	30 km
Length-at-age (cm) von Bertalanffy equation: $L(t) = L_\infty\left(1 - \exp\left(-k\left(t - t_0\right)\right)\right)$				Different equation form: $L(t) = L_\infty + \left(35.1 - L_\infty\right)^{k(1-t)}$	TL
L_∞	44.2	62.12	58.9	112.8	147.7
k	0.33 yr^{-1}	0.18 yr^{-1}	0.146 yr^{-1}	0.145 yr^{-1}	0.10 yr^{-1}
t_0	0.75 yr	-1.06 yr	-0.84 yr	n/a	-0.02 yr
Weight-at-length (kg) $W = \alpha L^\beta$					SL
α	1.68×10^{-5}	9.2×10^{-6}	2.45×10^{-4}	1.76×10^{-6}	1.15
β	3	3.187	2.91	3.3978	3.088
Maximum age	50 yr	15 yr	85 yr	20 yr	30 yr
Age at maturity	7 yr	3 yr	7 yr	4 yr	4 yr
Fecundity-at-length $F = \eta L^\gamma$	Fecundity at weight $F = (\eta + \gamma W)W$				
η	2.89×10^5	1.41×10^{-7}	4.24×10^{-15}	2.82×10^{-4}	1
γ	1.03×10^5	3.187	5.95	3.0011	3
Natural mortality rate	0.14 yr^{-1}	0.25yr^{-1}	0.06 yr^{-1} (males, young females) 0.09 yr^{-1} (females > 15 yr)	0.18 yr^{-1}	0.15 yr^{-1}
Available to fishery	29 cm (4 yr)	38 cm (4yr)	40 cm (7 yr)	3 yr	55 cm (6 yr)

Fish species

Invertebrates

Parameter	Dungeness crab	Red abalone	Red Sea Urchin
Pelagic larval duration	n/a	n/a	n/a
Mean larval dispersal	75 km	1 km	50 km
Home range diameter	14 km	1 km	0.001 km
Length-at-age (cm) von Bertalanffy equation: $L(t) = L_\infty\left(1-\exp\left(-k\left(t-t_0\right)\right)\right)$			
L_∞	24	19.24	11.25
k	0.345 yr^{-1}	0.217 yr^{-1}	0.28 yr^{-1}
t_0	0.068 yr	0 yr	0 yr
Weight-at-length (kg) $W = \alpha L^\beta$			
α	3.165×10^{-4}	1.61×10^{-4}	1
β	2.76	3.02	3
Maximum age	7 yr	30 yr	30 yr
Age at maturity	3 yr	3 yr	3 yr
Fecundity-at-length $F = \eta L^\gamma$	Fecundity at length $F = \eta + \gamma L$		
η	0.4×10^6	4.65×10^{-4}	5.47×10^{-6}
γ	0.3×10^6	4.518	3.45
Natural mortality rate (varies by length)	0.2 yr^{-1} (≤ 7 yr males and ≤ 4 yr females) 0.9 yr^{-1} (all older ages)	0.15 yr^{-1}	0.09 yr^{-1}
Available to fishery	16 cm (4 yr) (males)	8 yr	8.9 cm (5 yr)

b) EDOM Model – Life History Parameters

	Lingcod	Cabezon	Black Rockfish	Canary Rockfish
Annual survival rate (e-M, yr-1))	0.84	0.78	0.79	0.94
Body growth intercept (a, kg)	1.17	0.42	0.19	0.25
Body growth slope ®	0.95	0.93	0.90	0.96
Weight at maturity (wk, kg)	2.23	0.57	0.74	0.28
Recruitment compensation ratio (K)	10.00	5.00	2.00	20.00
Mean larval dispersal distrance (km)	10.00	45.00	45.00	45.00
Adult emigration rate (e, yr-1)	0.01	0.01	0.01	0.02
Mean adult dispersal distance (km)	5.00	5.00	5.00	10.00
Adult home range radius (km)	10.00	0.50	7.00	3.00
Unfished spawning biomass (tmt)	30.00	3.50	24.00	80.00
Ratio of current to unfished biomass	0.20	0.30	0.30	0.10