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PAPER · OPEN ACCESS

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To cite this article: Silfiana *et al* 2018 *J. Phys.: Conf. Ser.* **983** 012122

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Modeling of nitrogen transformation in an integrated multi-trophic aquaculture (IMTA)

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Abstract. The dynamic model of nitrogen transformation in IMTA (Integrated Multi-Trophic Aquaculture) is purposed. IMTA is a polyculture with several biotas maintained in it to optimize waste recycling as a food source. The purpose of this paper is to predict nitrogen decrease and nitrogen transformation in IMTA consisting of ammonia (NH_3), Nitrite (NO_2) and Nitrate (NO_3). Nitrogen transformation of several processes, nitrification, assimilation, and volatilization. Numerical simulations are performed by providing initial parameters and values based on a review of previous research. The numerical results show that the rate of change in nitrogen concentration in IMTA decrease and reaches stable at different times.

1. Introduction

Mathematical modeling is proposed to represent and explain the physical systems or problems in the real world so that the understanding of the real world problem becomes clearer. In general, dynamic system is defined as a real problem that is modeled in the form of differential equations. One example of dynamic systems is a system of ammonia, nitrite, and nitrate concentration changes in the fish culture.

Aquaculture can have an impact on the water environment, especially organic enrichment [1]. In particular, excess feed beyond the requirements of cultured fish in holding pens may negatively affect the animals under domestication by increasing ammonia toxicity and water turbidity. Nitrate and ammonia are the two important forms of inorganic nitrogen in the biomass production in marine systems [2]. Ammonia is a waste in aquaculture waters is the result of bacterial decomposition of the remaining feed and excretion of fish. Furthermore, through the process of nitrification, ammonia will turn into nitrites and nitrates. Nitrite as a result of ammonia oxidation is also an inorganic nitrogen compound, which can endanger the life of fish when presents in high quantities [3]. One effort to conduct aquaculture activities by minimizing the impact of enrichment of organic fisheries is primarily by applying the cultivation technique of Integrated Multi-trophic Aquaculture (IMTA). IMTA is an

aquaculture practice using more than one species of biotas which have an ecologically mutual relationship as part of the food chain in the region at the same time. The application of IMTA allows farmers to get several aquaculture products in the same area without increasing the horizontal area of the farm [4]. IMTA aims to be an ecologically balanced aquaculture practice that co-cultures species from multiple trophic levels to optimize the recycling of farm waste as a food resource [5].

A mathematical model has been developed to estimate nitrate release from other pellets in benthic sediment [6]. However, the model proposed is still a simulation of physical and biogeochemical processes during the formation of sediments due to pellets, and no stability analysis has been done. Previous research has also been conducted using the number of species, diversity, and similarities of macrobenthic communities with the result that the use of areas for polyculture and industrial activities can cause an environmental disturbance, so coastal management needs to be applied on a regular, temporal or spatial basis [7]. The dynamic model in the management of fish against nitrogen accumulation has proven to be an effective tool in understanding the dynamics of nitrogen and providing informative data for the management of aquaculture [8].

The development of aquaculture techniques, particularly the use of a stratified double floating net cage for polyculture can increase productivity, and maintain a healthy water ecosystem for sustainable aquaculture [9]. The IMTA system combines multiple species from different trophic levels within the infrastructure of the aquaculture system. The construction of mathematical modeling of pomfret, tiger grouper's growth, and nutrition by researchers [10], whereas the modeling in the IMTA waters environment has not been studied. Therefore, this paper discussed the dynamic model of nitrogen transformation processes concentration consisting of ammonia, nitrite, and nitrate. This model can be used to predict nitrogen decrease as well as nitrogen transformation processes in IMTA.

2. Methods

Floating net cage is one of the aquaculture practices operated in coastal areas of Indonesia that has been growing rapidly over the last two decades [11]. Environmental changes, especially water quality and sediment, will respond to animal composition and abundance [12]. An effort to improve the quality of aquatic environments was done by applying the integrated multi-trophic aquaculture (IMTA) to increase production capacity. IMTA is a way of cultivating a species by utilizing another biota (biofilter) to reduce the resulting contaminant. Phytoplankton in IMTA provides an important role because it has chlorophyll to perform photosynthesis. Through photosynthesis process, phytoplankton can reduce the levels of ammonia, nitrite, and nitrate in IMTA. The interaction of phytoplankton in cultivation is related to its role in reducing the concentration of ammonia, nitrite, and nitrite, which can be written in a dynamic system.

The relationship between ammonia, nitrite, nitrate, and phytoplankton is given in Figure 1.
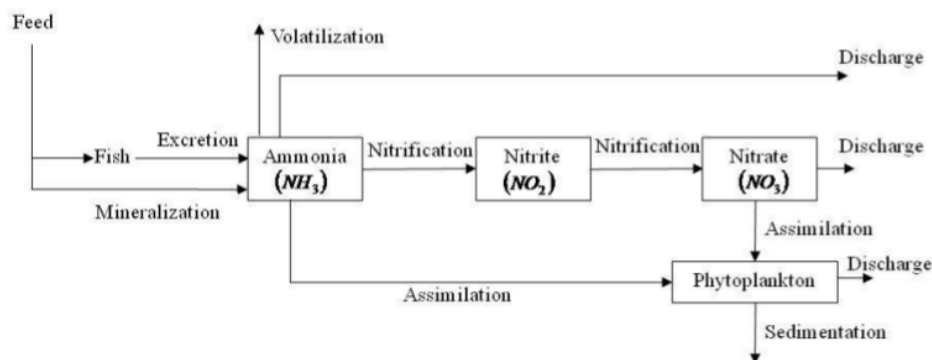

Figure 1. The relationship between ammonia, nitrite, nitrate, and phytoplankton

Nitrogen in the form of ammonia, nitrite, and nitrate is a key element in aquatic environments and cultivation. Feeding of nitrogen in the form of food is needed to increase the aquatic production of the cultivated animals and is considered an important fish management variable. Nitrogen input in the cultivation also increases the potential for pollution to the surrounding environment.

2.1. Development of Mathematical Models

Several previous studies have developed mathematical models related to the concentration of nitrogen with monoculture system. So, it is a necessary mathematical model that can describe the concentration of nutrients with the number of marine biotas. The concept of IMTA applied in this project is a semi-closed system. Therefore, the wave forming effect can be ignored.

Model of nitrogen transformation in IMTA follows the Lorenzen model [13]. This model illustrates the concentration of nitrogen, and phytoplankton in an open water aquaculture system consisting of three variables, namely ammonia, NOx, and phytoplankton. In previous research, Widowati et al [14] had broken down the NOx variable into two variable, which is nitrite and nitrate.

Ammonia can be transformed via some pathways: assimilated by phytoplankton, volatilized as gaseous ammonia, converted to nitrite/nitrate via nitrification process or discharged during water exchange. To construct the model, the following assumptions are taken:

1. Ammonia and nitrate as the main sources of nitrogen are key nutrients for phytoplankton growth.
2. The process of nitrogen transformation occurs on the water surface.
3. Reduction of phytoplankton due to sedimentation.
4. Ammonia, nitrite, and nitrate can be discharged during water exchange.

The parameter Λ shows the total ammonia input per unit time. The reduction of phytoplankton can be realized in the phytoplankton sedimentation rate parameter (μ).

The maximum absorption relationship of ammonia phytoplankton (α_1) and the growth rate of phytoplankton (β) can be written by equation (1):

$$PF = \alpha_1 \beta F \left(\frac{N_1}{N_1 + N_3} \right) \tag{1}$$

where PF is an absorption of nutrients by phytoplankton.

Taking into account the nitrate to chlorophyll ratio of phytoplankton (α_2) we get the equation

$$PF = \alpha_2 \beta F \left(\frac{N_3}{N_1 + N_3} \right) \tag{2}$$

Based on Figure 1, the model for absorption of nutrients as ammonia (N_1) by phytoplankton is given by the following equation:

$$\frac{dN_1}{dt} = \Lambda - (v + a + k_1)N_1 - \alpha_1 \beta F \left(\frac{N_1}{N_1 + N_3} \right) \tag{3}$$

where v denotes the volatilization rate of ammonia, a is water exchange rate, and k_1 and k_2 denote the nitrification rate.

Nitrite concentration denoted by N_2 can be written as the following equation:

$$\frac{dN_2}{dt} = k_1 N_1 - k_2 N_2 \tag{4}$$

Nitrate concentration denoted by N_3 based on nitrification and assimilation by phytoplankton can be written as follows:

$$\frac{dN_3}{dt} = k_2 N_2 - aN_3 - \alpha_2 \beta F \left(\frac{N_3}{N_1 + N_3} \right) \tag{5}$$

Equation (6) is used to predict the concentration of phytoplankton:

$$\frac{dF}{dt} = \alpha_1 \beta N_1 + \alpha_2 \beta N_3 - (a + \mu)F \tag{6}$$

where μ represents the sedimentation rate of phytoplankton.

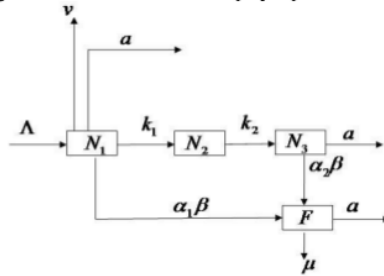The conceptual model of nitrogen transformation with phytoplankton can be shown in Figure 2.

Figure 2. Conceptual model of nitrogen transformation with phytoplankton

3. Results and discussions

To find out the model (3),(4),(5),(6), we need the values of the model parameters which can be seen in Table 1 and based on data variables $N_1(0) = 0.071, N_2(0) = 0.0042, N_3(0) = 0.7130, F(0) = 0.00952$ from Riau Archipelago [15-16].

Table 1. Model Parameters

Parameters	Definition	Value	Dimension	Source
Λ	total N waste input	4.0	mg g^{-1} day^{-1}	[6]
v	volatilization rate	0.05	day^{-1}	[6]
a	water exchange rate	0.05	day^{-1}	[6]
k_1	the rate constant for the oxidation of ammonia	0.00184	day^{-1}	[12]
k_2	the rate constant for the oxidation of nitrate	1.6041	day^{-1}	[12]
α_1	phytoplankton maximum uptake of ammonia	0.55	day^{-1}	[4]
α_2	phytoplankton maximum uptake of nitrate	0.45	day^{-1}	[4]
β	phytoplankton growth rate	1.6	day^{-1}	[4]
μ	sedimentation rate of phytoplankton	0.8	day^{-1}	[6]

The solution of the nitrogen reduction systems (ammonia, nitrite, nitrate) and phytoplankton are given in Figure 3.a to 3.d.
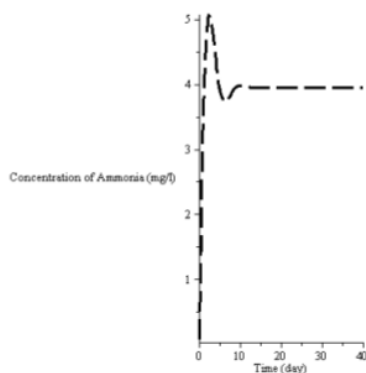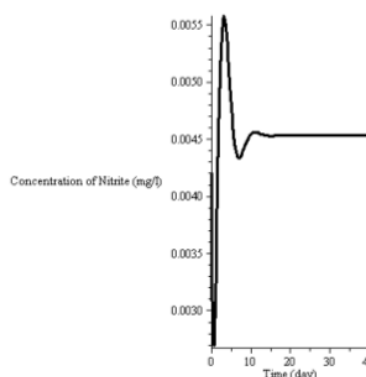
Figure 3.a. Behavior of Ammonia
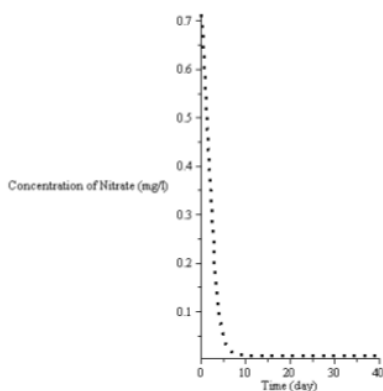

Figure 3.b. Behavior of Nitrite

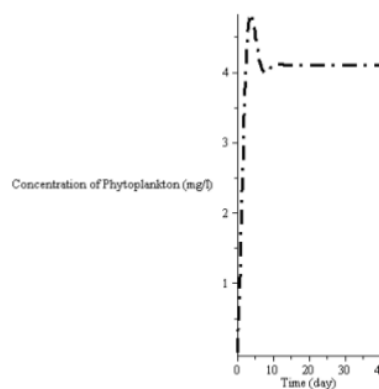**Figure 3.c.** Behavior of Nitrate

Figure 3.d. Behavior of Phytoplankton

Based on the numerical simulations obtained, it can be seen that the rate of change in the concentration of nitrogen compounds including ammonia, nitrite, and nitrate in waters integrating reduced IMTA cultivation. Figure 3.a shows that the concentration of ammonia was initially increased and then dropped until it reached stable around the 10th day. From Figure 3.b, we observe here that the concentration of nitrite reaches to its maximum level at five days. Further, decrease and reaches an asymptotic value at 15 days which is 0.0055 mg/ l.

Figure 3.c shows that the concentration of nitrate decreases until it reaches steady states at a faster time is the 10th day. While the concentration of phytoplankton based on Figure 3.d, almost the same as ammonia, initially experienced an increase and then decreased until it reached stable at around the 10th day. Based on these results, the productivity of phytoplankton is influenced by the availability of nutrients (an inorganic form of nitrogen).

4. Conclusion
The dynamic behaviour of nitrogen concentrations in IMTA associated with phytoplankton has been studied. From the simulation results obtained that the concentration of ammonia, nitrite, and nitrate will be stable and go to a fixed point. Changes in ammonia and nitrate concentrations are influenced by phytoplankton.

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