# Creating Food Systems: Re-Balancing Human-Influenced Ecosystems


## Summary

This paper concerns creating food systems: re-balancing human-influenced ecosy--system. Motivated by modeling an intact original Bolinao coral reef ecosystem before fishfarm introduction accurately, we analyze the developed coral reef foodweb and specify how each species interacts with each other by relative principles of biology. Then we synthesize contents of all components, and integrate the system of differential equations of all components to predict water quality until getting satisfactory results. Then we find that the current monoculture can't improve water quality sufficient for the continued healthy growth of Bolinao coral species and can't maximize the total value of harvest.

Based on the discussion to the original Bolinao coral reef ecosystem, we devise system of ordinary differential equations including analysis for the reasonable numbers of each species present and water quality. After modeling the current Bolinao monoculture milkfish and analyzing two conditions, we bring forward the model for remediation in Bolinao. One condition is milkfish farming suppressing other animal species, the other is that Milkfish farming does not totally suppress all other animal species. Then we develop a more reasonable commercial polyculture where farmers can maximize value and shorten the time for remediation, and we draw out a sketch diagram for local people to implement.

Afterward, we calculate the harvest value using different harvesting strategies and different levels of milkfish feeding with the help of mathematical software, and give an example of maximizing local total harvest value.

Finally, we write a letter to the director of the Pacific Marine Fisheries Council for action. We introduce a workable strategy for remediating Bolinao coral reef ecosystem and predict how the time it will take to remediate.



**Keys:** system of differential equations    remediation model    ecosystem

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## 1.Introduction

Gernerally speaking, the current monoculture has brought bad effect for remediating Bolinao coral reef ecosystem. After doing some research on the current situation , collecting and studying useful data, as well as modeling Bolinao ecosystem, we should find the relationship between biodiversity and water quality for coral growth. Introduce an appropriate set of commercial polyculture, and carry out a strategy for remediating an area like Bolinao and how long it will take to remediate.

So our goal and approach are pretty clear:

◇ Develop a model of an intact coral reef foodweb, we use system of ordinary differential equations.
◇ Specify the numbers of each species present in a reasonable way.
◇ Specify how each species interacts with the others.
◇ Show how our model predicts a steady state level of water quality sufficient for the continued healthy growth of your coral species.
◇ Model the current Bolinao monoculture milkfish.
◇ Analyse whether milkfish farming is to suppress other animal species, and Optimize Models.
◇ Model the remediation of Bolinao via polyculture, develop good commercial polycultur to remediate Bolinao, and predict the outputs of our model.
◇ Model to Solve how to maximize the value of the total harvest.
◇ Establish a strategy for remediating an area like Bolinao and predict how long it will take to remediate.

## 2.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.

Bolinao which is used to be filled with coral reef and supported a wide range of species is 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.

Our 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.

## 3.Conventions

### Terminology

- $Foodweb$: The set of organism relationships, often based on who-eats– who, or which organisms cycle a particular nutrient within and ecological community.
- $Monoculture$: The cultivation of a single crop (on a farm or area or country).
- $Polyculture$: Polyculture is agriculture using multiple crops in the same space, in imitation of the diversity of natural ecosystems, and avoiding large stands ...
- $E\cos ystem$: There are highly sensitive and delicately balanced ecosystems in the forest.

### Variables and Abbreviations

The variables and abbreviations used in this paper are listed in Table1, we have just listed some ones and the rest ones will be elaborated in full paper.

**Table1:** Variables and abbreviations list.

| Variable/Abbreviation | Signification |
|---|---|
| $F$ | The amount of phytoplankton |
| $P_{\max}$ | The maximum photosynthetic |
| $f(I)$ | $Steele-Formula$ |
| $f(N)$ | $Michaelis-Menten-Formula$ |
| $r_i$ | Breathing rate of phytoplankton |
| $e_i$ | Secretion rate of phytoplankton |
| $m_i$ | Death rate of phytoplankton |
| $c_i$ | Ingestion rate of milkfish |
| $\alpha$ | Conversion factor |
| $f_i$ | Defaecation rate of milkfish |
| $p_i / g_i$ | Ingestion rate/Growth budget |
| $POM$ | The amount of particulate organic |
| $x(t)$ | Population size |

| | |
|---|---|
| $\lambda_i$ | Demanding limits of each needing factor |
| $Q$ | Total weight of all milkfish in fish pens |

**4. Task Ⅰ : Model the original Bolinao coral reef ecosystem before fishfarm introduction.**

In order to model Bolinao coral reef ecosystem, we develop a model of an intact coral reef foodweb. Simplily, we select milkfish as the only predatory fish species, acanthuridae as one particular herbivorous fish, oysters as one mollusks, lobsters as one crustaceans, sea cucumbers as one echinoderms, seaweed as one algae and some bacterium.

**4.1 Summarise the Model in part1 and its correlative functions.**

So far most of the sea farming is based on the growth situation of monotypic species, which reckon without the community structure and inter annual change in the local ocean ecosystem. And aquaculture management didn't also be considered, as a result we can not harvest the ultimate global valuation.

While the original Bolinao Coral Reef Ecosystem we model integrate combination of ecosystem situation and growth of milkfish. So our Bolinao Coral Reef Ecosystem Model can achieve these objectives below. Firstly, comprehensively make use of the observation results from site A, site B, site C, site D in Bolinao, and describe the interaction between pivotal environmental factor, milkfish and local environment. Secondly, take impact ehach species interact with other species fully into account, as well as harvest volume. And estimate the numbers of other species from the perspective of environment in this area. Thirdly, study how different numbers of species make an impact on the Bolinao Coral Reef Ecosystem from species diversity and feeding types. Finally, adjust numbers of all the species to predict a steady state level of water quality, then choose the most reasonable numbers we think.

**4.2 Select the ocean area for study.**

Consider an area in the Philippines located in a narrow channel between Luzon Island and Santiago Island in Bolinao,Pangasinan, which used to be filled with coral reef and supported a wide range of species (Figure 1).

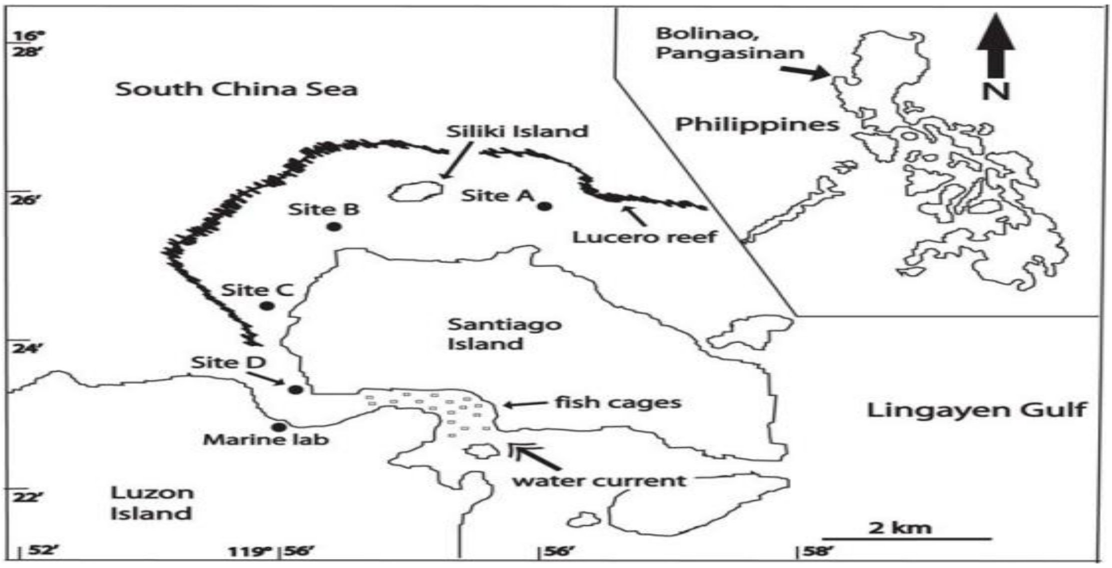
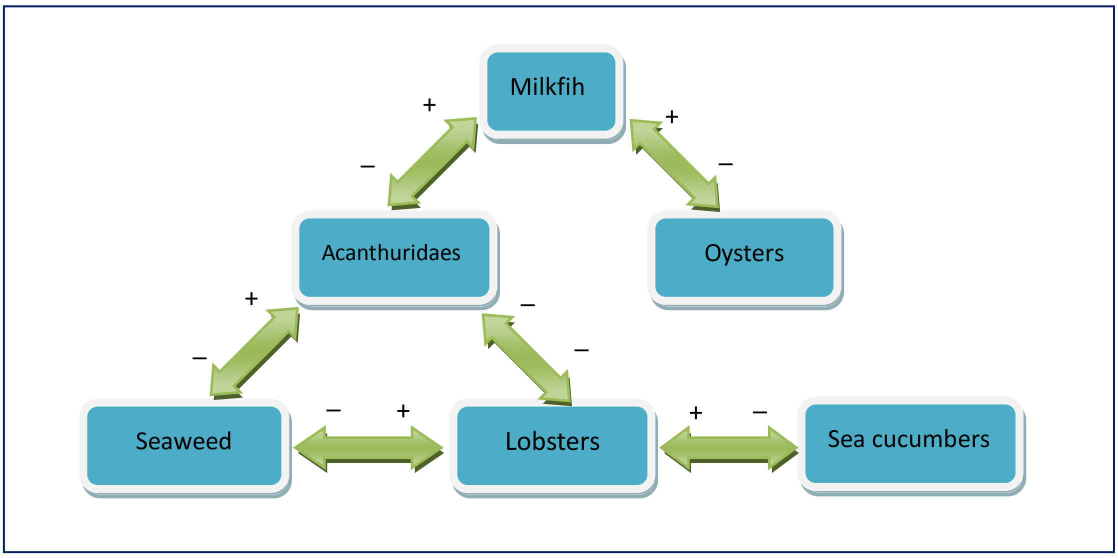



**Figure1:** Map of the Bolinao area. Sites A and B have fairly healthy coral reefs while Site C has fairly degraded reefs, Site D has a few corals still holding on but is mostly dead coral and algae at this point in time, and the area under the fish pens no longer has live coral at all. In the fish 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. (Figure1. from Garren et al. 2008)

**4.3 The foodweb we construct in Bolinao Coral Reef Ecosystem.**

In this part we adopt interspecfic relationship classification(**E. P. Odum-1971**), which is based on the impact on the species' numbers by interaction. The characteristics of influence one species make to the other can be shown by sign(±), "+" indicates enhance, and "—" indicates decrease.

**Figure2:** Flow of energy in the foodweb in Bolinao coral reef ecosystem.




In general, there is only 10%—20% of the energy which is absorbed from previous trophic level to be flowing to the next trophic level, and the other part 80%—90% will be released through repiration and excretal matters. In this paper, we choose 10% for further study, and set the initial living weight of milkfish to be 100kg. Then we could calculate the living weight of oysters is 500kg, the living weight of Acanthuridae is 500kg, the living weight of lobster is 500kg, the living weight of sea cucumber is 100kg, the living weight of seaweed is 7500kg.

**4.4 Calculate the numbers of each species.**

Bolinao Coral Reef Ecosystem Model consist of physical exchange, ecological processes, the individual growth of aquaculture species, the change of each species, without considering activities of human culture. Model forcing factors are solar light, water temperature, dissolved organic carbon(DOC), total dissolved nitrogen(TDN), the amount of phytoplankton(Chl a), particulate organic carbon(POC), particulate total nitrogen(PTN). Suppose the model space is zero-dimensional, that equals ecological factors are distributed uniformly among ecosystem model space. Simulate the exchange between sites(site A, site B, site C, site D) and South China Sea, as well as the change in seawater quality.

Use a standard formula for simulation of light condition in Bolinao Coral Reef Ecosystem, and estimate local cloud cover amount through situ measurement data. Estimate local seawater temperature by using the empirical formula. The exchange between Bolinao Coral Reef Ecosystem, South China Sea, and Lingayen Gulf has a serious impact on the water quality in Bolinao Coral Reef Ecosystem, so we introduce the trend of force water interface exchange, and use data to calculate。
The competition between seaweed and phytoplankton is also considered as a forcing function, and the growth of seaweed has associations with water temperature. We get its maximum growth rate by an experiment result from *Acta Ecologica Sinica* (*by Mao X H 1933*).

Ⅰ. Calculate the amount of phytoplankton(Chl a) in the seawater of Bolinao Coral Reef Ecosystem.
Bolinao Coral Reef Ecosystem Model simulate phytoplankton(Chl a) in the water, suspended particles(SPM)( the total amount of particulate organic carbon(POC) and particulate total nitrogen(PTN)), total dissolved nitrogen(TDN) as well as local solar situation. Consider TDN as the only factor influencing phytoplankton's growth.

Set $F$ to represent as the amount of phytoplankton(Chl a), $p_{\max}$ as the maxmum photosynthetic rate, $f(I)$ as $Steele-Formula$ estimating local sun's rays radiation, $f(N)$ as $Michaelis-Menten-Formula$ restricting nutrive salt for species, $r_b$ as breathing rate of phytoplankton, $e_b$ as secretion rate of phytoplankton, $m_b$ as

death rate of phytoplankton; $c_m$、$c_a$、$c_o$、$c_l$、$c_h$ as ingestion rate of milkfish(M)、acanthuridae(A)、oyster(O)、loster(L) and sea cucumber(H).
We get:

$$\frac{dF}{dt} = F\left(p_{\max} f\left(I\right) f\left(N\right) - r_b - e_b - m_b - c_m M - c_a A - c_o O - c_l L - c_h H\right) \tag{1}$$

Ⅱ. Calculate the amount of TDN in the seawater of Bolinao Coral Reef Ecosystem.
Set $N$ to represent as the amount of TDN, $\alpha$ as conversion factor of the weight of material, $e_m$、$\mathrm{e}_a$、$\mathrm{e}_o$、$\mathrm{e}_l$、$\mathrm{e}_h$ as excretion rate of milkfish(M)、acanthuridae(A)、oyster(O)、loster(L) and sea cucumber(H), $f\left(K\right)$ as growth function of seaweed.

We get:

$$\frac{dN}{dt} = \alpha F\left(e_b + m_b\right) + e_m M + e_a A + e_o O + e_l L + e_h H - \alpha F\left(p_{\max} f\left(I\right) f\left(N\right)\right) - f\left(K\right) \tag{2}$$

Ⅲ. Calculate the amount of suspended particles(SPM) in the seawater of Bolinao Coral Reef Ecosystem.

Set $M$ as the weight of SPM, $e_x$ as the suspending efficiency of SPM, $d_x$ as the sedimentation efficiency of SPM, $f_m$、$f_a$、$f_o$、$f_l$、$f_h$ as defaecation rate of milkfish(M)、acanthuridae(A)、oyster(O)、loster(L) and sea cucumber(H), $p_a$、$p_o$、$p_l$、$p_h$ as ingestion rate of acanthuridae(A)、oyster(O)、loster(L) and sea cucumber(H) for particulate organic matter(POM)
We get:

$$\frac{dM}{dt} = M\left(e_x - d_x\right) + f_m M + f_a A + f_o O + f_l L + f_h H - M\left(p_a A + p_o O + p_l L + p_h H\right) \tag{3}$$

Ⅳ. Calculate the living weight of milkfish、acanthuridae、oyster、loster and sea cucumber in the seawater of Bolinao Coral Reef Ecosystem.

Set $M$、$A$、$O$、$L$、$H$、$SW$ as living weight of milkfish、acanthuridae、oyster、loser 、 sea cucumber and seaweed, $g_m$、$g_a$、$g_o$、$g_l$、$g_h$、$g_{sw}$ as growth budget of milkfish、c、oyster、loster 、 sea cucumber and seaweed, $d_m$、$d_a$、$d_o$、$d_l$、$d_h$、$d_{sw}$ as death rate of milkfish、acanthuridae、oyster、loster、sea cucumber and seaweed
We get:

$$\frac{dM}{dt} = g_m M - f_m M - d_m M \qquad (4)$$

$$\frac{dA}{dt} = g_a A - f_a A - d_a A \qquad (5)$$

$$\frac{dO}{dt} = g_o O - f_o O - d_o O \qquad (6)$$

$$\frac{dL}{dt} = g_l L - f_l L - d_l L \qquad (7)$$

$$\frac{dH}{dt} = g_h H - f_h H - d_h H \qquad (8)$$

$$\frac{dSW}{dt} = g_{sw} SW - f_{sw} SW - d_{sw} SW$$

**Table2:** Main parameters in the model(data in Italic are for the proposed aquaculture scenario)

| Parameter | Study Item | Chosen Data |
|---|---|---|
| $P_{max}$ | Maxmum primary producer | $0.2h^{-1}$ |
| $I_{opt}$ | Best solar situation | $300W.m^{-2}$ |
| k | Absorption constant for TDN | $1.5mol.dm^{-1}$ |
| $m_b$ | Death rate of phytoplankton | $0.05.d^{-1}$ |
| Ecosystem area | Milkfish<br>Acanthuridae<br>Oyster<br>Loster<br>Sea cucumber<br>Sea weed | $391hm^2$,***2103***$hm^2$<br><br>$4400hm^2$,***2806***$hm^2$ |
| Ecosystem density | Milkfish<br>Acanthuridae<br>Oyster<br>Loster<br>Sea cucumber<br>Sea weed | $59m^{-2}$<br><br>$12m^{-2}$ |
| $d_m$<br>$d_a$<br>$d_o$<br>$d_l$<br>$d_h$ | Death rate of milkfish<br>Death rate of acanthuridae<br>Death rate of oyster<br>Death rate of loster<br>Death rate of sea cucumber | |

Some of the data above is from ZHU Ming-yuan,Application of Ecological Model in Studying the Sustainable Development of Coastal Shellfish Culture.[D] July 23 ,2002, and some data is from www.seaword.org/infobooks/Coral/home.html

The chosen data in Table 1 are only the main parameters in Bolinao coral reef ecosystem. And the amount of particulate organic matter(POM) can also be calculated by introducing an empirical equation as follow.

$$POM = \left(\frac{90.977}{SPM} + 15.8\right) \times \frac{SPM}{100} \qquad (9)$$

POM represent as the weight of particulate organic matter, SPM represent as the weight of suspended particles. Equation(9) is an empirical equation which is brought forward by ZHU Ming-yuan after studying survey data in Sanggou Bay. Because the ocean condition in Sanggou Bay(in China) is similar to that in Bolinao coral reef ecosystem.

**5. TaskⅡ: Model the current Bolinao monoculture milkfish.**

**5.1:** Suppose milkfish farming were to suppress other animal species. In this situation we examine the impact by removing all herbivorous fish, all molluscs, all crustaceans, and all echinoderms . In order to simplify the study we set the population to zero of, and all the other populations to be the same as in our full model above. In this case we know that both the growth of milkfish and water quality will be greatly influenced Because species diversity will also greatly decrease, excretal matters from milkfish will increase. At the same time, this will increase the work of decomposer in Bolinao coral reef ecosystem. With the long-term accumulation of excretal matters from milk--fish which consist of abundant nitrogen and phosphor necessary for marine plants' growth, the marine plants will grow fast and the water quality will also become bad. In the long run, the number of milkfish will be reduced as a result of food reduction. So we conclude that milkfish farming will suppress the growth of other local animal species more or less, if farmers do not restrict milkfish number and not apply useful management. While their number goes up to some degree, their growth will be restricted by living space、condition、nutrition matters etc, and milkfish may stop to grow.

Before modeling, we make these following assumptions. First, the numbers of milkfish in fish pens are distributed uniformly. Second, there are no milkfish escape from fish pens and there are no more milkfish being thrown into fish pens. Third, population size(quantity or density of the studying species) $x(t)$ is continuously differentiable function. So the dynamic change $\frac{dx}{dt} = (b-d)x$ can be described by the function as follow.
We get:

$$dx/dt = (b-d)x \qquad (10)$$

$t$ represents as time, $b$ represents ad birth rate, and $d$ represents as death rate. And both of them depend on $x(t)$ and $t$.

Introduce a constant term that models farmer feeding of the penned milkfish. Based on this introduction, we make further assumption that each milkfish forages equal food. When the population size(quantity or density of the studying species) increase, each milkfish will certainly forage different food resource. On the contrary, the growth rate of local population will be reduced. Finally we suppose relative total growth of local population size($\frac{1}{x} \bullet \frac{dx}{dt}$) is of one dimension for population size.

So $dx/dt = (b-d)x$ can be optimized further.

We get:

$$dx/dt = rx\left(1 - x/k\right) \qquad (11)$$

$r$ is a constant number and greater than zero, which can indicate the characteristics among milkfish. $k$ is also a constant number and greater than zero, which indicate abundance degree of feeding source. When $x = k$, population size will stop increasing. In the end we know $k$ shows the maximum scale local environment could support.

Since feeding resource could only support $k$ milkfish, each milkfish could get $\frac{1}{k}$ of the total feeding resource. At the time of $k$, $x(t)$ milkfish could consume $\frac{x(t)}{k}$ of the total feeding resource, and the leftover feeding resource for milkfish is $1 - \frac{x}{k}$.

From model(11), we know that relative growth of population size has direct ratio with the leftover feeding resource. However intraspecific completion, lack of habitat and feeding resource, and increase of disease will appear, which are to restrict the growth of population size.

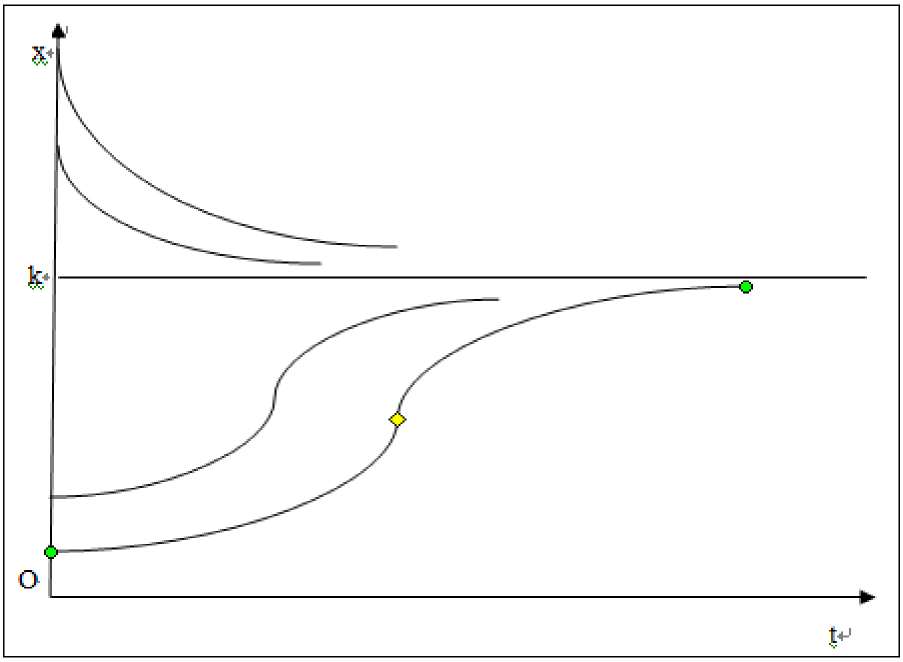
Model(11) has two equilibrium state when $x = 0$ and $x = k$. Because while $0 < x < k$, we get $dx/dt > 0$; while $x > k$, we get $dx/dt < 0$, the equilibrium state($x = k$) is globally stable and the state($x = 0$) is unstable.

Model(11) is differential equations with variables. We set initial value put into fish pens to be $x(t=0) = x_0 = 24000$. Through mathematical software(in this paper we use Matlab), we conclude $x(t)$ (the number of milkfish in fish pens at any time).

We get:

$$x(t)=\frac{kx_0}{(k-x_0)e^{-rt}+x_0} \tag{12}$$

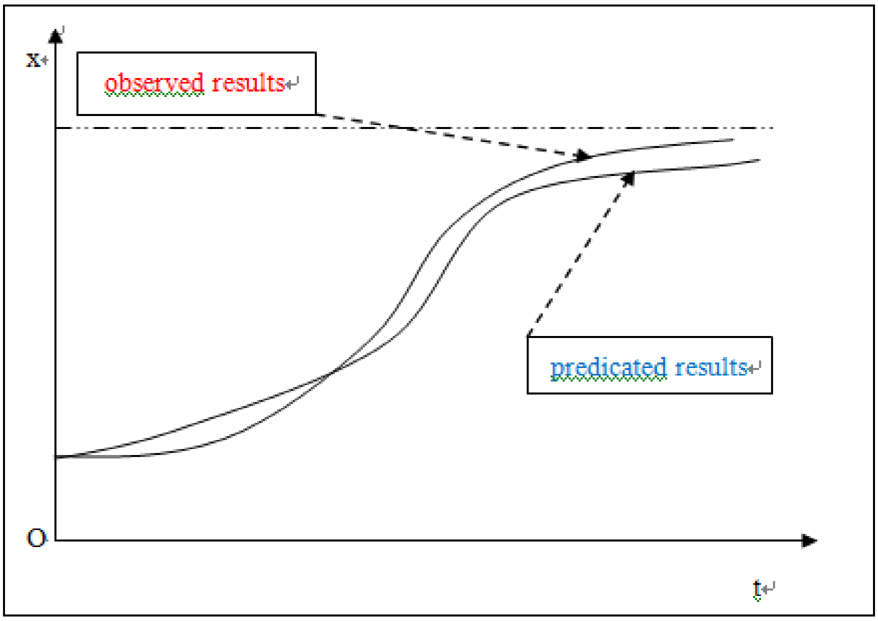
**Figure3:** The curve chart of number of milkfish in fish pens at any time.




From Figure3 we get the following conclusions.

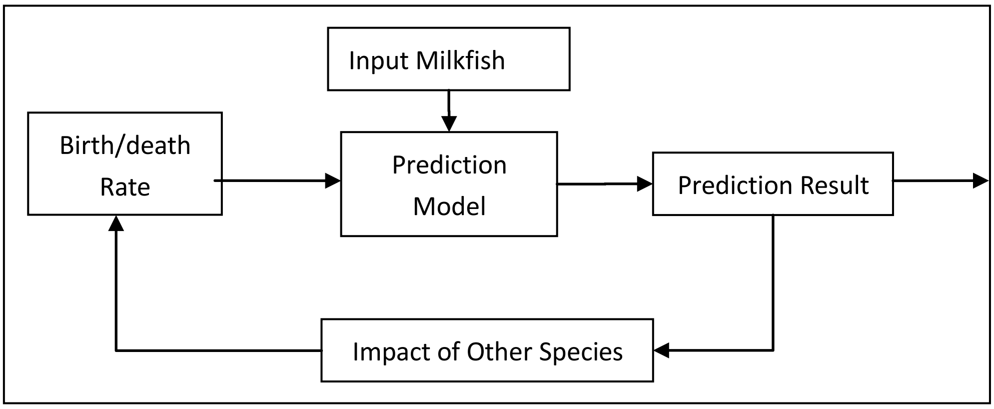
During short time, the growth of population size accord with exponential trend basically if the initial value of the population size is smaller, because resources supply is sufficient and the impact of direct density-dependent factors is faintish. With the culture period going, the increase rate of population size will decrease and reach saturation, arriving $x=k$. Because impact of direct density-dependent factors and feeding resources will be strengthened. And the water quality is not good for Bolinao coral to grow, because predatory animals are too many and coral can not support the ecosystem any more. At this time farmers should catch about 40% of the total milkfish, and the water quality is the best for continuous growth of coral. The recovery time of $x(t)$ to $x=k$ depend on growth rate of $r$. The bigger the value of $r$ is, the shorter the recovery time is . And $r$ can be controlled by farmers.

**Figure4:** The comparison between predicated results and observed results.




**5.2:** If milkfish farming were not to suppress other animal species, and water quality is not as bad as predicated results from part **2a** suggest. In this situation, we start reintroducing all deleted species. So we must reconsider the extra impact on milkfish from other reintroduced species. Other species' population size and activities will influence milkfish's growth. Some relationship is competition, some is predatory-pre relationship.

**Figure5:** Simple design procedure of our model.




We use a correction coefficient to replace the impact of other reintroduced species, this correction coefficient is based on transfer efficiency among foodweb in **Figure2**.

Set correction coefficient to be $\lambda$, and $\lambda = 1 - \left(\frac{1}{n}\right)^3$ .Because there are three trophic levels in Bolinao coral reef ecosystem, they are producers(seaweed), primary consumers(Acanthuridaes, oyster, sea cucumber), and secondary consumers (milkfish).

We get:

$$x(t)=\frac{kx_0}{(k-x_0)e^{-rt}+x_0}\left(1-\left(\frac{1}{n}\right)^3\right) \tag{13}$$

Pay attention: $n$ represents as the number of the kind of species at secondary level, but $n \geq 4$. And there are 3 trophic levels existing in Bolinao coral reef ecosystem, so we select $\lambda = 1-\left(\frac{1}{n}\right)^3$. The best advantage of this model is that farmers could change the number of the herbivorous animal to clean the water quality in fish pens. After using mathematical software(Matlab) to simulate Model(13), we get similar results and the results accord with observation.

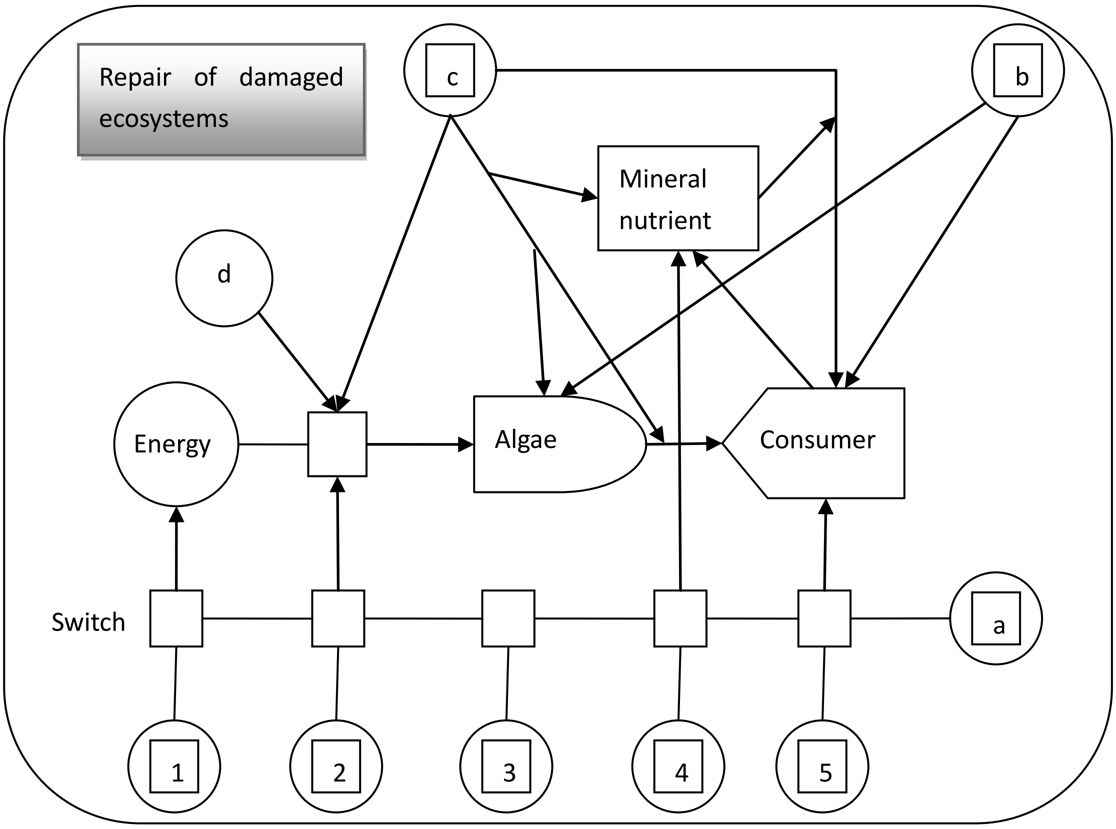
## 6. TaskⅢ: Model the remediation of Bolinao via polyculture.

In this part we use polyculture industry to take the place of current monoculture, seeking to make the water quality good enough that the original Bolinao coral reef ecosystem we modeled in **part 1** is able to re-establish itself without any help from humans. The feasible method is to introduce an interdependent set of species such that, whatever feeds the milkfish farmer puts in, the combination of all the species in the ecosystem 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, we could seek to commercially harvest edible biomass to feed humans and increase value from polyculture.

**6.1:** Develop a commercial polyculture to remediate Bolinao.
Because Milkfish farming does not totally suppress all other animal species and some species can decompose excretal matter and other organic matter, we introduce additional species to clear water.

In Bolinao coral reef ecosystem, it is impossible to invest massive fund to re-establish the structure of the current Bolinao situation. It is more important to enhance functional restoration, and more significant to make it be a more useful and serviceable ecosystem. Environmental stress factor should be considered in analyse restoring Damaged ecosystem. So we design the following sketch map(**Figure6**) to study.

**Figure6:** The sketch map of restoring damaged ecosystem.

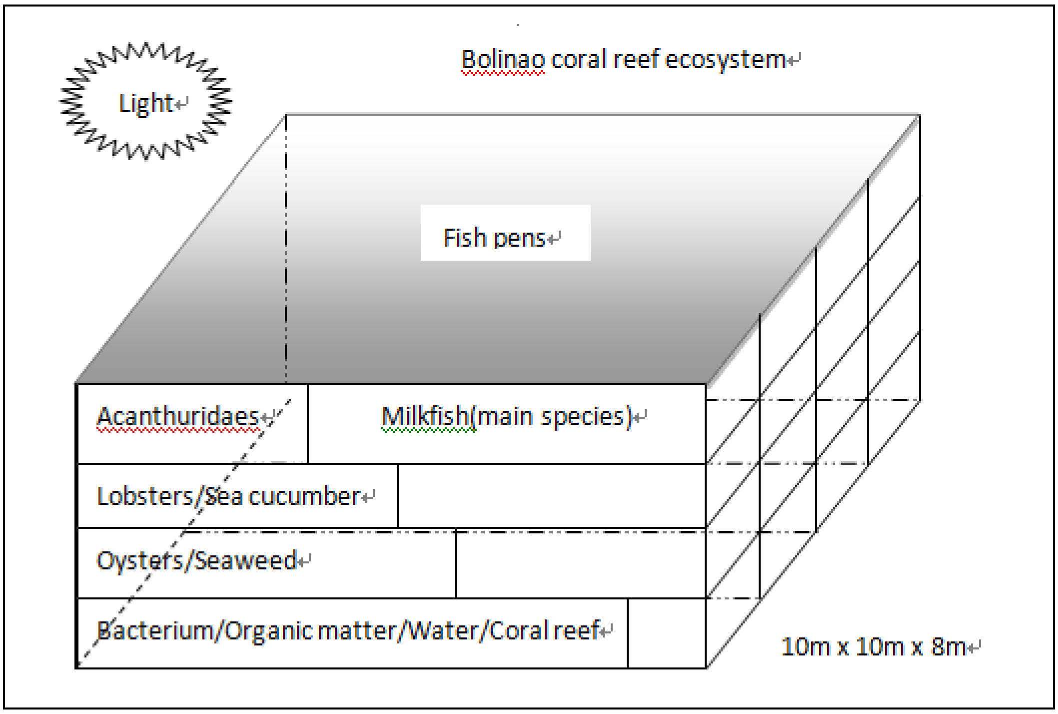



In this sketch map there are 5 stress factors, the smaller the number is , the more serious the influence is. And there are 4 kinds of restoration methods(a、b、c、d). From a to d, the cost increase in sequence.

Functional groups is the basic cell target cell in re-establishing the structure and restoring the function of ecosystem. It is quite important to study combination of Biodiversity in restoring damaged ecosystem. Based on **Figure6**, concerning 5 stress factors, define and select plant species which can bear 1 ~ 5 or even more stress factors. There're many ways to restore damaged ecosystem, for example, design good combination and take advantage of relative technology. The current monoculture in Bolinao is simple, functions are damaged in some way, and the kind of species is rare. It is especially important to choose one particular herbivorous fish (of your choice), one mollusc species, one crustacean species, one echinoderm species, and one algae species as well as Microorganism existing with milkfish.

As for restoring Bolinao ecosystem, it is possible to transform it into a helpful and healthy ecosystem by introducing economically valuable filter feeder. For example mussels, oysters, clams. In our model we select oysters、lobsters、sea weed、sea cucumber and acanthuridaes. And get the following model(**Figure7**).

**Figure7:** The commercial polyculture Model in Bolinao to remediate Bolinao




The density of milkfish is $500/m^2$. Milkfish grow quite fast, after beening fed about one month, length of each one will reach 5 ~ 7cm. After two months, length of each one will reach 12 ~ 15cm. After 8 ~ 10 months, length of each one will reach 35 ~ 40cm, weight of each one will reach 250 ~ 500g, at this time milkfish can be sold at market.

The temperature where milkfish must be controlled between 15 ~ 40 degree Celsius, the best degree Celsius is 28 ~ 35 degree Celsius, and milkfish can not grow in the water below 10 degree Celsius. Rice Bran, soybean cake, groundnut cake and man-made complex bait and etc could be used to feed milkfish and other species during their growth.

**6.2:** Report on the output of our Model.

In this part we optimize the combination of all species including milkfish, restrict their growth degree Celsius, restrict their food resource, and restrict fish pens(living space), restrict the density of milkfish, restrict intensity of illumination, and restrict bacterium living in fish pens. We could also restrict the ratio of nitrogen and phosphorus in order to stop water nutrition enrichment.

**Table3:** Organism information.(from Garren et al 2008)

| 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) |

The density of milkfish is 5/$m^2$(Part **Task 3a**), the value of harvested milkfish is about ＄1278USD/metric ton, so we conclude tha the total number of milkfish in each fish pens is 500. At the same time weight of each milkfish is about 250 ~ 500g. In this paper we select average weight to be 375g. In the end we calculate the whole weight milkfish in fish pens: $50000\times375g=18750000g=17.75 metric\,ton$. Finally, we get total economic value in each fish pens is $17.75\times1278=22684.5$ ＄.

**7. Task Ⅳ: Discuss the harvesting of each species for human consumption.**

**7.1:** Judge the importance of carnivorous fish and harvested seaweed.
In part **1** we have deduced a conclusion from premises (**Model 1**):

$$\frac{dF}{dt}=F\left(p_{\max}f\left(I\right)f\left(N\right)-r_b-e_b-m_b-c_mM-c_aA-c_oO-c_lL-c_hH\right) \tag{1}$$

From **Model 1** we could calculate the total weight of all phytoplankton(Chl a) in each fish pens, introducing integral operation. As for the integral time, we select average integral time to be 9 month since milkfish could be sold at market after 8 ~ 10 months' feeding.
We get Model14:

$$F=\int_0^9\left(p_{\max}f\left(I\right)f\left(N\right)-r_b-e_b-m_b-c_mM-c_aA-c_oO-c_lL-c_hH\right)dt \tag{14}$$

From **Model13** we could calculate the total number( $x(9)$ ) of milkfish after 9 months' feeding. As for the culture period, we select average growing time 9 months.

$$x(9)=\frac{kx_0}{\left(k-x_0\right)e^{-r9}+x_0}\left(1-\left(\frac{1}{n}\right)^3\right)$$

From **Mode4** We could calculate the total weight of each milkfish after 9 months' feeding. As for the integral time, we select the same as Model14.

While **Mode4:** $$\frac{dM}{dt} = g_m M - f_m M - d_m M \qquad (4)$$

We get:

$$M = \int_0^9 (g_m M - f_m M - d_m M)dt \qquad (15)$$

Using Model13 to multiply Model15, we get total weight($Q$) of all milkfish in each fish pens. We select $Q$ to represent total weight of all milkfish in each fish pens.

$$Q = x(9) \times M = \frac{kx_0}{(k - x_0)e^{-r9} + x_0}\left(1 - \left(\frac{1}{n}\right)^3\right) \times \int_0^9 (g_m M - f_m M - d_m M)dt \qquad (16)$$

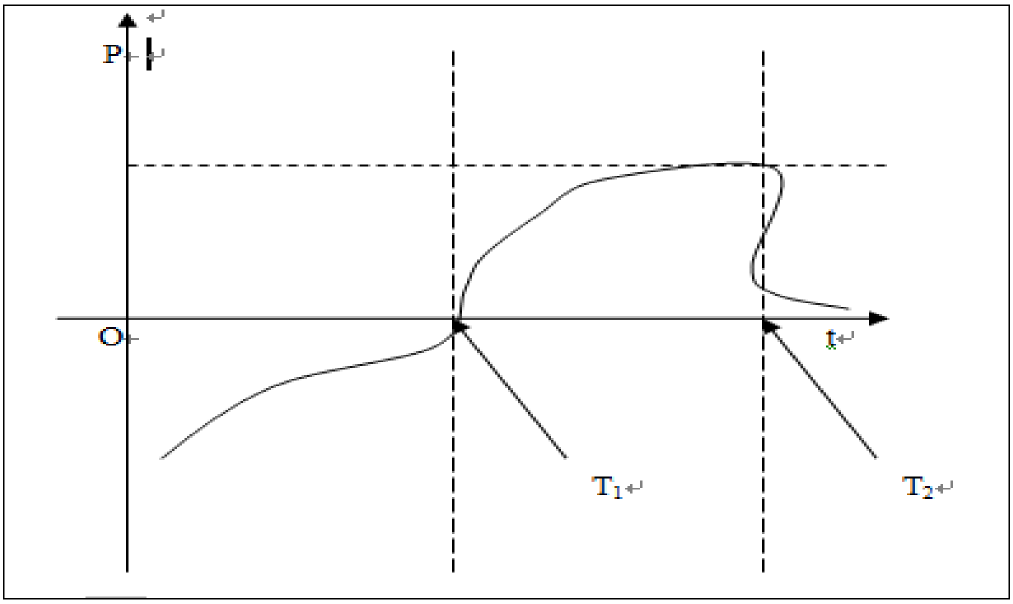
After inquiring prices of phytoplankton(Chl a) and milkfish, we could compare the economic value between them, and calculate their differentials( we define $P$ to represent). Set $P_1$ to represent the unit value of phytoplankton(Chl a), $P_2$ to represent the unit value of milkfish.

**Model17:**

$$\begin{aligned} P &= P_1 \times F - P_2 \times Q \\ &= P_1 \int_0^9 \left( p_{\max} f(I) f(N) - r_b - e_b - m_b - c_m M - c_a A - c_o O - c_l L - c_h H \right) dt \\ &\quad - P_2 \times \frac{kx_0}{(k - x_0)e^{-r9} + x_0}\left(1 - \left(\frac{1}{n}\right)^3\right) \times \int_0^9 (g_m M - f_m M - d_m M)dt \end{aligned}$$

Using mathematical software(Matlab) to simulate the trend of Model17, we get the following curve diagram.

**Figure8:** The trend of Model17 in curve diagram.




**7.2:** Define the value of edible biomass and calculate maximum harvest value.

From Figure9 we learn $P$ is unstable, $P$ is less than zero at $T_1$, $P$ reaches the maximum at T2, $P$ will get close to zero at infinity. So we can not conclude that 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.

But we can we define the value of edible biomass as the sum of the values of each species harvested, minus the cost of milkfish feed, minus the cost of restoration, minus the cost of culture facilities.

**Table4:** Variation range of all species and other factors concerning needing.(from Agra Europe Weekly, 2007)

| Needing Factors | Lower Limit | Upper Limit |
|---|---|---|
| Milkfish（M） | 3 | 5 |
| Acanthuridae(A) | 1 | 1 |
| Oyster(O) | 0.15 | 0.25 |
| Loster(L) | 0.2 | 0.3 |
| Sea Cucumber(H) | 0.1 | 0.15 |
| Sea Weed(SW) | 1.5 | 2.5 |

| | | |
|---|---|---|
| Feeding Cost(FT) | 0.13 | 1.62 |
| Restoration Cost(RC) | 0.1 | 0.6 |
| Culture Facilities Cost(FC) | 0.8 | 1 |

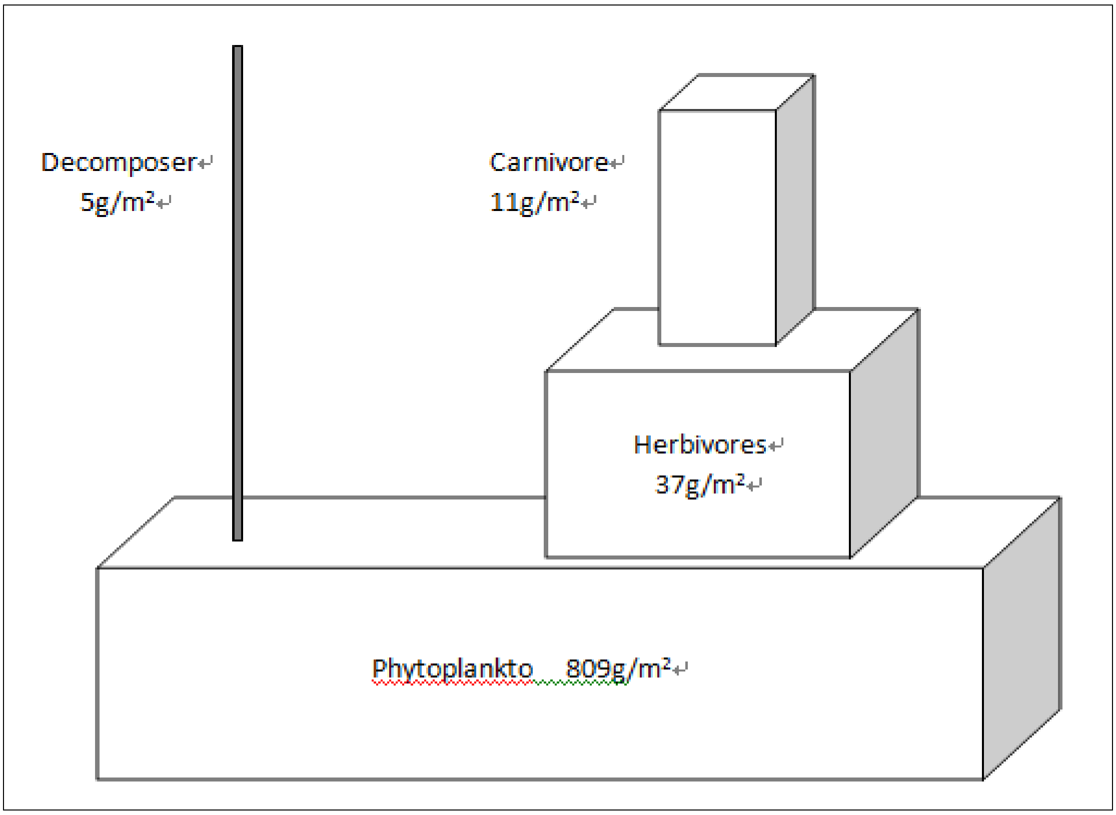
We select OFR to represent the value of edible biomass, $\lambda_1$ ~ $\lambda_9$ represent the demanding limits of each needing factor. M, A, O, L, H, SW, FT, RC, FC represent the needing amount of each needing factors.
We get:

$$OFR = \lambda_1 M + \lambda_2 A + \lambda_3 O + \lambda_4 L + \lambda_5 H + \lambda_6 SW - \lambda_7 FT - \lambda_8 RC - \lambda_9 FC \tag{18}$$

If we introduce the value of each needing factors into **Model18**, we will soon get the value of edible biomass with the help of mathematical software(Matlab).

**8. Task Ⅴ: Maximize the value of the total harvest.**

**Figure9:** Biomass pyramid(Gray,1987), and we have made some change.




Based on **Figure10** we could estimate living weight of each trophic level for further calculating total value. And we seriouly consider contribution of decomposer.

$$\frac{dM}{dt} = g_m M - f_m M - d_m M \quad (4)$$

$$\frac{dA}{dt} = g_a A - f_a A - d_a A \quad (5)$$

$$\frac{dO}{dt} = g_o O - f_o O - d_o O \quad (6)$$

$$\frac{dL}{dt} = g_l L - f_l L - d_l L \quad (7)$$

$$\frac{dH}{dt} = g_h H - f_h H - d_h H \quad (8)$$

$$\frac{dSW}{dt} = g_{sw} SW - f_{sw} SW - d_{sw} SW$$

These differential equations above is from Models in **part 1**. And we set the integral time to be average value(9 months). So we could carry out their the values of edible biomass functions as follows.

We get:

$$M = \int_0^9 \left( g_m M - f_m M - d_m M \right) dt \quad (19)$$

$$A = \int_0^9 \left( g_a A - f_a A - d_a A \right) dt \quad (20)$$

$$O = \int_0^9 \left( g_o O - f_o O - d_o O \right) dt \quad (21)$$

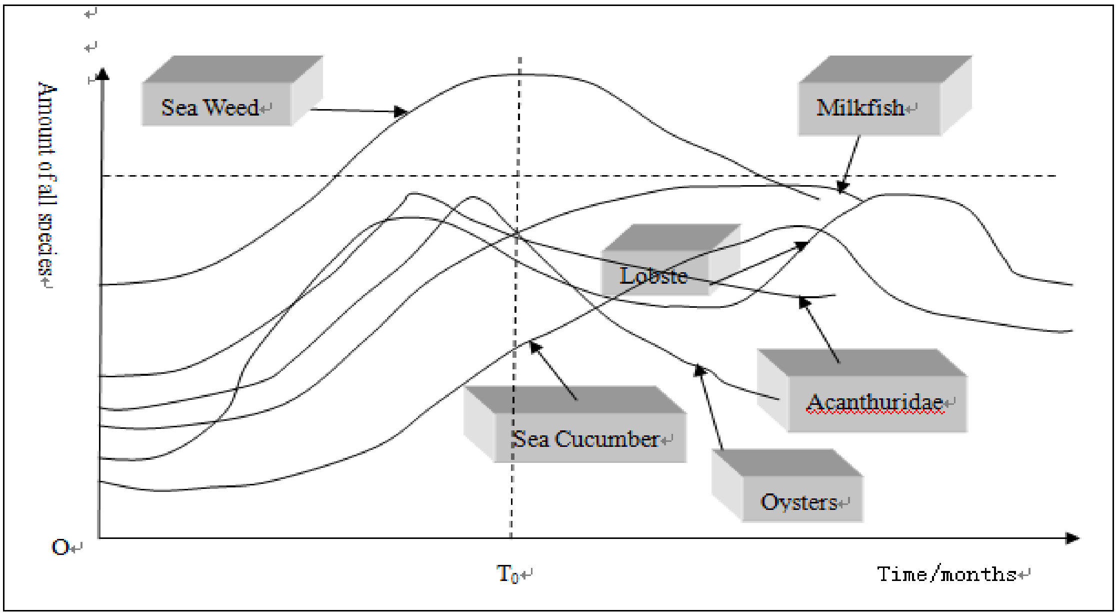
$$L = \int_0^9 \left( g_l L - f_l L - d_l L \right) dt \quad (22)$$

$$H = \int_0^9 \left( g_h H - f_h H - d_h H \right) dt \quad (23)$$

$$SW = \int_0^9 \left( g_{sw} SW - f_{sw} SW - d_{sw} SW \right) dt \quad (24)$$

With the help of mathematical software(Matalab), we get the trend of each species in polyculture fish pens. It is clear that we should catch each commercial species at point of $T_0$(about the ninth of the polyculture procedure)**.** $T_0$ is the best time for farmers to catch milkfish and other species which could bring them other income.

**Figure10:** The trend of the amount of all species with time going.




Because in our Model of Bolinao coral reef ecosystem in **part 1**, we have made water quality get close to the stable state by coordinating proportional allocation and restricting relative factors.

Commercial milkfish need only about 9 months to grow into the state of being sold at market. At the same time we introduce polyculture methods, so what we could harvest not only comes from milkfish, but also from other species in some degree. Our ways of harvest is catch 60% of the total milkfish in fish pens, 50% of the acanthuridae, 50% of the oysters, 55% of the lobsters, 50% of the sea cucumber, 50% of the seaweed. And only during egg laying period , we throw the most baits into fish pens for milkfish. As for other times , we throw lesser baits depending on the local food resource and need of milkfish. This way of harvest is quite helpful to recover for Bolinao coral reef ecosystem, and helpful to improve local sea water quality. On the one hand local farmers can be supported financially and nutritionally, on the other hand species in the ecosystem can restrict with each other, developing into virtuous cycle in the long time.

## 9. TaskⅥ: Write an information paper to the director of the Pacific Marine Fisheries Council.

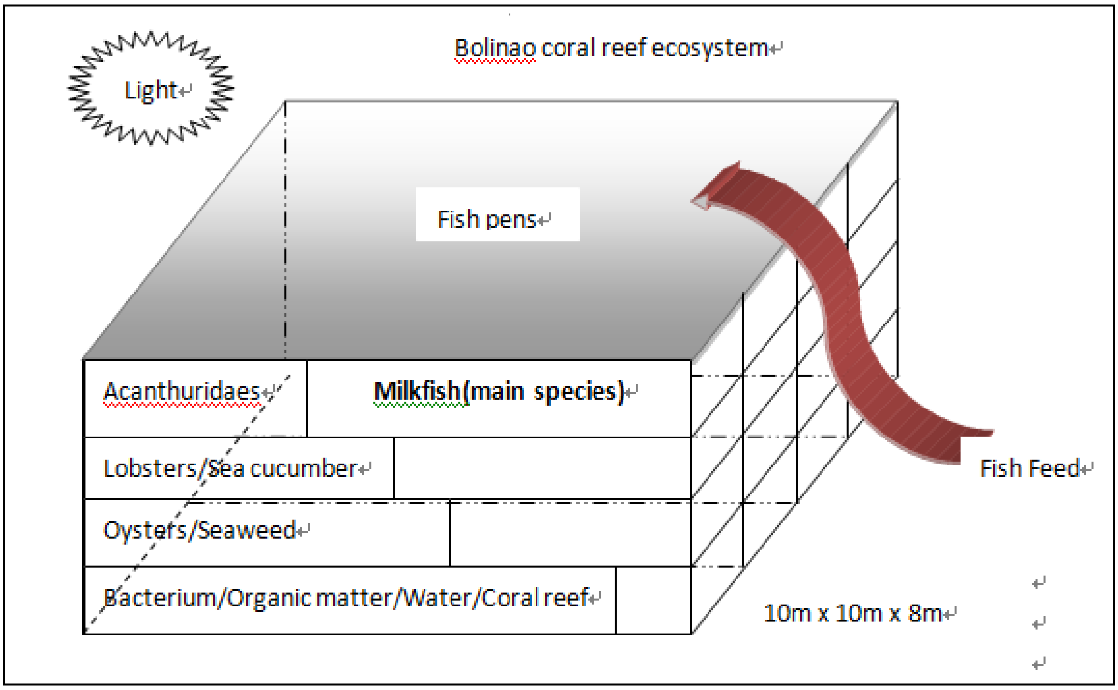
**Dear Mr Director:**

We have just taken part in the The Interdisciplinary Contest in Modeling organized by America. Our research subject is Creating Food Systems: Re-Balancing Human--influenced Ecosystems. After four days' study, we get some discoveries about the importance of species diversity and water quality during coral's whole growth.

Less than 1% of the ocean floor in Bolinao is covered by coral. Yet, 25% of the local ocean's biodiversity is supported in these areas. Thus, conservationists are concerned when coral disappears, since the biodiversity of the region disappears shortly thereafter. 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 as a result of the current monoculture, which can not deal with the relationship between corals and milkfish. 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). But the current water quality is not beneficial for corals to grow, and local ecosystem can not recover as soon as possible.

Nowadays, we want to give you some advice about how to save and restore Bolinao ecosystem. In order to solve this problem, we introduce a set of polyculture to replace the local current monoculture. We choose satisfactory milkfish, aucanthuridae, oysters, lobsters, seaweed, and sea cucumber as the cultured species. Then put them together into fish pens in appropriate proportions. The specification of each fish pens is about 10m x 10m x 8m with stocking densities of ~ 50,000 fish per pen and 10 pens per hectare, however where these fish pens should be put is based on local situation. We have drawn the sketch diagram of restoration as follows.

**Figure11:** The sketch diagram of restoration for Bolinao coral reef ecosystem




Commercial milkfish need only about 9 months to grow into the state of being sold at market, which could help to shorten the time for restoration. At the same time we introduce polyculture methods, so what we could harvest not only comes from milkfish, but also from other species in some degree. Our ways of harvest is catch 60% of the total milkfish in fish pens, 50% of the acanthuridae, 50% of the oysters, 55% of the lobsters, 50% of the sea cucumber, 50% of the seaweed. And only during egg laying period , we throw the most baits into fish pens for milkfish. As for other times , we throw lesser baits depending on the local food resource and need of milkfish. This way of harvest is quite helpful to recover for Bolinao coral reef ecosystem, and helpful to improve local sea water quality. On the one hand local farmers can be supported financially and nutritionally, on the other hand species in the ecosystem can restrict with each other, developing into virtuous cycle in the long time.

We optimize the combination of all species including milkfish, restrict their growth degree Celsius, restrict their food resource, and restrict fish pens(living space), restrict the density of milkfish, restrict intensity of illumination, and restrict bacterium living in fish pens. We could also restrict the ratio of nitrogen and phosphorus in order to stop water nutrition enrichment, which accords with Principle of Ecology and strengthens energy flow among the species. The economic value will be 3 times more than the past monoculture. What's more important, this way could reduce the funds to re-establish Bolinao ecosystem.

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