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A Mathematical Model of Coral Reef Response to Destructive Fishing Considering Some Biological Interactions

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Abstract. In this paper, we propose a system of nonlinear ordinary differential equations to model the interactions between coral, napoleon fish, clownfish and starfish biomasses. We consider some biological interactions, i.e. commensalism between napoleon fish and coral in favor of napoleon fish, competition between napoleon fish and clownfish, and predator-prey relationships between napoleon fish and starfish, and starfish and coral. We take into account coral damage from destructive fishing and consider constant yield, constant effort, and napoleon fish and clownfish harvesting. Using the standard theory of dynamical system, we determined analytical results such as equilibria for the system with and without harvesting. We show numerical simulations and conduct sensitivity analyses to illustrate the analytical result above.

Keywords: *coral reef, differential equation, stability, biological interaction*

INTRODUCTION

Oceans are an enormous part of the water that covers roughly 70 % of the earth. Coral reefs are the center of biodiversity in the world's oceans, home to a quarter of all marine life [1]. They provide habitats and haven for many marine organisms. Coral reefs are severely important for many reasons such as coastal defense from negative effect of wave action [2] and storm and essential nutrients source for marine food chains. Besides, coral reefs are very beneficial for many people in terms of economy, fisheries, and income through tourism.

The whole marine ecosystem is being threatened by the degradation of our reefs. Many factors are killing the coral reefs of our oceans. The rising temperature of sea-surface causes bleaching on coral. Coral reefs experienced global bleaching event by the time of 2015-2016 [3], and the rate of recruitment by corals has been substantially diminished owing to adult mortality from global warming [4]. Global climate change also affects the acidification of the ocean that reducing the PH level of it. Ocean acidification associated with the reduction in carbonate ion which reduces biogenic calcification and encourages the dissolution of carbonate substrate is of particular concern considering coral reef reduction [5]. Another element that causes the degradation of coral reefs is human activities, such as waste discarded by humans end up into the ocean causes water pollution and unethical fishing methods also affect the ecosystem of marine. The unethical fishing methods including overfishing, blast fishing, and poison fishing directly damage coral reefs. Exploitative fishing practices reduced populations of reef fish that usually keep coral predators and algae in check [1].

Although these are multiple factors of coral reefs degradation, we focus on the impact of destructive fishing practices rather than the natural disturbance. Blast fishing is considered one of the most destructive anthropogenic threats to coral reef ecosystems and the damaging effects are numerous [6]. Saila et al. [7] used a model contains an explicit relationship between the amount of coral reef and the biodiversity of the associated fish that is harvested by destructive fishing methods. Pet-Soede et al. [6] developed a model to calculate the costs and benefits of blast fishing at the level of Indonesian society as a whole. Then, Peng et al. [8] proposed a model of constant rate harvesting using Holling Type-II predator-prey system. Subsequently, by using Crowley-Martin type functional response, [9] extends the fishery model with harvesting for both prey and predator population. Other models include Quintero et al. [1]which examine the destructive fishing effects on the coral reefs with predator-prey in the Raja Ampat coral ecosystem.

The focus of this paper is to present an effect of excessive and destructive fishing practices in the coral reefs ecosystem considering some biological interactions such as predator-prey, commensalism, and competition. The mathematical model consists of four components: the coral reefs, a corallivore, a predator of the corallivore which has a commensal relationship with coral and another fish lives in coral compete with the predator which is life in coral too. We describe the mathematical model of the coral ecosystem we have built including the general ecosystem model and the constant effort harvesting model in Section 2. In section 3, we carry out mathematical analysis on the general

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ecosystem model. The constant effort model analysis is presented in section 4. Finally, we provide the estimates for the model parameters and simulation included sensitivity analysis.

MATHEMATICAL ANALYSIS

General Ecosystem Model

The model proposed is a system of four non-linear ordinary differential equations describing biomasses of humphead wrasse, clownfish (anemonefish), coral, and starfish. We assume that (i) starfish is the only prey for wrasse, (ii) coral is the only prey for starfish.

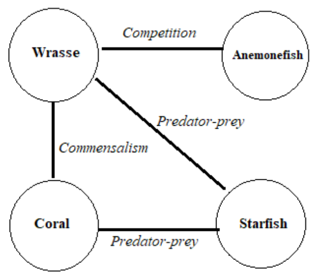

FIGURE 1. Population Diagram Flow

Let $W(t)$ be the density of humphead wrasse population, $A(t)$ be the density of anemonefish population, $C(t)$ be the density of coral reef population, and $S(t)$ be the density of starfish population at time t. The coral reef dynamics in the general ecosystem model.

$$\begin{aligned}
\frac{dW}{dt} &= W\left[r_1\left(1-\frac{W}{K_1+bC}\right)+\alpha_1 S\right]-\beta WA \\
\frac{dA}{dt} &= A\left[r_2\left(1-\frac{A}{K_2+bC}\right)\right]-\beta WA \\
\frac{dC}{dt} &= C\left[r_3\left(1-\frac{C}{K_3}\right)-\frac{\gamma_1 S}{C+q}\right] \\
\frac{dS}{dt} &= S\left[r_4\left(1-\frac{S}{K_4}\right)-\alpha_2 W+\frac{\gamma_2 C}{C+q}\right]
\end{aligned} \tag{1}$$

with initial condition $W(0)=W_0$, $A(0)=A_0$, $C(0)=C_0$, and $S(0)=S_0$.

First, we non-dimensionalize Equation 1 in order to simplify analysis - decreasing sixteen parameters to ten. Then we have :

$$\begin{aligned}
\frac{dw}{d\tau} &= w\left[\phi_1\left(1-\frac{w}{1+\theta_1 c}\right)+\delta_1 s\right]-\mu wa \\
\frac{da}{d\tau} &= a\left[\phi_2\left(1-\frac{a}{1+\theta_2 c}\right)\right]-\mu wa \\
\frac{dc}{d\tau} &= c\left[\phi_3(1-c)-\frac{us}{c+p}\right] \\
\frac{ds}{d\tau} &= s\left[\phi_4(1-s)-\delta_2 w+\frac{c}{c+q}\right]
\end{aligned} \tag{2}$$

with $\phi_i = \dfrac{r_i}{\gamma_2}$, for $i = 1,2,3,4$ represents the natural instrinsic growth rates for W, A, C and S respectively, $\delta_1 = \dfrac{\alpha_1 K_4}{\gamma_2}$ is the expressions related to the increase wrasse due to consumption of starfish, $\delta_2 = \dfrac{\alpha_2 K_1}{\gamma_2}$ is decrease in starfish from predation by wrasse, the parameter $u = \dfrac{K_4 \gamma_1}{\gamma_2 K_3}$ is the decrease in the coral due to starfish consumption, and $\theta_1 = \dfrac{K_3 b_1}{K_1}$, $\theta_2 = \dfrac{K_3 b_2}{K_2}$ are the conversion rate b_1 and b_2 which is additional carrying capacity of wrasse and anemonefish respectively gain from the presence of coral, $\mu = \dfrac{\beta K_1 K_2}{\gamma_2}$ is the competition rate of wrasse and anemonefish, and $p = \dfrac{q}{K_3}$ is related to the mid-saturation threshold from coral consumption relative to the carrying capacity of the coral.

Now that we analyze the system, first, we calculating the equilibria and their existence, then determining their stability. The system has sixteen equilibria, denoted by $E_i = (w*, a*, c*, s*)$ for $i = 1, ..., 8$ as in the Table 1 below :

TABLE 1. Equilibria of General Ecosystem Model

The Existence of Equilibria					
Equilibria	Existence	Stability	Equilibria	Existence	Stability
$E_0 = (0,0,0,0)$	Always	Unstable	$E_8 = (w_1^*, a_1^*, 0, s_1^*)$	If $\mu > \frac{\phi_2(\delta_1\delta_2+\phi_1\phi_4)}{\delta_1\phi_4+\phi_1\phi_4}$ and $\mu + \phi_4 + \delta_2\phi_1\phi_2 > \phi_2(\mu\delta_2 + \phi_1\phi_4)$	Unstable
$E_1 = (0,0,0,1)$	Always	Unstable	$E_9 = (0,0,c_2^*,s_2^*)$	If $\phi_3 > u$	Unstable
$E_2 = (0,1,0,0)$	Always	Unstable	$E_{10} = (0, \theta_2+1, 1, 0)$	Always	Unstable
$E_3 = (0,1,0,1)$	Always	Unstable	$E_{11} = (\theta_1+1, 0, 1, 0)$	Always	If $\phi_2 < \mu(\theta_1+1)$
$E_4 = (1,0,0,0)$	Always	Unstable	$E_{12} = (w_3^*, 0, c_3^*, s_3^*)$	If $\phi_3 > u$	Unstable
$E_5 = (0,0,1,0)$	Always	Unstable	$E_{13} = (0, a_4^*, c_4^*, s_4^*)$	If $\phi_3 > u$	Unstable
$E_6 = (\frac{\phi_2(\mu-\phi_1)}{\mu^2-\phi_1\phi_2}, \frac{\phi_1(\mu-\phi_2)}{\mu^2-\phi_1\phi_2}, 0, 0)$	If $\phi_1 < \mu$ and $\phi_2 > \mu$	Unstable	$E_{14} = (w_5^*, a_5^*, 1, 0)$	If $\mu > \frac{\phi_i(\theta_2+1)}{\theta_1\theta_2+\theta_1+\theta_2+1} fori = 1,2$	Unstable
$E_7 = \left(\frac{\phi_4(\delta_1+\phi_1)}{\delta_1\delta_2+\phi_1\phi_4}, 0, 0, \frac{\phi_1(\delta_2+\phi_4)}{\delta_1\delta_2+\phi_1\phi_4}\right)$	If $\delta_1 > -\phi_4$ and $\delta_2 > -\phi_4$	Unstable	$E_{15} = (w_6^*, a_6^*, c_6^*, s_6^*)$	Always	Unstable

Harvesting Model

After evolving the system as it is without harvesting, now we consider a model with human intervention. First, we let H as a measured effort placed into fishing wrasse and anemonefish and D as the rate of destroyed coral from cyanide and blast fishing.

$$
\begin{aligned}
\frac{dW}{dt} &= W\left[r_1\left(1 - \frac{W}{K_1 + bC}\right) + \alpha_1 S\right] - \beta WA - HW \\
\frac{dA}{dt} &= A\left[r_2\left(1 - \frac{A}{K_2 + bC}\right)\right] - \beta WA - HA \\
\frac{dC}{dt} &= C\left[r_3\left(1 - \frac{C}{K_3}\right) - \frac{\gamma_1 S}{C+q}\right] - DC \\
\frac{dS}{dt} &= S\left[r_4\left(1 - \frac{S}{K_4}\right) - \alpha_2 W + \frac{\gamma_2 C}{C+q}\right]
\end{aligned}
\tag{3}
$$

with initial condition $W(0) = W_0$, $A(0) = A_0$, $C(0) = C_0$, and $S(0) = S_0$. Under constant effort harvesting, we define $H > 0$ and $D > 0$.

Table 2 provides our model parameters description with their respective units.

TABLE 2. Parameters Description of The Models

Parameter Description	Units
r_1 = Instrinsic growth rate for wrasse	$\frac{1}{yrs}$
r_2 = Instrinsic growth rate for anemonefish	$\frac{1}{yrs}$
r_3 = Instrinsic growth rate for coral	$\frac{1}{yrs}$
r_4 = Instrinsic growth rate for starfish	$\frac{1}{yrs}$
K_1 = Carrying capapacity of wrasse	$\frac{Kg}{km^2}$
K_2 = Carrying capapacity of anemonefish	$\frac{Kg}{km^2}$
K_3 = Carrying capapacity of coral	$\frac{Kg}{km^2}$
K_4 = Carrying capapacity of starfish	$\frac{Kg}{km^2}$
α_1 = Benefit rate from wrasse predation on starfish	$\frac{km^2}{kg*yrs}$
α_2 = Predation rate from wrasse on starfish	$\frac{km^2}{kg*yrs}$
b_1 = Conversion factor for wrasse benefit from coral	unitlessd
b_2 = Conversion factor for anemonefish benefit from coral	unitless
q = Starfish mid-saturation threshold from coral consumption	
γ_1 = Predation rate from starfish on coral	$\frac{1}{yrs}$
γ_2 = Benefit rate from starfish on coral	$\frac{1}{yrs}$
β = Competition rate between wrasse and anemonefish	unitless
H = Harvesting rate for wrasse and anemonefish	$\frac{1}{yrs}$
D = Instrinsic destruction rate for coral	$\frac{1}{yrs}$

As the Equation 1 above, non-dimensionalize the Equation 3 to decrease the parameters so that it will get easier to analyze.

After getting a non-dimensionalize system, then analyze the system. First, we calculating the equilibria and their existence, then determining their stability. The system has sixteen equilibria, denoted by $E_i = (w*, a*, c*, s*)$ for $i = 1, ..., 8$ as in the Table 3 below :

TABLE 3. Equilibria of Harvesting Model

The Existence of Equilibria					
Equilibria	Existence	Stability	Equilibria	Existence	Stability
$E_0 = (0,0,0,0)$	Always	If $\phi_i > h$ for $i = 1,2$ and $\phi_3 > d$ then unstable	$E_8 = (w_3^*, a_3^*, 0, s_3^*)$	Always	Unstable
$E_1 = (0,0,0,1)$	Always	If $\phi_1 + \delta_1 > h$ and $phi_2 > h$ then unstable	$E_9 = (0,0,c_4^*, s*_4)$	Always	Unstable
$E_2 = (0, -\frac{h-\phi_2}{\phi_2}, 0, 0)$	If $\phi_2 > h$	Unstable	$E_{10} = (0, a_5^*, -\frac{d-\phi_3}{\phi_3}, 0)$	If $\phi_3 > d$ and $\theta_2(dh + \phi_2\phi_3) + \phi_2\phi_3 > \theta_2(d\phi_2 + h\phi_3) + h\phi_3$	Unstable
$E_3 = (0, -\frac{h-\phi_2}{\phi_2}, 0, 1)$	If $\phi_2 > h$	If $\phi_2 > \frac{h(\mu+\phi_2)+\mu\phi_2}{\delta_1+\phi_1}$ then unstable	$E_{11} = (0, a_6^*, c_6^*, s_6^*)$	Always	Unstable
$E_4 = (-\frac{h-\phi_1}{\phi_1}, 0, 0, 0)$	If $\phi_1 > h$	Unstable	$E_{12} = (w_7^*, 0, -\frac{d-\phi_3}{\phi_3}, 0)$	If $\phi_3 > d$ and $\theta_1(dh + \phi_1\phi_3) + \phi_1\phi_3 > \theta_1(d\phi_1 + h\phi_3) + h\phi_3$	If $\phi_1 > h$ and $\phi_3 > d$ then unstable
$E_5 = (0, 0, -\frac{d-\phi_3}{\phi_3}, 0)$	If $\phi_3 > d$	Unstable	$E_{13} = (w_8^*, 0, c_8^*, s_8^*)$	Always	Unstable
$E_6 = (w_1^*, a_1^*, 0, 0)$	If $\phi_i > \frac{h\mu+\phi_1\phi_2}{h+\mu}$ for $i = 1,2$	Unstable	$E_{14} = (w_9^*, a_9^*, -\frac{d-\phi_3}{\phi_3}, 0)$	If $\phi_3 > d$	Unstable
$E_7 = (w_2^*, 0, 0, s_2^*)$	If $\delta_1 + \phi_1 > h$ and $h\delta_2 + \phi_1\phi_4 > \delta_2\phi_1$	Unstable	$E_{15} = (w_{10}^*, a_{10}^*, c_{10}^*, s_{10}^*)$	Always	Using Routh-Hurwitz Criterion is proven stable

Parameter Description

Table 4 provides our model parameters with their respective units, also the value of the parameters that we get from previous research [1] and/or estimated value.

TABLE 4. Parameters Value of The Model

Parameter Description	Units	Values	References
r_1 = Instrinsic growth rate for wrasse	$\frac{1}{yrs}$	0.00015	[1]
r_2 = Instrinsic growth rate for anemonefish	$\frac{1}{yrs}$	0.00013	Estimated
r_3 = Instrinsic growth rate for coral	$\frac{1}{yrs}$	0.00129	Estimated
r_4 = Instrinsic growth rate for starfish	$\frac{1}{yrs}$	1.3^{-3}	Estimated
K_1 = Carrying capapacity of wrasse	$\frac{Kg}{km^2}$	120667	[1]
K_2 = Carrying capapacity of anemonefish	$\frac{Kg}{km^2}$	1000	Estimated
K_3 = Carrying capapacity of coral	$\frac{Kg}{km^2}$	50000	[1]
K_4 = Carrying capapacity of starfish	$\frac{Kg}{km^2}$	550	[1]
α_1 = Benefit rate from wrasse predation on starfish	$\frac{km^2}{kg*yrs}$	5×10^{-17}	[1]
α_2 = Predation rate from wrasse on starfish	$\frac{km^2}{kg*yrs}$	6.21545×10^{-9}	
b_1 = Conversion factor for wrasse benefit from coral	unitless	7.242494	Estimated
b_2 = Conversion factor for anemonefish benefit from coral	unitless	2.757506	Estimated
q = Starfish mid-saturation threshold from coral consumption	$\frac{kg}{km^2}$	33138	Estimated
γ_1 = Predation rate from starfish on coral	$\frac{1}{yrs}$	0.007215	[1]
γ_2 = Benefit rate from starfish on coral	$\frac{1}{yrs}$	0.005	[1]
β = Competition rate between wrasse and anemonefish	unitless	0.56×10^{-5}	Estimated
H = Harvesting rate for wrasse and anemonefish	$\frac{1}{yrs}$	$(0,0.1)$	Estimated
D = Instrinsic destruction rate for coral	$\frac{1}{yrs}$	$(0,0.1)$	Estimated

SIMULATION

In this section, we will numerically simulate our dimensionless model in the previous section. After providing all the value of parameters that we can see in the Table 4, we will assume the initial conditions of each population $w(0) = 0.1, a(0) = 0.07, c(0) = 0.28, s(0) = 0.02$. In addition, the main of these simulations are the parameters of harvest and destructive practices which are h and d respectively to find out how to minimize this human activity in nature.

Simulation of Harvest and Destructive Elimination

The following simulation is the general ecosystem model that has $d = 0$ and $h = 0$, which means there are no harvesting and destructive fishing practices.

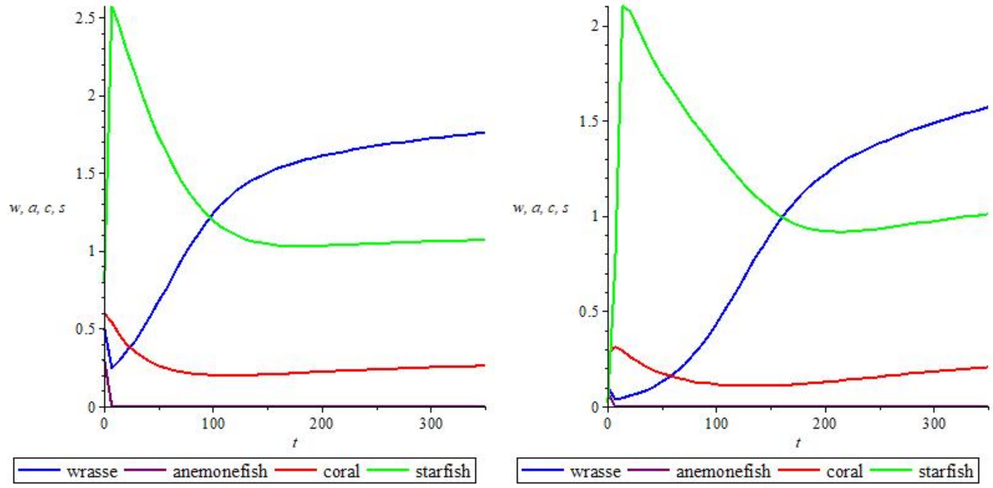

FIGURE 2. Coexixtence Simulation in the exclusion of harvest and destruction with varying initial condition ($w(0) = 0.5, a(0) = 0.3, c(0) = 0.6, s(0) = 0.6$) and ($w(0) = 0.1, a(0) = 0.07, c(0) = 0.28, s(0) = 0.02$)

Figure 2 shows the difference between two cases of initial condition to study the significance of initial condition to the simulation. Both of them show that all the species can live in coexistence with each other. In Figure 2 (a), the starfish biomass begins to grow sharply and then steeply declines until it gets stable at a 200-year mark. And also, the wrasse biomass increases along with the starfish and gets stable at a 300-year mark. On the other hand, the coral biomass and anemone biomass decrease from the initial condition and get stable without increasing. Figure 2 (b) has the same behavior with Figure 2 (a) except the difference of initial condition that affects the beginning of the biomass.

Simulation with Harvest and Destruction

In this section, the simulation of harvest and destruction model provided. Assume that the value of harvest and destruction are $h = 0.009$ and $d = 0.009$ respectively. The simulation will be displayed to all the populations with values $h = 0$ and $d = 0$ as compared to $h = 0.009$ and $d = 0.009$. And also provided the simulations without harvesting but there is damage to coral reefs namely $h = 0$ and $d = 0.009$ and vice versa i.e. by harvesting and without damage $h = 0.009$ and $d = 0$.

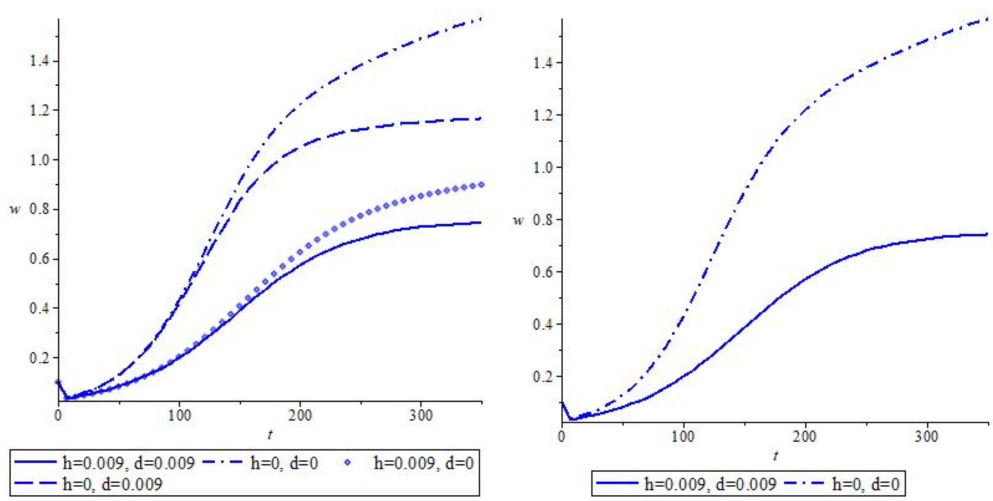

FIGURE 3. Harvest and Destruction Comparison Simulation on Wrasse Population

Figure 3 shows effect harvest and destruction on wrasse biomasses. The comparison harvest and destruction can be seen in Figure 2 that harvest has a higher effect on wrasse than destruction only because of harvest harm directly to the wrasse biomass than destruction. And it goes even worst when both harvest and destruction happen at the same time because it implies direct deprivation of wrasse biomass and its home which the coral.

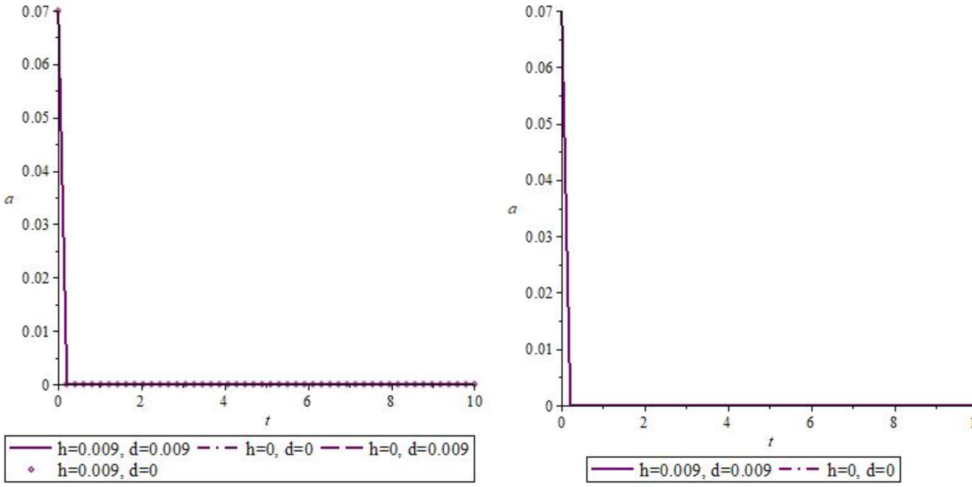

FIGURE 4. Harvest and Destruction Comparison Simulation on Anemonefish Population

Figure 4 shows the effect on anemonefish biomass by considering harvest and destruction. The same behavior in wrasse also occurs in anemonefish, in which harvesting has a big effect on its population flow.

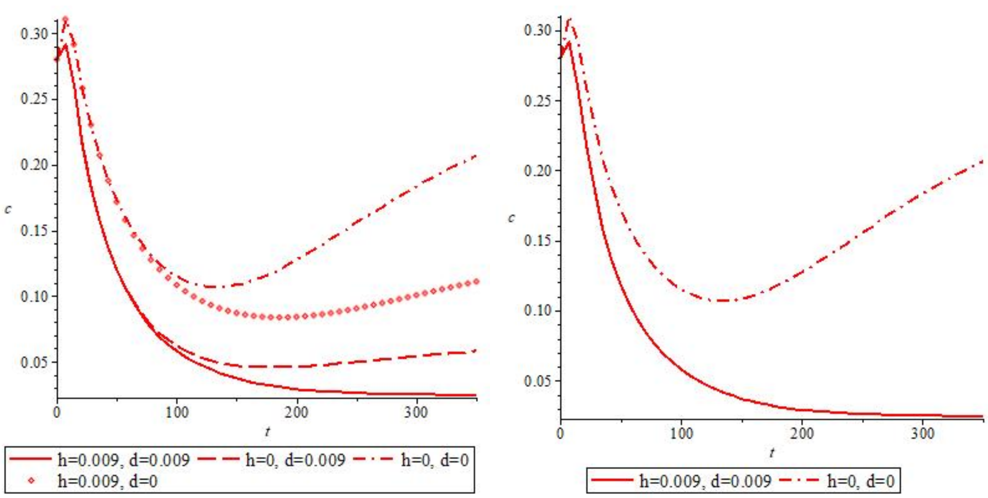

FIGURE 5. Harvest and Destruction Comparison Simulation on Coral Population

Figure 5 provides an effect on the coral population by harvest and destruction. Note that the destruction gives more effect on coral than harvest itself. This result is clear because the destruction affects the direct removal of coral biomass. If the harvest and destruction occur at the same time, it makes the coral biomass even decrease than harvest alone but it does not appear to amount for something far more different than the destruction only.

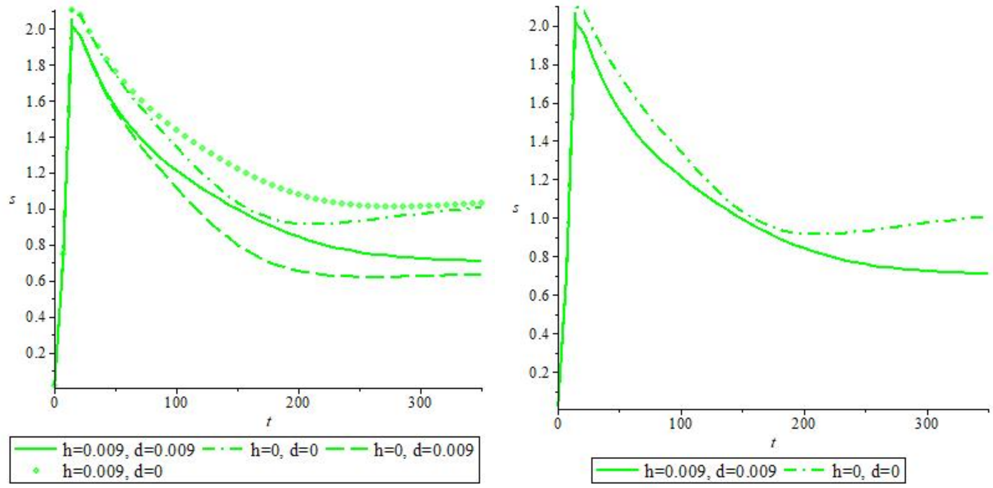

FIGURE 6. Harvest and Destruction Comparison Simulation on Starfish Population

Figure 6 shows that in the starfish biomass, there is difference in result with wrasse or coral biomass. Because the fishing practices give a benefit to starfish, whereas the predator of starfish being decreased so that starfish can grow easily.

SENSITIVITY ANALYSIS

In this section, sensitivity analysis of the system is provided to show which parameter has the largest effect on the system. Considering harvest and destruction practices, the parameters of harvest and destruction which is h and d respectively analyzed to the system. First, we show how much destruction influence the system by define $h = 0$ and $d = [0, 0.1]$.

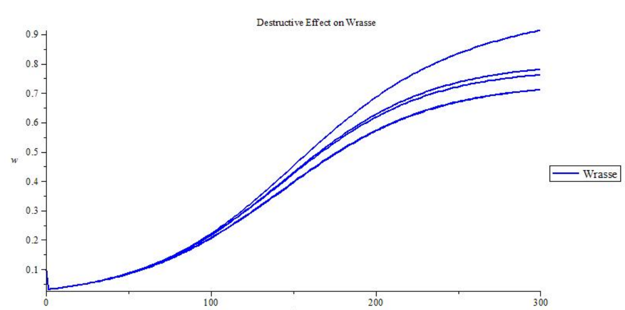

FIGURE 7. Sensitivity Analysis of Destruction Parameter on Wrasse Biomass

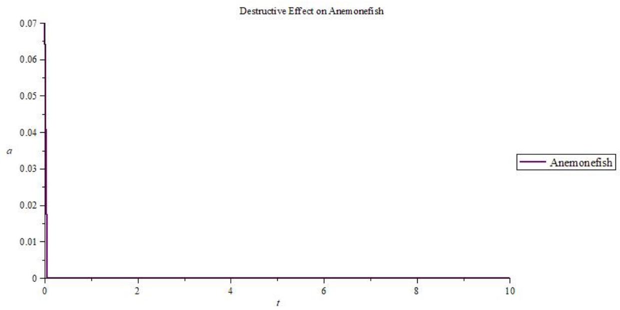

FIGURE 8. Sensitivity Analysis of Destruction Parameter on Anemone Biomass

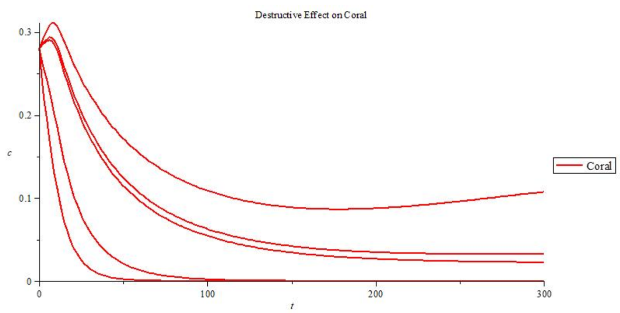

FIGURE 9. Sensitivity Analysis of Destruction Parameter on Coral Biomass

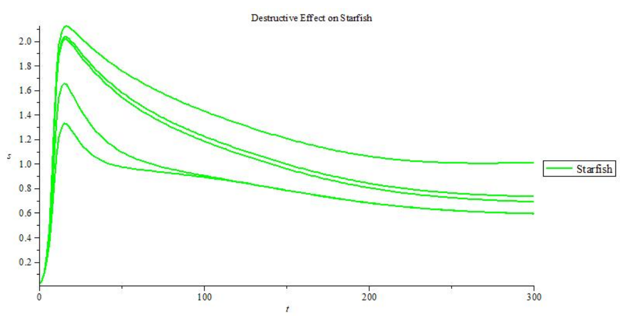

FIGURE 10. Sensitivity Analysis of Destruction Parameter on Starfish Biomass

Figure 7, Figure 8, Figure 9, and Figure 10 show the plots of sensitivity index on destruction by all species which wrasse, anemonefish, coral and starfish respectively, by any given time t. The increasing of destruction has a little effect on wrasse and anemonefish biomasses because they do not really depend on the coral biomass which has destroyed. In another situation, coral biomass is affected by the sudden increase in destruction. In Figure 9 shows the sensitivity of coral biomass due to destruction increasing. Whereas, starfish biomass approach equilibrium and stay in reasonable biomass. Due to the destruction of coral affect the carrying capacity of the wrasse which the predator of starfish, so starfish get the benefits of this situation that starfish biomass keep on stable condition.

After showing the effect of destruction parameter to the system, we will show how big harvest influence the system by defining $d = 0$ and $h = [0, 0.1]$.

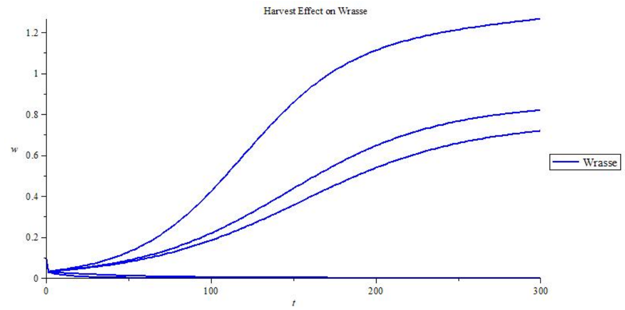

FIGURE 11. Sensitivity Analysis of Harvest Parameter on Wrasse Biomass

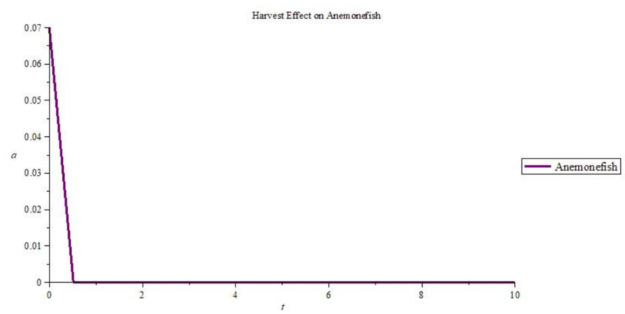

FIGURE 12. Sensitivity Analysis of Harvest Parameter on Anemonefish Biomass

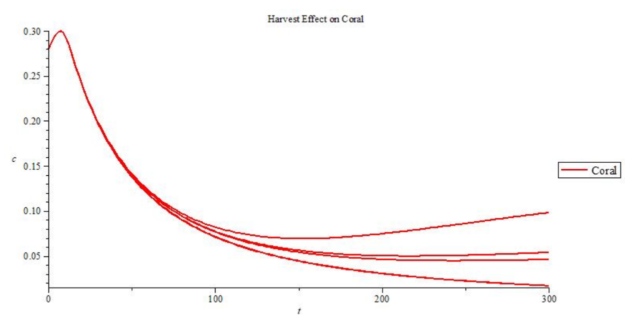

FIGURE 13. Sensitivity Analysis of Harvest Parameter on Coral Biomass

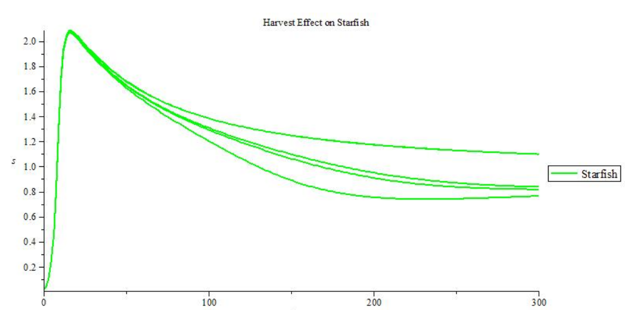

FIGURE 14. Sensitivity Analysis of Harvest Parameter on Starfish Biomass

Figure 11, Figure 12, Figure 13, and Figure 14 provide the plots of sensitivity index on harvesting by all species which wrasse, anemonefish, coral and starfish respectively, by any given time t. Note that a sudden of the increasing harvest would give wrasse biomass and anemonefish a continuing decline. So that the sensitivity index of wrasse and anemonefish is negative since the harvest would remove wrasse and anemonefish. But, Figure 11 and Figure 13 shows that coral and wrasse have replaced each other considering the destruction analysis in Figure 7 and Figure 9. The increase in harvest doesn't give a big effect on the coral due to the lost of wrasse and anemonefish would not stop the growth of coral. Figure 14 shows the sensitivity index of starfish is positive due to the removes of its predator which is wrasse so starfish can grow to larger biomass.

CONCLUSION

Coral reefs around the world are experiencing degradation due to many factors i.e overfishing and destructive fishing such as blast fishing and poisson fishing. Since overfishing and destructive fishing has affected the coral reef life, our study showed a mathematical model analysis of its response to destructive fishing practices that is these practices should be stopped by every fisherman. The explicit result of this response is in our numerical analysis which shows the increase of destructive fishing practice indirectly leads to a more prompt depletion of coral. Moreover, our sensitivity analysis provided that starfish (corallivore) is more beneficial from the increasing of destruction than harvesting the predator of it. And it also showed how big the influence of harvest to wrasse and anemonefish biomass and destruction to coral biomass.

The outcome of this study, since the harmful of destructive fishing practices, we should limit these practices. Limiting this practices would make the marine ecosystem continue to balance, and by balancing the natural ecosystem, fisherman can still be a fisherman to live other people by harvest the fishes. One way to reduce this practice is to set the regulation by the government that contains penalties for violators with the most severe punishment and also educate the fisherman to stop this practice.

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