2009

ICM: The Interdisciplinary Contest in Modeling

Creating Food Systems: Re-Balancing Human-Influenced Ecosystems

Background

Less than 1% of the ocean floor is covered by coral. Yet, 25% of the ocean's biodiversity is supported in these areas. Thus, conservationists are concerned when coral disappears, since the biodiversity of the region disappears shortly thereafter.

Consider an area in the Philippines located in a narrow channel between Luzon Island and Santiago Island in Bolinao, Pangasinan, that used to be filled with coral reef and supported a wide range of species (Figure 1). The once plentiful biodiversity of the area has been dramatically reduced with the introduction of commercial milkfish (*Chanos chanos*) farming in the mid 1990's. It's now mostly muddy bottom, the once living corals are long since buried, and there are few wild fish remaining due to over fishing and loss of habitat. While it is important to provide enough food for the human inhabitants of the area, it is equally important to find innovative ways of doing so that allow the natural ecosystem to continue thriving; that is, establishing a desirable polyculture system that could replace the current milkfish monoculture. The ultimate goal is to develop a set of aquaculture practices that would not only support the human inhabitants financially and nutritionally, but simultaneously improve the local water quality to a point where reef-building corals could recolonize the ocean floor and co-exist with the farms.

A desirable *polyculture* is a scenario where multiple economically valuable species are farmed together and the waste of one species is the food for another. For example, the waste of a fin-fish can be eaten by filter feeders and excess nutrients from both fish and filter feeders can be absorbed by algae which can also be sold, either as food or commercially useful by-products. Not only does this reduce the amount of nutrient input from the fish farming into the surrounding waters, it also increases the amount of profit a farmer can make by using the fish waste to generate a greater quantity of usable products (mussels, seaweed, etc.)

For modeling purposes, the primary animal organisms involved in these biodiverse environments can be partitioned into predatory fish (phylum Chordata, subphylum Vertebrata); herbivorous fish (phylum Chordata, subphylum Vertebrata); molluscs (such as mussels, oysters, clams, snails, etc., phylum Mollusca); crustaceans (such as crabs, lobsters, barnacles, shrimp, etc., phylum Arthropoda, subphylum Crustacea); echinoderms (such as star fish, sea cucumbers, sea urchins, etc.; phylum Echinodermata); and algae. By feeding types, there are primary producers (photosynthesizers—these can be single cell phytoplankton, cyanobacteria, or multicellular algae); filter feeders (strain plankton, organic particles, and sometimes bacteria out of the water); deposit feeders (that eat mud and digest the organic molecules and nutrients out of it); herbivores (eat primary producers); and predators (carnivores). Just as on land, most of the carnivores eat herbivores or smaller carnivores, but in the ocean they can also eat many of the filter feeders and deposit feeders. Most animals have growth efficiencies of 10–20%, so 80–90% of what they ingest ends up as waste in one form or another (some dissipated heat, some physical waste, etc.). The role of coral in this biodiverse environment is largely to partition the space and allow species to condense and coexist by giving a large number of species each its own chance at a livable environment in a relatively small space—the aquatic analogue of high-rise urbanization. Coral also provides some amount of filter feeding, which helps clean the water. The ability of an area to support coral depends on many factors, the most important of which is water quality. For example, corals in Bolinao are able to live and reproduce in waters that contain half a million to a million bacteria per milliliter and 0.25ug chlorophyll per liter (a proxy for phytoplankton biomass). The fish pen channel currently sees levels upwards of ten million bacteria per milliliter and 15ug chlorophyll per liter. Excess nutrients from the milkfish farms encourage fast-growing algae to choke out coral growth, and particulate influx from the milkfish farms reduces corals ability to photosynthesize. Therefore, before coral larvae can begin to grow, acceptable water quality must be established. Other threats to coral include degradation from increasing ocean acidity due to increased atmospheric CO_2, and degradation from increasing ocean temperature due to global warming. These can be considered second order threats which we will not specifically address in this problem.

Problem Statement

The challenge for this problem is to come up with viable polyculture systems to replace the current monoculture farming of milkfish that would improve water quality sufficiently that coral larvae could begin settling and recolonizing the area. Your polyculture scenario should be economically interesting and environmentally friendly both in the short and long term.

1. MODEL THE ORIGINAL BOLINAO CORAL REEF ECOSYSTEM BEFORE FISHFARM INTRODUCTION: Develop a model of an intact coral reef foodweb containing the milkfish as the only predatory fish species, one particular herbivorous fish (of your choice), one mollusc species, one crustacean species, one echinoderm species, and one algae species. Specify the numbers of each species present in a way you find reasonable; cite the sources you use or show the estimates you make in arriving at these population numbers. In articulating your model, specify how each species interacts with the others Show how your model predicts a steady state level of water quality sufficient for the continued healthy growth of your coral species. If your model does not yield a high enough level of water quality, then adjust your number of each species in a way you find most reasonable until you do achieve a satisfactory quality level, and describe clearly which species numbers you adjusted and why your changes were reasonable.

2. MODEL THE CURRENT BOLINAO MONOCULTURE MILKFISH:

a. First examine the impact if milkfish farming were to suppress other animal species. Do this by removing (setting the population to zero of) all herbivorous fish, all molluscs, all crustaceans, and all echinoderms. Set all other populations to be the same as in your full model above. Since you have removed the milkfish's natural food supply, you will need to introduce a constant term that models farmer feeding of the penned milkfish; choose this term to keep your model in equilibrium. What steady state level of water quality does your model now predict? Is water quality sufficient for the continued healthy growth of your coral species? Compare and describe how your result compares to observations.

b. Milkfish farming does not totally suppress all other animal species and water quality is probably not as bad as your results from part 2a suggest, so use your model to simulate the current Bolinao situation by reintroducing all deleted species and adjust only those populations until water quality matches that currently observed in Bolinao. Compare your populations with those currently observed in Bolinao and discuss what changes to your model could bring your population predictions into closer agreement with observations.

3. MODEL THE REMEDIATION OF BOLINAO VIA POLYCULTURE: You now strive to replace the current monoculture with a polyculture industry, seeking to make the water clear enough that the original reef ecosystem that you modeled in part 1 can re-establish itself without any help from humans. The idea is to introduce an interdependent set of species such that, whatever feed the milkfish farmer puts in, the combination of all of his/her "livestock" will use it entirely so that there are no (or only minimal) leftover nutrients and particles (feed and feces) falling onto the newly growing reef habitat below. Additionally, you seek to commercially harvest edible biomass from this polyculture in order to feed humans and increase value.

a. Develop a commercial polyculture to remediate Bolinao. Do this by starting with your "current" penned model from part 2b, and introduce into it additional species that both help clean the water and yield valuable, harvestable biomass. For example, you could line the pens with mussels, oysters, clams or other economically valuable filter feeder to remove some of the waste from the milkfish. Economically valuable algae could be grown on the sides of the pens near the surface (where they get enough light), and some of these could feed the small herbivorous fish that feed the milkfish. Clearly present your model and its steady state populations.

b. Report on the outputs of your model. What did you optimize, what constraints did you enforce, and why? What water quality does your model yield? How much harvest does your model yield, and what is its economic value? How much does it cost you to further improve water quality? In other words, from your optimal scenario, how many dollars of harvest does it cost you to improve water quality by one unit?

4. SCIENCE: Discuss the harvesting of each species for human consumption. How do we use your model for predicting or understanding harvesting for human consumption? Does a harvested pound of carnivorous fish count the same as a harvested pound of seaweed so that we seek to maximize total weight harvested, or do we differentiate by value (as measured by price of each harvested species) so that we seek to maximize the value of the harvest? Or do we seek to maximize the total value of harvest minus cost of milkfish feed? Should we define the value of edible biomass as the sum of the values of each species harvested, minus the cost of milkfish feed?

5. MAXIMIZE THE VALUE OF THE TOTAL HARVEST: We now wish to maintain an acceptable (maximal) level of water quality while harvesting a high (maximal) value of marketable (because edible and sell-able for byproducts are equally legitimate ways to maximize value) biomass from all living species in the model for human consumption. Change your model to harvest a constant amount from each species. What is the total value of biomass (as defined above) you can harvest and the corresponding water quality? Try different harvesting strategies and different levels of milkfish feeding (always choosing values that will keep your model in equilibrium), and graph water quality as a function harvest value. What strategy is optimal and what is the optimal harvest?

6. CALL TO ACTION: Write an information paper to the director of the Pacific Marine Fisheries Council summarizing your findings on the relationship between biodiversity and water quality for coral growth. Include a strategy for remediating an area like Bolinao and how long it will take to remediate. Present your optimal harvesting/feeding strategy

from part 5 above along with persuasive justification, and present suggested fishing/harvest quotas that will implement your plan. Show the leverage of your strategy by presenting the ratio of the harvest value under your plan to the harvest value under the current Bolinao scenario. Discuss the pros and cons from an ecological perspective of implementing your polyculture system.

Getting Started References
http://en.wikipedia.org/wiki/Integrated_Multi-trophic_Aquaculture
http://en.wikipedia.org/wiki/Coral_reef
http://www.seaworld.org/infobooks/Coral/home.html

Supplementary Information

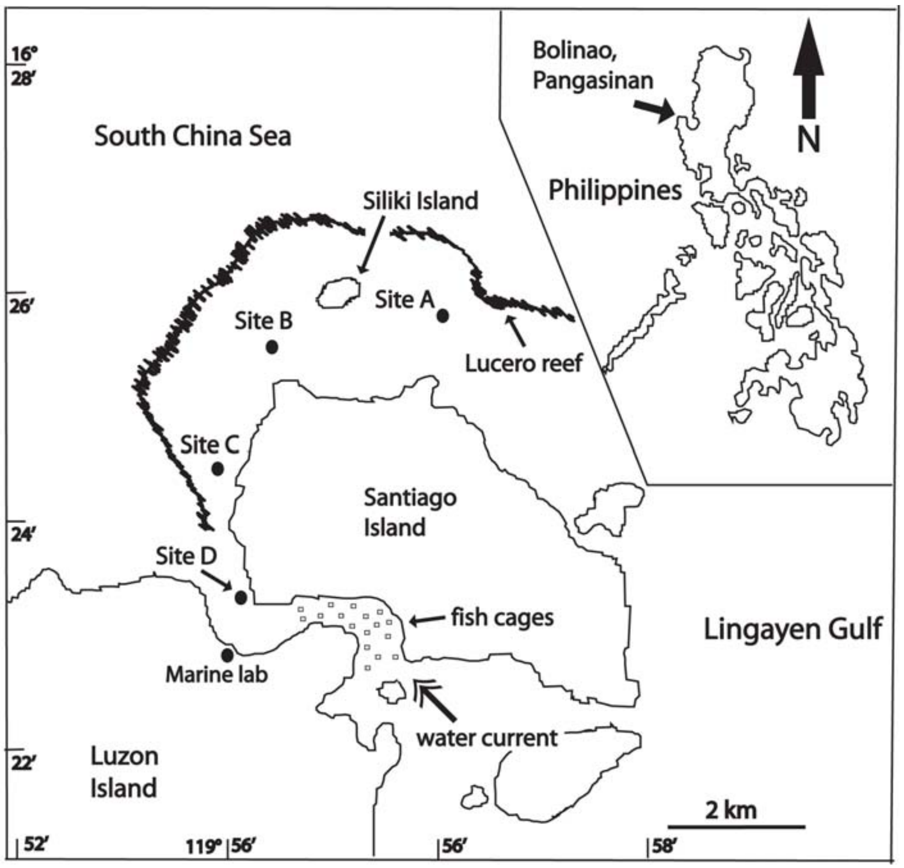

Figure 1. Map of the Bolinao area and the sites sampled for water quality data listed in Tables 1 and 2. Sites A and B have fairly healthy coral reefs while Site C has fairly degraded reefs, Site D has a few corals still holding on but is mostly dead coral and algae at this point in time, and the area under the fish pens no longer has live coral at all. In the fish pen channel, farmers employ nets measuring roughly 10m x 10m x 8m with stocking densities of ~ 50,000 fish per pen and 10 pens per hectare. (Fig. from Garren et al. 2008)

The following tables are representative of the data you will be able to find through public searches. These data may not be complete for your purposes and are intended only to help give you ideas on how to get started. You should use the best-suited and most complete data that you find.

Characteristics of Site Water

Site	**Dissolved Organic Carbon (DOC) (uM)**	**Total Nitrogen (Dissolved, uM)**	**Chl *a* (ug/L)**	**Particulate Organic Carbon (POC) (ug/L)**	**Total Nitrogen (Particulate, ug/L)**
A	69.7± 1.3	7.4±0.4	0.25± 0.03	106± 4	9±15
B	80.4± 2.9	8.0± 0.2	0.28± 0.03	196± 57	39± 15
C	89.6± 1.7	14.2± 0.7	0.38± 0.03	662± 68	54± 17
D	141± 2.9	30.5± 1.3	4.5± 0.2	832± 338	86± 45
Fish Pens	162± 18.5	39.8± 2.7	10.3± 0.2	641± 60	86± 18

Table 1. Water characteristics of Bolinao sites. (from Garren et al. 2008)

Microbial Abundances and Particle Characteristics of Site Water

Site	Virus-like Particles Abundance (# / ml)	Free-living Bacteria Abundance (cells / ml)	Particle-Attached Bacteria Abundance (cells / ml)	% of total bacteria attached to particles	# of Particles per ml (particle defined as larger than 3um)		Avg Particle size (um^2)
					Detritus	Phytoplankton cells	
A	$1.0 \pm 0.07 \times 10^7$	$5.4 \pm 0.3 \times 10^5$	$5.3 \pm 2.2 \times 10^2$	<0.1	$3.4 \pm 0.2 \times 10^3$	$1.6 \pm 0.2 \times 10^2$	42.7
B	$0.8 \pm 0.04 \times 10^7$	$4.2 \pm 0.6 \times 10^5$	$3.9 \pm 0.6 \times 10^2$	<0.1	$4.4 \pm 0.2 \times 10^3$	$1.0 \pm 0.1 \times 10^2$	19.7
C	$1.7 \pm 0.1 \times 10^7$	$3.0 \pm 0.04 \times 10^5$	$113.7 \pm 3.6 \times 10^2$	3.7	$9.6 \pm 0.8 \times 10^3$	$1.1 \pm 0.1 \times 10^2$	65.8
D	$7.0 \pm 0.3 \times 10^7$	$6.1 \pm 0.6 \times 10^5$	$144.5 \pm 5.6 \times 10^2$	2.3	$14.4 \pm 0.1 \times 10^3$	$9.7 \pm 0.7 \times 10^2$	576.1
Fish Pens	$6.1 \pm 0.7 \times 10^7$	$9.9 \pm 0.3 \times 10^5$	$583.2 \pm 28.1 \times 10^2$	5.6	$11.3 \pm 0.5 \times 10^3$	$78.4 \pm 5.5 \times 10^2$	280.8

Table 2. Bacteria and particle abundances in Bolinao. (from Garren et al 2008)

Organism Information

Organism	Trophic Classification	What it eats	How much it eats	What it excretes	Value when harvested
Milkfish (data from Homer et al. 2002)	predator	Fish feed or smaller fish	In pens: 6.58kg/m^2 of Pen/ 5months	242–493 g dry weight of sediment/ m^2/day. This sediment is ~ 10% carbon, 0.4% nitrogen, and 0.6% phosphorus (as % dry weight)	$1,278 USD/metric ton (from Agribusiness Weekly)
Herbivorous Fish (*Siganus doliatus,* a rabbit fish, used as representative)	herbivore	Macro algae (fleshy algae)	~18–22 cm^3 of algae material/ m^2 of reef/ month (from Fox & Bellwood 2008)		

Crustaceans (data averaged over one crab (*Menaethius monoceros*) and one amphipod (*Cymadusa imbroglio*) from Cruz-Rivera & Paul 2006)	Herbivore	Macro algae and cyanobacteria	~10–20mg wet weight of food/ individual/ day		Values for the various edible crustaceans can be found through public.
Molluscs (Averaged over 5 species of mussels and oysters from Hawkins et al. 1998)	Filter Feeder	Particles 1–16um in diameter	They clear 5–7L of water/hr of particles and absorb 4–15mg organic material per gram dry soft tissue weight (a measure of animal size) per hour		Also available on web for variety of species.
Echinoderm (urchin, *Tripneustes gratilla*, from the Philippines as representative. Data from Dy et al. 2002)	Herbivore	Fleshy algae	~0.05 g wet weight algae/ g dry weight urchin/ hour where the average dry weight of an individual urchin was 6.9 g	0.2–11.5mg dry weight feces/g dry weight urchin	
Algae (Yokoya and Oliveira 1992)	Primary producer	Sunlight, carbon dioxide, nitrogen and phosphorus	Depending on temperature, economically important red algae can double their mass (wet weight) in as little as 2.8 days (*Hypnea cornuta*) and as long as 50.0 days (*Pterocladia capillacea*)	These organisms can extrude excess photosynthate in the form of dissolved organic carbon but this is a difficult number to quantify. Simply keep in mind that this process is occurring as you think about the ecological perspective in part 6.	

References for Information found in the Table:

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Marianne Holmer, Nuria Marba, Jorge Terrados, Carlos M. Duarte, Mike D. Fortes (2002). Impacts of milkfish (Chanos chanos) aquaculture on carbon and nutrient fluxes in the Bolinao area, Philippines. *Marine Pollution Bulletin* 44: 685–696.

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A. J. S. Hawkins, R. F. M. Smith, S. H. Tan, Z. B. Yasin (1998). Suspension-feeding behaviour in tropical bivalve molluscs: Perna viridis, Crassostrea belcheri, Crassostrea iradelei, Saccostrea cucculata and Pinctada margarifera. *Marine Ecology Progress* 166: 173–185.

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B. F. McPherson (1968). Feeding and oxygen uptake of the topical sea urchin Eucidaris Tribuloides. *Biology Bulletin* 135: 308–321.