The role of top-predator in the preservation of coral reefs ecosystem

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Abstract

The coral reef ecosystem in Indonesian as part of Coral Triangle Region has been significantly decreasing in the last decades. This damage has been known widely due to coastal development, pollution, and uncontrolled fishing and harvesting. Among other many living species in the environment, the existence of coral reefs is directly related to the existence of *Drupella sp.* and *Acanthaster planci* as the coral predators, while the existence of the predators also related to the Napoleon wrasse and Giant triton/ Trumpet shell as the top predator. This study discusses the interaction among the coral reefs, the predators and the top predators, which is represented in a dynamical model of predator-prey-top predator. In the absence of top predators, the system is reduced as a two-predator-prey model with only one surviving predator, *Acanthaster planci*, which has more effective predation behavior. The role of Napoleon wrasse as a top predator of both *Acanthaster planci* and *Drupella sp.* is significantly important to protect the coral reef from the excessive predation from *Acanthaster planci* and *Drupella sp.* A stable co-existence is shown between coral reef, *Acanthaster planci* and Napoleon wrasse. With the appearance of Giant tritons which predate only *Acanthaster planci*, a co-existence between five species may occur with abundant species of Giant triton.

Keywords: Coral Reef Conservation, Multi-stage predator-prey model, Stability.

1. Introduction

Over the past ten years, coral reefs of the Coral Triangle Region has been increasingly threatened. This huge region covers the territories of Indonesia, Malaysia, Papua New Guinea, the Philippines, Solomon Islands and Timor Leste. This region contains approximately 30 percent of world's coral reefs and 75 percents of total known coral species [1].The excessive damage of the reefs is largely contributed from human activities and has become great concern of authorities in respected countries. The diversity of the valuable Indonesian coral reef is threatened and forced to being damage because of illegal fishing. Excessive fishing and harvesting are giving impacts to almost 85% coral reef damage [1] besides other biological factor such as predator prey interaction. The coral is predated and bioresied by some species such as *Drupella sp.* and *Acanthaster planci* [2], [3], [4], [5]. The extremely explosion of those two species population in a sufficient time interval and wide area could make the disturbance of coral reef existence. On the other hand, the existence of Napoleon wrasse (*Cheilinus undulatus*) and Giant triton (*Charonia tritonis*) which live in coral reef environment [6], [7], [8], are taking a role as the predators of both species. These two species may reduce the interaction between coral reef population and *Drupella sp.* and *Acanthaster planci* and potentially form a stable coexistence of those different species.

Napoleon wrasse, as the top predator of coral reef ecosystem, predates both *Drupella sp.* and *Acanthaster planci*, while *Acanthaster planci* is predated by both Napoleon wrasse and *Charonia tritonis* that is also known as the giant trumpet shell. In this paper the interaction between coral reef, *Drupella sp.* and *Acanthaster planci* as predators and Napoleon wrasse (*Cheilinus undulatus*) and Giant triton (*Charonia tritonis*) as top predators is modeled mathematically in the form of five dimensional dynamical system. The existence of possible equilibria and their stability are analized.

2. Derivation of the model

We derive a multi-stage predator-prey model involving population of Coral reef, *Drupella sp.*, *Acanthaster planci*, Napoleon wrasse and Giant triton, which are denoted by C, D, A, N and G are respectively. At the lowest stage, Coral as the main prey is predated by A and D. At the second stage, there are two top predators, N is predatory to both A and D, whereas G acts as predator to A only. The interaction diagram between those

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five species is shown in Figure 1. Note that all population C, D, A, N and G are measured in densities. The full system of the multi-stage predator-prey model is constructed in Equation (1), with the corresponding state variables and parameters are given in Table I. In the following sections, dynamical analysis and numerical simulations are thoroughly discussed.

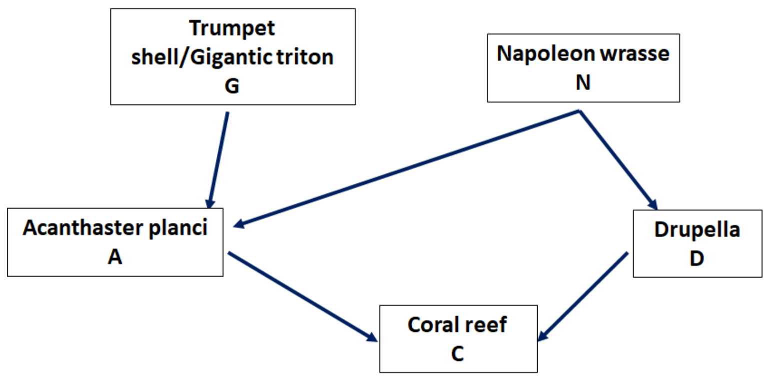

Fig. 1: Interaction Diagram $C - A - D$.

TABLE I: Variables and parameters of the dynamical model

Variables & parameters	Description	Dimension
$C(t)$	Density of coral	biomass per unit area
$D(t)$	Density of *Drupella sp*	biomass per unit area
$A(t)$	Density of *Acanthaster planci*	biomass per unit area
$N(t)$	Density of Napoleon wrasse	biomass per unit area
$G(t)$	Density of Giant triton	biomass per unit area
α_c	Growth rate of Coral	biomass per unit time
C_0	carrying capacity of coral reef	biomass per unit time
μ_d	Natural death rate of *Drupella sp.*	biomass per unit time
μ_a	Natural death rate of *Acanthaster planci*	biomass per unit time
μ_n	Natural death rate of Napoleon wrasse	biomass per unit time
μ_g	Natural death rate of Giant triton	biomass per unit time
a	Proportion of coral reef decreasing caused by *Drupella sp.*	biomass per unit time
b	Proportion of coral reef decreasing caused by *Acanthaster planci*	biomass per unit time
e	Predation rate of *Drupella sp.* w.r.t coral reef	biomass per unit time
f	Proportion of *Drupella sp.* decreasing caused by Napoleon wrasse	biomass per unit time
h	Predation rate of *Acanthaster planci* w.r.t coral reef	biomass per unit time
k	Proportion of *Acanthaster planci* decreasing caused by Napoleon wrasse	biomass per unit time
m	Proportion of *Acanthaster planci* decreasing caused by Giant triton	biomass per unit time
p	Predation rate of Napoleon wrasse w.r.t *Drupella sp.*	biomass per unit time
q	Predation rate of Napoleon wrasse w.r.t *Acanthaster planci*	biomass per unit time
r	Predation rate of Giant triton w.r.t *Acanthaster planci*	biomass per unit time

In order to determine the impact of coral reef existence to the existence of *Drupella sp.*, Napoleon wrasse, *Acanthaster planci* and Giant triton case, we consider to the following model

$$
\begin{aligned}
\frac{dC}{dt} &= \alpha_c C(1-\frac{C}{C_0}) - aDC - bAC,\\
\frac{dD}{dt} &= D(eC - fN - \mu_d),\\
\frac{dA}{dt} &= A(hC - kN - mG - \mu_a),\\
\frac{dN}{dt} &= N(pD + qA - \mu_n),\\
\frac{dG}{dt} &= G(rA - \mu_g).
\end{aligned} \tag{1}
$$

3. DYNAMICAL MODEL OF $C - D - A$

In order to understand the complex biological process of the system (1), we will start with the interaction system C-A-D, i.e. in the absence of Napoleon wrasse and Giant triton

$$
\begin{aligned}
\frac{dC}{dt} &= \alpha_c C(1-\frac{C}{C_0}) - aDC - bAC,\\
\frac{dD}{dt} &= D(eC - \mu_d),\\
\frac{dA}{dt} &= A(hC - \mu_a).
\end{aligned} \tag{2}
$$

The model (2) is a special case of the known two-predator-one-prey system in which the non-linear logistic terms are not included in the dynamic of predators, see for example in [9], [10].

3.1. Analysis of co-existence and Stability of the $C - D - A$ Model

In the absence of predators, it is assumed that coral grow with logistic model. The other two predators are assumed to grow with the main logistical support from preys. The system (2) has four equilibria

$$
\begin{aligned}
CDA_1 &= \{A = 0, C = 0, D = 0\}\\
CDA_2 &= \{A = 0, C = C_0, D = 0\}\\
CDA_3 &= \left\{A = 0, C = \frac{\mu_d}{e}, D = \frac{\alpha_c\,(C_0\,e - \mu_d)}{a C_0\,e}\right\} \qquad (3)\\
CDA_4 &= \left\{A = \frac{\alpha_c\,(C_0\,h - \mu_a)}{hbC_0}, C = \frac{\mu_a}{h}, D = 0\right\},
\end{aligned} \tag{4}
$$

where, CDA_3 and CDA_4 exist only if $\mu_d < C_0 e$ and $\mu_a < C_0 h$, respectively. It can be shown that CDA_1 and CDA_2 are unstable, and the System (2) has only one stable equilibrium, which can be identified with the predation effectiveness ratio

$$
\rho_{AD} = \frac{\frac{h}{\mu_a}}{\frac{e}{\mu_d}}, \tag{5}
$$

precisely, it can be summarized as follow. The equilibrium CDA_3 is locally asymptotically stable, and CDA_4 is unstable if $\rho_{AD} < 1$, and CDA_4 is locally asymptotically stable, and CDA_3 is unstable if $\rho_{AD} > 1$. This is consistent with the results in [9], [10], that only one predator, which is more effective in predating, will survive in a two-predator-one-prey system. In the next discussion we assume that $\rho_{AD} > 1$, allowing single predator A survive at the end, in the absence of N and G (see Figures 2). The other case can be done similarly.

4. Dynamical model $C-D-A-N$

In the absence of Giant triton G, we have the following system

$$\begin{aligned}\frac{dC}{dt}&=\alpha_c C(1-\frac{C}{C_0})-bDC-bAC,\\ \frac{dD}{dt}&=D(eC-fN-\mu_d),\\ \frac{dA}{dt}&=A(hC-kN-\mu_a),\\ \frac{dN}{dt}&=N(pD+qA-\mu_n).\end{aligned}\tag{6}$$

For simplicity of the dynamics and notations, let

$$\begin{aligned}C_5&=\frac{Co\ (\alpha_c q-b\mu_n)}{\alpha_c q}\\ N_5&=\frac{hCo\ (\alpha_c q-b\mu_n)-q\mu_a\alpha_c}{k\alpha_c}\\ C_6&=\frac{Co\ (\alpha_c p-a\mu_n)}{\alpha_c p}\\ N_6&=\frac{e\,(\alpha_c p-a\mu_n)\,Co-p\alpha_c\mu_d}{\alpha_c pf}.\end{aligned}\tag{7}$$

$$\begin{aligned}p_0&=\frac{\mu_n eaCo}{\alpha_c\,(Co\,e-\mu_d)}\\ q_0&=\frac{\mu_n hbCo}{\alpha_c\,(Co\,h-\mu_a.)}\end{aligned}\tag{8}$$

The System (6) has six possible equilibria, $CDAN_i, i=1..6$ which are given in Table II. The following properties are obtained from the stability analysis at each equilibrium.

1) $CDAN_i, i=1..4$ are unstable
2) $CDAN_5$ exists if and only if $q>q_0$
3) $CDAN_6$ exists if and only if $p>p_0$
4) $CDAN_5$ is stable if $k\,(\alpha_c\,(\mu_d-eCo)\,q+e\mu_n Co\,b)-f\,(\alpha_c\,(\mu_a-hCo)\,q+\mu_n hCo\,b)>0$
5) $CDAN_6$ is stable if $-k\,(\alpha_c\,(\mu_d-eCo)\,p+e\mu_n Co\,a)+f\,(\alpha_c\,(\mu_a-hCo)\,p+\mu_n Co\,ha)>0$

It is concluded from condition for existence of $CDAN_5$, we have $C_5>C_4$ and $A_5<A_4$. This is as expected that the role of Napoleon wrasse as top predator gives positive effect in improving the ultimate stage of coral and reducing the *Drupella sp*.

TABLE II: Existance and stability conditions of the System $C-D-A-N$

Critical Point	Existence condition	Stability condition
$CDAN_1=\{A=0,C=0,D=0,N=0\}$	-	Unstable
$CDAN_2=\{A=0,C=Co,D=0,N=0\}$	-	Unstable
$CDAN_3=\left\{A=0,C=\frac{\mu_d}{e},D=\frac{\alpha_c\left(Co\,e-\mu_d\right)}{aCo\,e},N=0\right\}$	-	Unstable
$CDAN_4=\left\{A=\frac{\alpha_c(Co\,h-\mu_a)}{hbCo},C=\frac{\mu_a}{h},D=0,N=0\right\}$	-	Unstable
$CDAN_5=\left\{A=\frac{\mu_n}{p},C=C_5,D=0,N=N_5\right\}$	$q>\frac{\mu_n hbCo}{\alpha_c(Co\,h-\mu_a)}$	
$CDAN_6=\left\{A=0,C=C_6,D=\frac{\mu_n}{p},N=N_6\right\}$	$p>\frac{\mu_n eaCo}{\alpha_c\left(Co\,e-\mu_d\right)}$	

Note that, in the case of uniform predation $(a=b,p=q)$, then either $CDAN_5$ or $CDAN_6$ is stable.

5. Dynamical model $C - D - A - N - G$

We consider now the full system (1). Due to complexity, we restrict for the case of uniform predation ($a = b, p = q$). Nine equilibria are obtained with a coexistence equilibrium $CDANG = (C^*, D^*, A^*, N^*, G^*)$, with

$$\begin{aligned} C^* &= C_5 \\ A^* &= \frac{\mu_g}{r} \\ D^* &= \frac{r\mu_n - p\mu_g}{rp} \\ N^* &= N_6 \\ G^* &= \frac{(hf - ke)(\alpha_c p - \mu_n b)\, Co + p\alpha_c (k\mu_d - \mu_a f)}{\alpha_c pfm}. \end{aligned} \tag{9}$$

This special case of coexistence (9) shows that with the appearance of Giant triton, *Drupella sp.* may exist in the competition, where the equilibria Coral and *Acanthaster planci* remain the same as in the case of the absence of Giant triton.

6. Numerical simulation

With limited measurement data in the field, it is not possible to visualize the interaction dynamics for the real condition in the field. Instead the simulations are performed to show some sensitivity analysis. All data for simulations are given in Table III.

TABLE III: Parameter Values.

Parameter	Value	Reference
C_0	1	Assumption
$a = b$	1×10^{-4}	Stability and existance conditions
α_c	$\frac{0.1}{365}$	Frasser (2000)
μ_d	$\frac{1}{7\times365}$	Ismail (2000)
μ_a	$\frac{1}{8\times365}$	Frasser (2000)
μ_n	$\frac{1}{30\times365}$	
μ_g	$\frac{1}{15\times365}$	
e	5×10^{-4}	Stability and existance conditions
h	7×10^{-4}	Stability and existance conditions
$q = p$	1×10^{-3}	Stability and existance conditions
k	2×10^{-3}	Stability and existance conditions
f	1×10^{-2}	Stability and existance conditions
m	1×10^{-3}	Stability and existance conditions
r	1×10^{-2}	Stability and existance conditions

Figures 2 shows that the higher ρAD, i.e. when *Acanthaster planci* more effective in predating the coral than *Drupella sp*, eventually the reduction of coral due to consumtion from both predators is higher. When Napoleon wrasse is involved in the system, as shown in Figure 3, the coral reefs can preserve the existence. The involvement of top predator causes *Acanthaster planci* and *Drupella sp.* to decrease significantly, and even the population of *Drupella sp.* eventually disappears from the ecosystem. This indicates that the role on Napoleon wrasse is essential in maintaining the ecosystem with an acceptable level of coral.

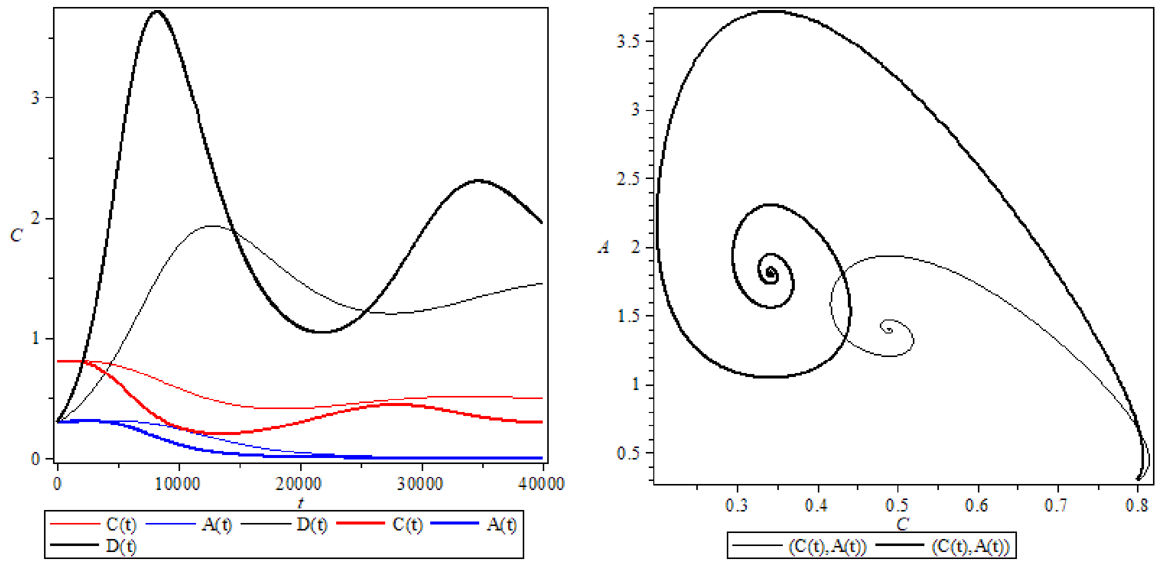

Fig. 2: Simulation of the C-D-A system for ρ_{AD}=1.6 and 2.29-bold (left), and the corresponding orbits (right)

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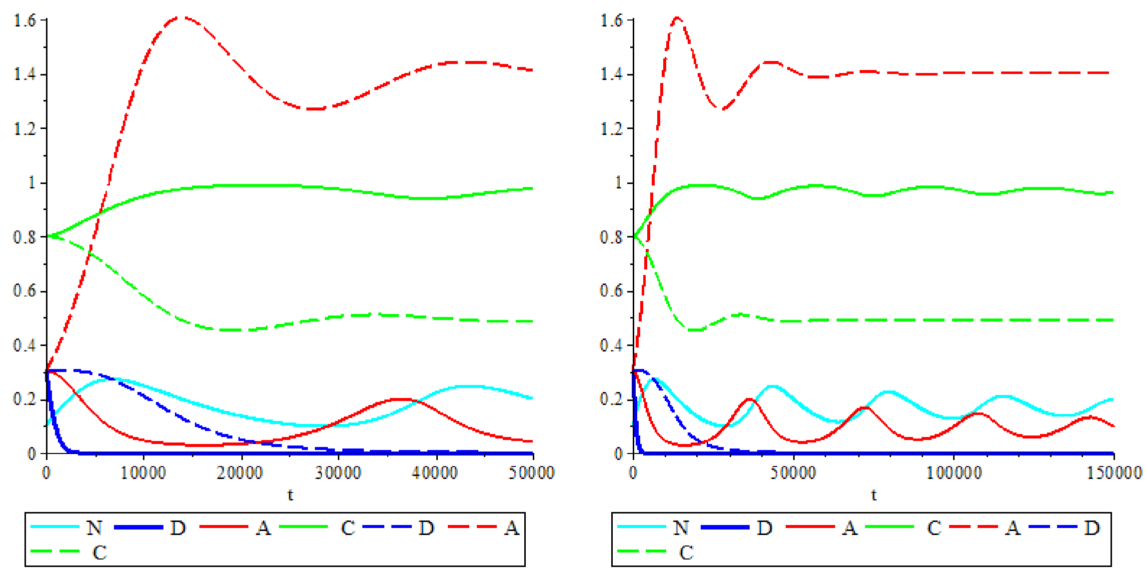

Fig. 3: Simulation of the C-D-A-N system, CDA_4 (dash) and $CDNA_5$ (solid)

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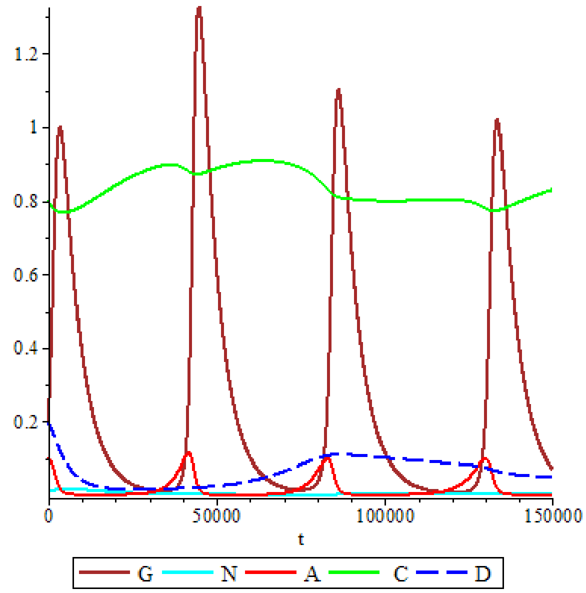

Fig. 4: Simulation of the C-D-A-N-G system

The *Drupella sp.* and *Acanthaster planci* outbreaks, as a mesopredator, could often lead to declining of coral reef populations, sometimes destabilizing communities and driving local extinctions [13]. This simulation is consistent with a study in [14] that drawing the predator depletion corresponding to the prey increasing in the community composition of reef fishes ecosystem.

7. Conclusion

A dynamical interaction model between Coral reef, *Drupella sp.*, *Acanthaster planci*, Napoleon wrasse and Giant triton is constructed as a structured predator-prey system. Stability analysis of critical points of the System 1 is difficult to perform thoroughly. Under selected cases, co-existences and stability analysis are shown. In the absence of top predators, the system Coral-*Drupella sp.*-*Acanthaster planci*, only the most effective predator, in this case *Acanthaster planci* will coexist with coral. The role of Napoleon wrasse is essential in controlling the dominant of *Acanthaster planci*, and the coexistence of Coral-*Acanthaster planci*-Napoleon wrasse gives better environment to reduce the level of *Acanthaster planci* and to improve the level of Coral. In the model, although Giant triton takes part in reducing the *Acanthaster planci*, with the dependence of growth rate on *Acanthaster planci*, the population of Giant triton may grow fast with the increase of *Acanthaster planci*. This results may give good direction in getting more comprehensive observation and measurements in the field.

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