Modeling the Potential of Periphyton based Fish Production in Pond Culture System

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Abstract

To evaluate the potential of fish production from Periphyton-based aquaculture system, a simple dynamic simulation model was constructed. The model consists of three state variables, periphyton biomass (PB; g), fish biomass (FB; g) and nutrient stock and six rate variables (nutrient inflow, nutrient uptake by periphyton, periphyton grazing by fish, periphyton degradation rate, fish harvesting and mortality rates). In the model, it was assumed that PB is minimum before fish were stocked and that fish grazing would cease whenever PB would be lower than that minimum biomass. This model was implemented in Stella 8 and run with a time-step of 0.05 day. Parameter values were derived from the literature. We assumed a maximum periphyton density of 100 g dm m^{-2}. PB_{max} was derived from this value by multiplying with the substrate area. Simulated PB increased from 10 g m^{-2} initially to 100 g m^{-2} after 24 days. Before day 30, periphyton productivity was greater than the consumption of the periphyton by fish. After day 105, fish grazing exceeded periphyton productivity as a result of increased FB and PB decreased steadily until reaching a value of about 75 g m^{-2} on day 182. The scenario in the model also showed that the optimum application rate of nutrient is at 15 g m^{-2} urea per two weeks. In the model a 1:1 ratio of substrate area to pond size tends to produce larger FB which was 1000 kg ha^{-1}. Therefore, periphyton can increase the productivity and efficiency of aquaculture systems; however more research is needed for optimization.

Key words: Fish farming, Nutrients, Modeling, Periphyton

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Introduction

As the world population increases, the demand for high protein foods will gradually rise. This demand is not likely to be covered by livestock production, and with the total fish catch from wild fishing grounds have however, seem to have reached their natural limits (FAO, 2006). Aquaculture production thus seems to be the answer to the increased demand for fish. Hence, aquaculture has been and still growing faster than other animal food production sectors (FAO, 2006).

Nevertheless, feed in aquaculture production are quite expensive and represent about 60% of the total operation costs (EL-Sayed, 1998). Often, formulated fish feed has been used as the main source of protein and energy in fish feeds (EL-Sayed and Gaber, 2004). However, low availability, competition and continuously fluctuating prices of fish feed are affecting aquaculture production and consequently the profitability of the sector. As a result, a lot of effort has been focused on feed alternatives to commercially formulated diets both from plant and animal sources (Beveridge, 2000; Waidbacher ***et al,*** 2006; Liti ***et al,*** 2005). In order to enhance aquaculture production and improve food security, as well as, to reduce the level of poverty in developing countries, a search for cheap and naturally available feed is required.

Periphyton can, therefore, serve as an alternative source of food for fish. This is because it is stable and more efficient in utilizing nutrients in pond water. More fish may be able to utilize periphyton than phytoplankton and commercially formulated diets (Van Dam ***et al,*** 2002). Periphyton is a matrix of algae, heterotrophic microbes and animals attached to submerged substrate in almost all aquatic ecosystems. There are many substrates ranging from natural to artificial one (e.g. coral reefs, stones, tree branches or shrub species, higher aquatic plants, bamboos, plastics).

The composition, biomass and productivity of periphyton, like in all other natural systems vary with season, year, location and grazing pressure. In culture systems, a range of 19-113 grams free dry matter of periphyton is reported by Azim ***et al.*** (2002) on bamboo substrate. Fish production has been shown to be greater with additional substrates compared to the controls without substrates (Azim ***et al.,*** 2002). This model was, therefore, aimed at investigating periphyton-based fish production, the combined effects of periphyton productivity, nutrient uptake, the effects of substrate area, nutrient application rate and harvesting on fish production and grazing through a simple simulation model of Periphyton-based fish production for management of fish culture in ponds.

Table 1 System boundaries assumed in the model

Parameters	System boundary
Time boundary	One year scenario
Pond size	75 m^2 (10 x 7.5 x 1)
Stocking density	1 fish per m^2
Max. Periphyton density	100g dm/m^2
Substrate area	1:1 ratio with pond size
Substrate material	Bamboo
Nutrient	Nitrogen in urea

Materials and methods

To estimate the fish production from periphyton-based pond, a simple dynamic simulation model (STELLA 8) was constructed. The model consists of three state variables (periphyton biomass, fish biomass and nutrient stock) and six rate variables (nutrient inflow, nutrient uptake by periphyton, periphyton grazing by fish, periphyton degradation rate, fish harvesting and mortality rates).

In the model the following assumptions were made: Periphyton was grazed only by fish and grazing was efficient; environmental conditions (e.g. light, temperature) remained constant; the pond water flow rate was constant.

Conceptual model

Periphyton is a potential feed in aquaculture pond systems. The biomass of periphyton is determined by the biomass of grazers and availability of nutrients (Fig. 1). As a result of these limiting nutrients and grazing, the biomass of periphyton does not grow indefinitely.

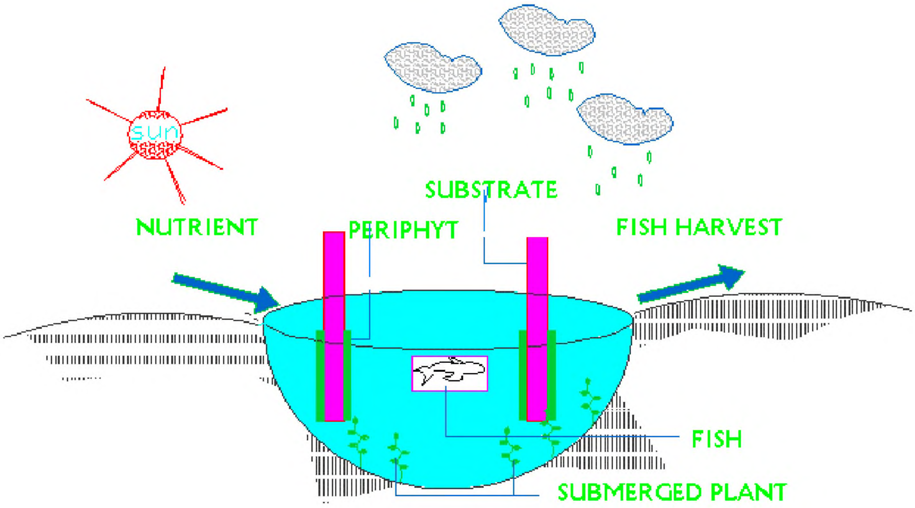


Fig. 1 Conceptual model of Periphyton-based fish production in a pond

Mathematical model

$$\frac{dPB}{dt} = \left(U,_{max} \cdot \frac{N}{N + K_p} \cdot PB\right) - \left(Max,_{gra} \cdot \frac{P}{P + K_g} \cdot F\right) - \left(\frac{KPB^2}{PB,_{max}}\right)$$

Where: dPB/dt is rate of change in periphyton biomass with time; K is the relative growth rate of periphyton per day. PB is periphyton biomass; PB_{max} is the maximum periphyton biomass; U_{max} is the maximal N uptake rate per periphyton.

N is the nitrogen concentration in pond water; Kp is the half saturation constant of periphyton for nitrogen; Max $_{gra}$ is the maximal P grazing rate per fish; Kg is the half saturation constant of fish for periphyton; F is fish biomass.

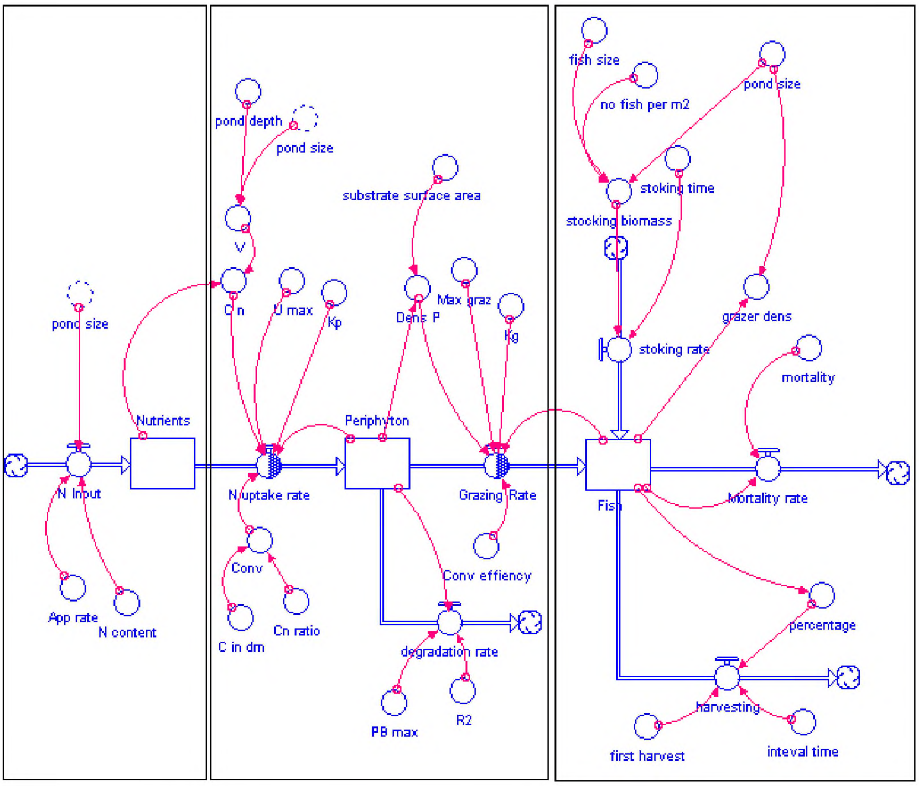


Fig. 2 Stella diagram of the periphyton growth model output in ponds

Stella software-dynamic simulation modeling package was used to estimate the potential of fish production from periphyton-based pond culture. Then a simple dynamic simulation model was constructed and parameter values were used from previous related works (Table 2).

Table 2 Parameters value used to develop the model

Parameters	Values	Units
Application rate	1,00	g urea per m^2 per day
N content	0,45	g N per g Urea
Pond size	75,00	m^2
Initial Nutrients	0,00	g dm
Pond depth	1,00	m
Volume	75,00	m^3
U max	1,30	g N per g Periphyton per day
Kp	1,00	g N per m^3
C in dm	0,38	
Cn ratio	10,00	
Initial Periphyton	1,00	g Periphyton
P max	7500,00	g Periphyton
R2	0,12	day
Substrate area	75,00	m^2
Max grazing	0,03	g N per g Fish per day
Kg	20,00	g P per m^2
Conversion efficiency	2,00	
Initial fish	0,00	g Fish
Fish size	10,00	g Fish
No fish per m2	1,00	individual
Stocking time	30,00	day
R1	0,00	Per day
K1	750,00	g Fish

Source (Azim, 2001; Azim *et al.,* 2002; Senzia *et al.,* 2002; Van Dam *et al.,* 2002)

Scenario evaluation and discussion

Periphyton biomass and productivity

Fish culture in pond is traditionally based on the production of phytoplankton. However, phytoplankton blooms and collapse are not always stable and this may lead to massive algal mortality and subsequent depletion of oxygen in the pond. Moreover, many herbivorous fish species are unable to efficiently utilize phytoplankton. Therefore, Periphyton can serve as alternative source of food for fish (Van Dam ***et al.,*** 2002). Growth of Periphyton layer on a substrate usually starts with the accumulation of dissolved organic matter and subsequent pull of bacteria, followed by algae and invertebrates. This growth can take weeks, but in some studies this was even observed within days. In the model it was observed that Periphyton growth reaches a maximum density of 99 g m^{-} around 24 days (Fig. 3a). This result compares well with the literature value of 100 g m^{-} (Van Dam ***et al.,*** 2002). The input of nitrogen in the pond results in an increase of Periphyton until a maximum density is reached. The nutrient concentration levels down when Periphyton density increases. With the stocking of the fish after 30 days and subsequent growth, Periphyton density decreases due to grazing by the fish and eventually an equilibrium point is reached (Fig. 3b). Fish grazing reduces the Periphyton biomass, keeping it from reaching its maximum biomass and maintaining its productivity. In the model, it was observed that the Periphyton had a minimum biomass before fish were stocked and that fish grazing would stop whenever the biomass of Periphyton would be lower than that of the minimum biomass.

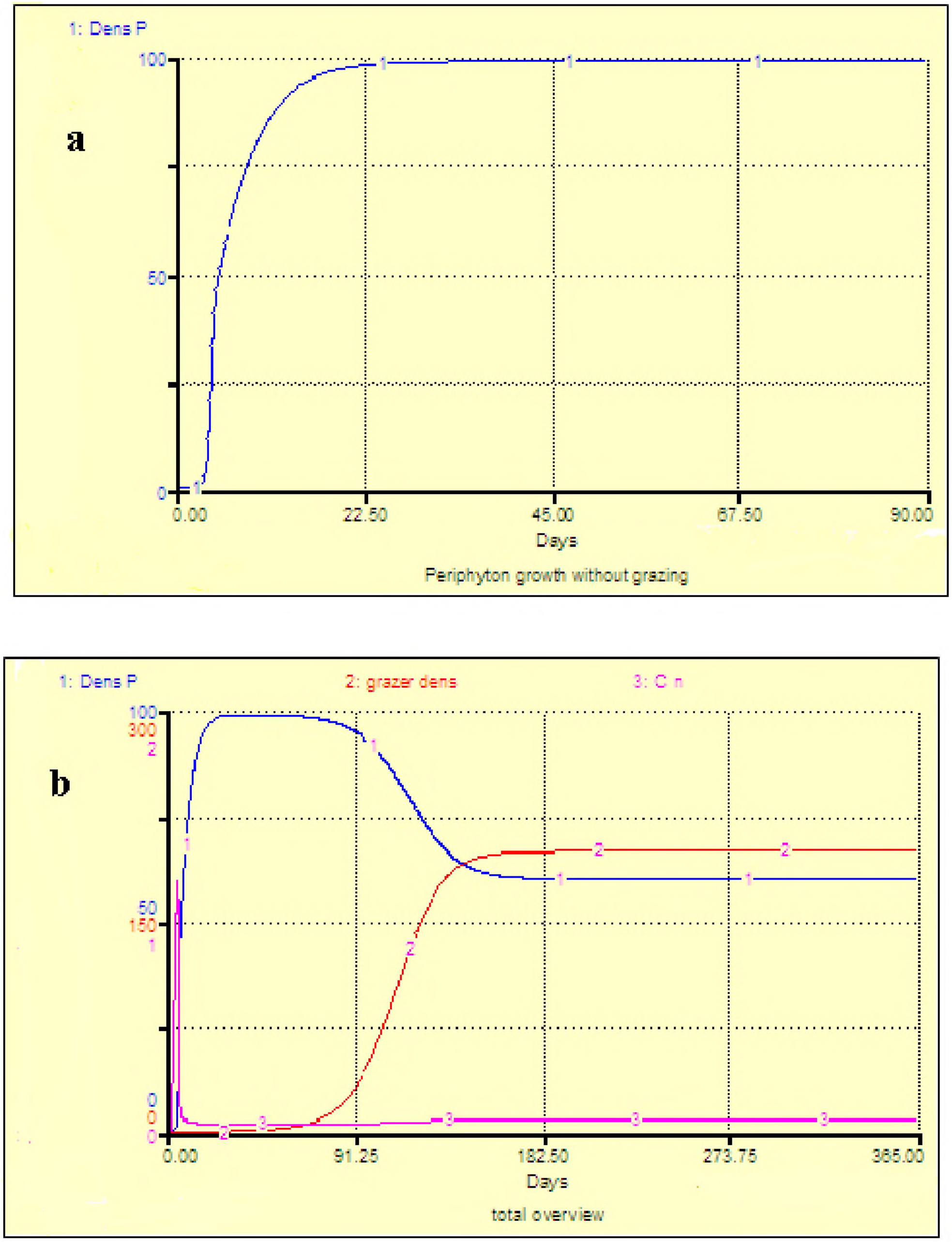


Fig. 3 Periphyton growth without grazing (a) and Simulation of the variation between nitrogen concentration, periphyton density and fish density (b).

Substrate area

Substrate area and type have significant effect on periphyton growth. A number of reports on comparison of periphyton growing on natural and artificial substrates pointed out significant difference in species composition and periphyton biomass (Van Dam ***et al.,*** 2002). The difference is mainly attributed to substrate to pond area ratio and the type of substrate used to grow the periphyton. In the model the optimal substrate area was 1 m per 1 m of pond area because at this ratio maximum periphyton (99 g m') and fish densities (1000kg ha^{-1}) were attained (Fig. 4). Substrate area above the optimal value results in lower fish density. This may be because of the fact that the model did not account the change in the substrate area in the PBmax (maximum periphyton density* SA) and also food is less available for fish (food is more dispersed). On the other hand less substrate area will lead to a higher fish density because of a high periphyton density but this is not realistic because periphyton density cannot go beyond 100 g m^{-} (Van Dam ***et al.,*** 2002).

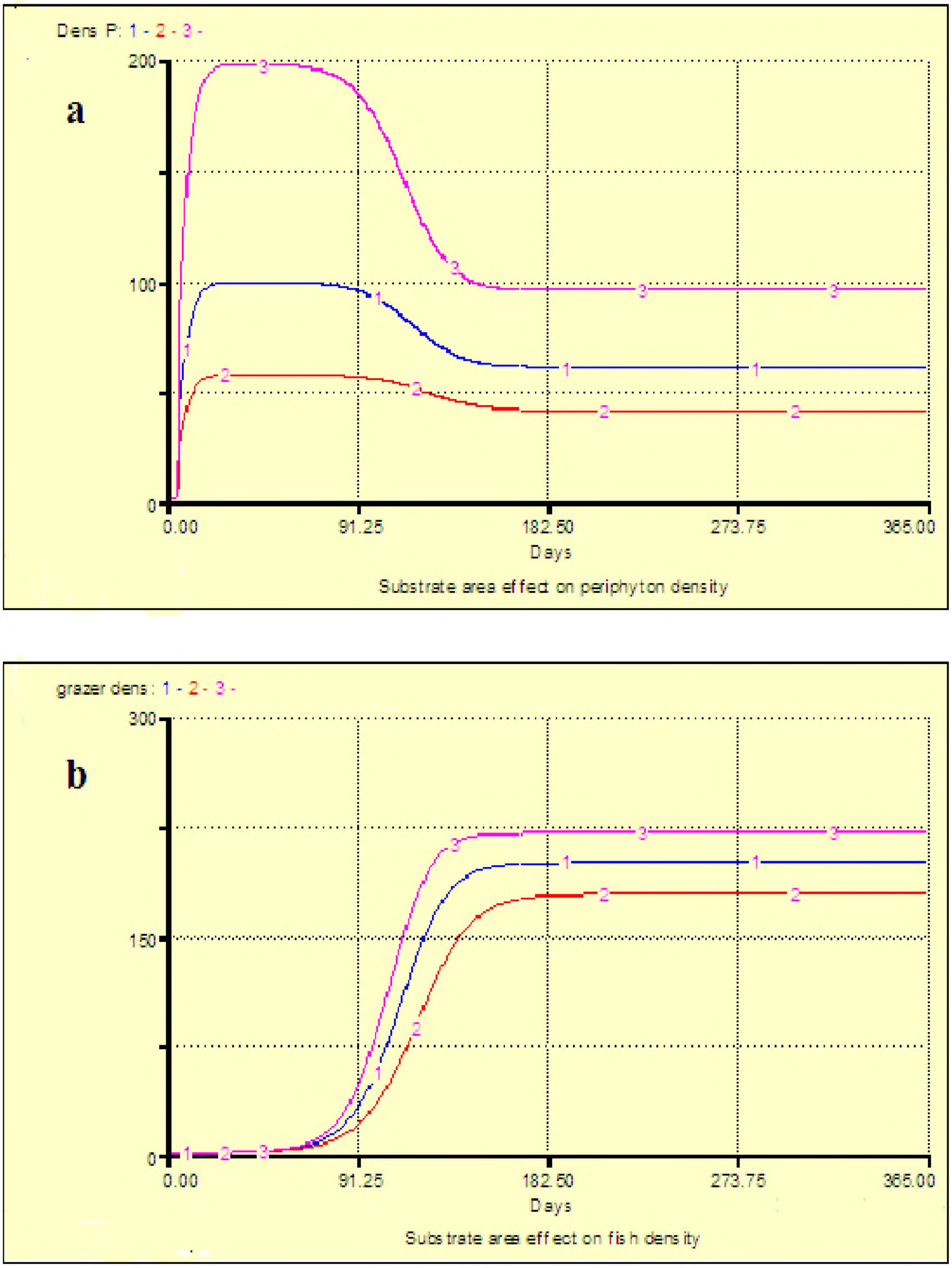
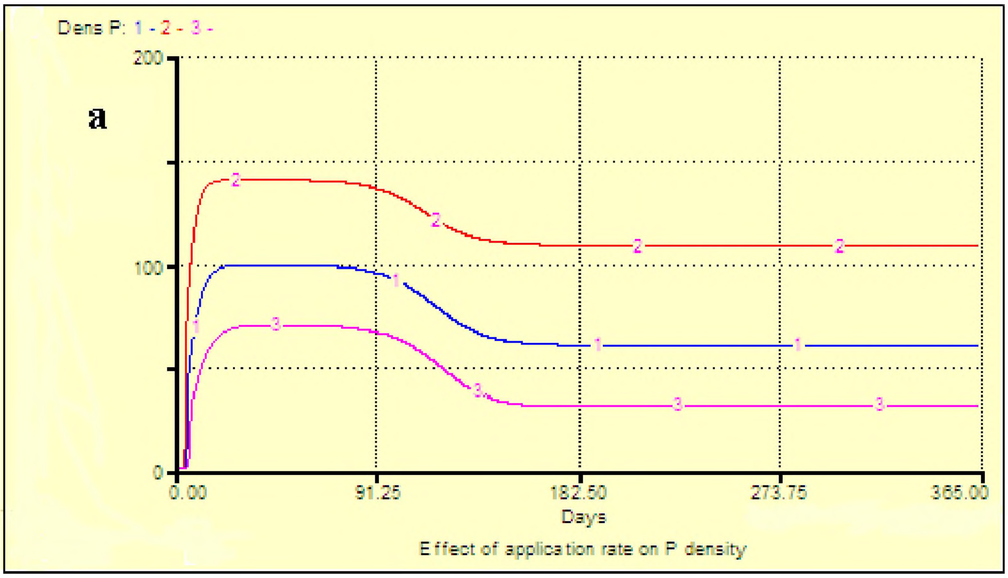


Fig. 4 Substrate area effect (SA) on Periphyton density (a) ***(****Pond to SA ratio (m*^{2}*): (1)1:1, (2)1:2, (3) 1:0.5****)*** and Substrate area effect on fish densities (b).

Nutrient application rate

Periphyton growth rate and composition are influenced by the spatial and temporal dynamics of environmental factors. Nutrients, underwater light, climate, temperature and other biological components are some of the major physical and chemical parameters that bring about the dynamics of periphyton and phytoplankton (Jones, 1977; Reynolds, 1984). However, inorganic nutrients have strong effect on periphyton biomass which is a common phenomenon in many water enrichment studies. It stimulates periphyton productivity; however, it does not mean that lower nutrient concentrations always result in lower biomass and productivity. The simulation result from the model showed an optimal density of fish and periphyton at 15 g m' application rate of urea every 2 weeks (Fig. 5a-b). This value compares well to the literature, 14 g m' (Azim, 2001). Higher application rates lead to unrealistic growth of periphyton (beyond 100 g m") and lower application rates have lower yields. In the model, periphyton was growing beyond its maximum density, because the model did not include a limit to periphyton growth. Apparently the optimum fish harvest is 1000 kg ha"^{1} (Fig. 5c). In this way there will be a sustainable harvest where the periphyton density will not be depleted and hence fish production is maintained at its maximal growth.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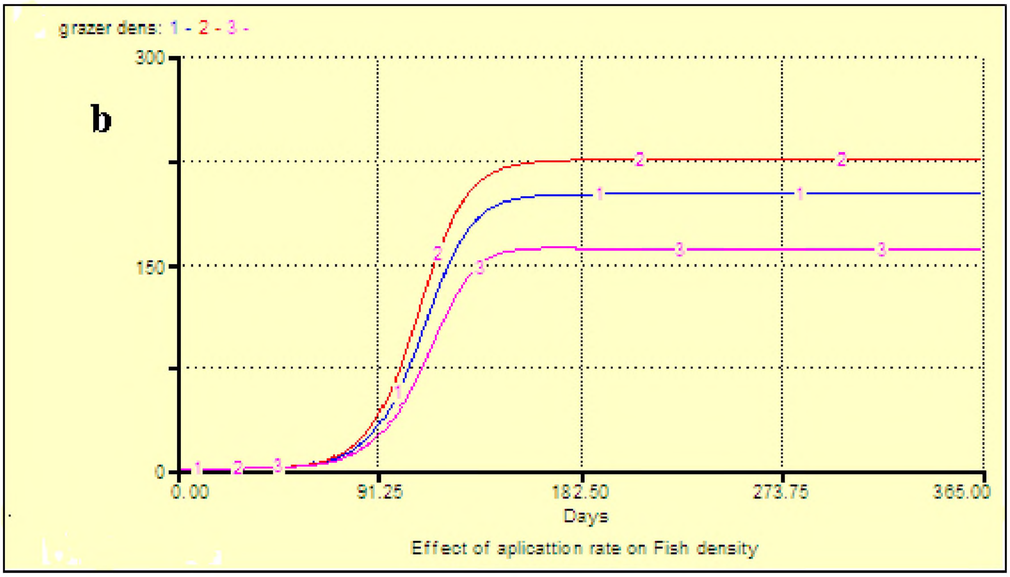
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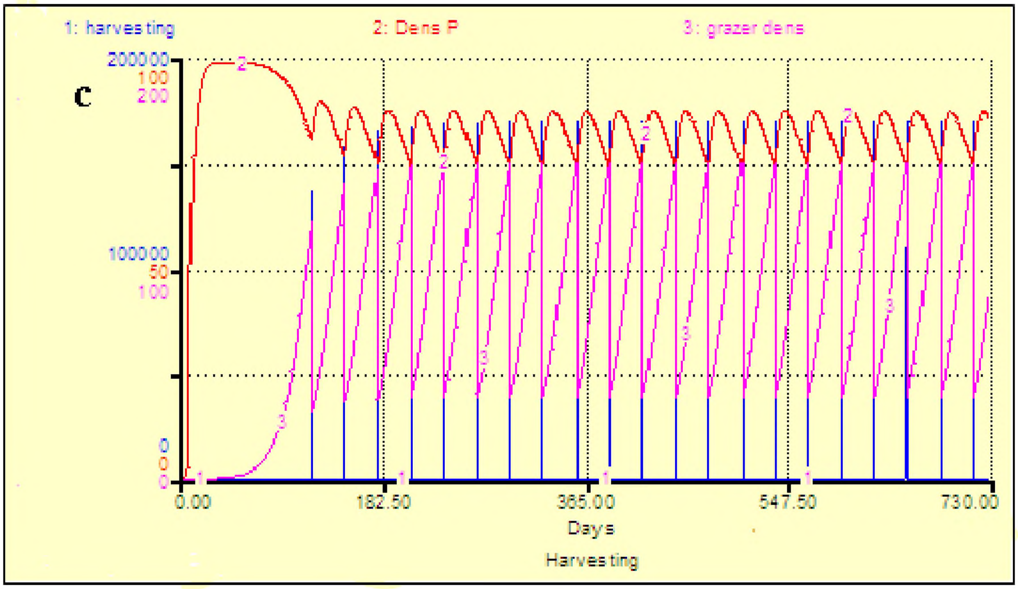

Fig. 5 Effect of nutrient application rate on Periphyton density (a), Effect of nutrient application rate on fish densities (b) and Effect of fish harvesting on Periphyton density(c).

Validation and Sensitivity analysis

Internal consistency validation was carried out for the model. Accordingly, the model equations, the dimensions and units were consistent and correct. The model results are acceptable and realistic. Nutrient application rate and maximum grazing were found to be the most sensitive parameters influencing periphyton biomass, a 10 % change in these parameters results in 5 % change in periphyton biomass. The scenario in the model showed that the optimum application rate of nutrient is at 15 g urea per two weeks per m . In the model a 1:1 ratio of substrate area to pond size tends to produce larger fish biomass. Optimum sustainable harvesting is at 1000 kg ha^{-1}.

Conclusions and Recommendations

The model showed that periphyton can increase the productivity and efficiency of aquaculture systems. It does indeed seem to be stable than phytoplankton as a result of which the risk of community collapse and water quality deterioration is much smaller. Apparently the model does not account for the many interactions that would occur in Periphyton-based fish production. However, for improved management and manipulation of periphyton layers in fishponds, more knowledge and research about the basic processes in the periphyton assemblage is needed. Furthermore, the model has to be externally validated based on a real ground truth data.

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