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BIOMASS PRODUCTION AND NITROGEN DYNAMICS IN AN INTEGRATED AQUACULTURE/AGRICULTURE SYSTEM

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A combined aquaculture/agriculture system that brings together the three major components of a Controlled Ecological Life Support System (CELSS) - biomass production, biomass processing, and waste recycling, was developed to evaluate ecological processes and hardware requirements necessary to assess feasibility of and define design criteria for integration into the KSC Breadboard Project. The system consists of a 1 m^2 plant growth area, a 500 liter fish culture tank, and computerized monitoring and control hardware. Nutrients in the hydroponic solution were derived from fish metabolites and fish food leachate. In five months of continuous operation, 27.0 kg of lettuce (*Lactuca sativa* cv. Waldmann's Green) tops, 39.9 kg of roots and biofilm, and 6.6 kg of fish (tilapia, *Oreochromis aureus*), wet weights, were produced with 12.7 kg of fish food input. Based on dry weights, a biomass conversion index of 0.52 was achieved. A nitrogen budget was derived to determine partitioning of nitrogen within various compartments of the system. Accumulating nitrogen in the hydroponic solution indicated a need to enlarge the plant growth area, potentially increasing biomass production and improving the biomass conversion index. A computer simulation model is being developed to project production potentials and define data needs for more effective management of the system.

INTRODUCTION

One objective of CELSS research is the development of systems that recycle inedible waste into high quality edible biomass. The concept of recycling mass for the purpose of optimizing secondary production of edible food stuffs and minimizing waste has been the subject of several investigations utilizing combined aquaculture/hydroponic systems. Zweig(1), Serfling and Mendola(2), Pierce(3) and Bender(4) reported on "soft technology" systems suitable for home use, that produced high quality vegetables and fish protein while effectively utilizing space, nutrients and water. These systems generally consisted of a fish culture tank, a vegetable growing area and in some cases a biological filtration system for the microbial conversion of ammonia (NH_4) to nitrites (NO_2) and nitrates (NO_3). The systems were designed primarily for use in greenhouse environments in temperate climates. The use of hydroponic systems to prevent the accumulation of nitrate nitrogen and orthophosphorus in recirculated water in fish culture systems was evaluated by Lewis et al(5) who found acceptable water quality could be maintained by allowing plant growth to serve as a sink for undesirable levels of nutrients. McMurtry et al(6) found that the integration of fish culture, biological filtration, and hydroponic vegetable culture was an economical way to commercially produce bush bean, cucumber, tomato, and tilapia.

Development of secondary production combined aquaculture/ hydroponic systems in CELSS would optimize energy and materials utilization, provide resiliency and stability, and maximize the use of available space. Fish were selected as candidates for secondary producers in CELSS for the following reasons. They occupy a low position in the food chain, are a good source of high quality animal protein, and can be cultured in nutrient solution tanks already in use. Tilapia (Oreochromis aureus) were chosen because they are tolerant to extremes in water quality, resistant to disease, and fast growing, reaching a harvestable size in 6 months (7). This species of tilapia is also omnivorous, easy to handle, and populations are readily manageable in controlled environments (7).

As part of ongoing CELSS research, system scale-up and integration, we designed a combined aquaculture/agriculture system that incorporated the three major components of CELSS - biomass production, biomass processing, and waste processing. In this system biomass production included fish, higher plants, and algae. Biomass processing based on the incorporation of inedible plant biomass, fish processing waste, biomass conversion by-products, and table scraps into a fish diet is being evaluated. This system will potentially allow for waste management by the use of condensate and gray water, control of oxygen and carbon dioxide balance, and the recycling of nutrient solution.

One goal of this research was to quantify the biomass production potential of fish, lettuce, and biofilm (organic matter and attached microbial community). Other objectives were to describe the partitioning of nitrogen between system compartments, evaluate the response of biological components, and develop a computer simulation model of nutrient dynamics and biomass production. A computer monitoring and control system was designed and system hardware and software were also tested and evaluated during this study.

MATERIALS AND METHODS

The integrated system consisted of a 500 liter conical bottom fish culture tank and a 1 m^2 plant growing area. Thirty various sized (27-144g) tilapia were stocked at the beginning of the study. Twenty additional fish were stocked after 28 days to give a total fish biomass of 4.9 kg at that time. Plans are to operate the system at the CELSS Breadboard Project scale of one person. This stocking density should provide three filets per week. A commercial fish chow was fed at the rate of 2% body weight per day divided into three feedings. Every 2 weeks fish were weighed to monitor growth and adjust feeding rate.

Lettuce (*Lactuca sativa*, cv. Waldmann's Green) was planted on six polyvinyl chloride (PVC) pipes which were 2 inches in diameter and 1.5 m long. Plants were spaced 15 cm apart, 9-10 plants per pipe. The lettuce was planted and harvested approximately every 7 days.

Water from the fish culture tank was pumped through the PVC pipe where it served as the nutrient solution for the plants. Lettuce roots were in direct contact with the solution where they functioned as a biofilter substrate for bacterial colonization, allowing for nitrification of ammonia. Free ammonia (NH_3) is toxic to fish (8), therefore the biofilter component is important in this system. Solution flow through each PVC pipe ranged between 0.5 and 1.5 L/min. Water samples were collected weekly from the tank for chemical analyses. Parameters monitored included pH, conductivity, macronutrients, micronutrients, ammonia, total kjeldahl nitrogen, total suspended solids and total organic carbon. Light was provided by three high pressure sodium (HPS) lamps which produced an average photosynthetic photon flux (PPF) of 245 umol s^{-1} m^{-2}, with an 18 hours on and 6 hours off photoperiod. Air temperature over the plant canopy was ambient, averaging 29.2 $\pm$ 2.1 ^{o}C. Relative humidity was controlled at 65% and tank water temperature was 24.1 $\pm$ 1.4 ^{o}C. Solution pH was controlled at a maximum of 6.2 units and averaged 5.8 $\pm$ 0.5 units. Dissolved oxygen was measured daily and remained at 6.6 $\pm$ 0.6 ppm.

At the start of the study the nutrient solution was one quarter strength Hoagland's and was replenished twice during the next two weeks until the fish food leachate and fish metabolites provided enough plant nutrients. Total minerals added during the first two weeks of the study, exclusive of fish feed were as follows:

Element	mg
N	7.35
P	1.09
K	8.19
Ca	7.00
Mg	1.68
S	2.24
Fe	4.34
Mn	0.031
Zn	0.0031
Cu	0.0012
B	0.033
Mo	0.00062

After the second replenishment, the addition of nutrients to the solution was totally through fish feed wastes and fish metabolites.

A simulation model was developed to examine biomass production and nutrient dynamics. The model diagram was drawn using energy circuit language symbols (9). Programming was conducted with Lotus 1-2-3 (10).

RESULTS AND DISCUSSION

After 5 months of continuous operation the system produced 27.0 kg of lettuce tops, 39.9 kg of roots and biofilm, and 6.6 kg of fish on a wet weight basis. During this 5 month period 12.7 kg of feed was added. This resulted in a biomass conversion index, based on dry weights, of 0.52. The partitioning of nitrogen added to the system over the 5 month period is described in Figure 1. Fish tissue incorporated 35.2% of the nitrogen while lettuce tops contained 7.9%, and the roots and biofilm accounted for 12.5%. The nutrient solution retained 35.5% of the nitrogen. Loss of nitrogen gas through denitrification and from ammonia volatilization, in addition to unquantified biofilm inside system plumbing was believed to account for the remaining 8.9%.

Figure 2 shows the behavior of NO_3, NO_2, and NH_4 in the solution over time. A dramatic increase in NH_4 and NO_3 occurred after the addition of 20 fish on day 28. The relationship between ammonium ion (NH_4^+) and free ammonia is pH dependent (11). In order to keep the NH_3 below toxic levels we maintained the solution pH below 7.0. Ammonium and NO_3 increased at equal rates until about day 84, after which time NH_4 levels fell and NO_3 continued to rise, suggesting the development of an adequate community of nitrifying bacteria. Nitrite, the end product of the first stage of nitrification, stabilized after a small peak around day 28 which coincided with the addition of fish.

Preliminary work on a biomass production model of the system is shown in Figure 3 which depicts the producer module with its lettuce storage, the consumer module with fish storage, and the biofilm with attached microbes. Results of the simulation run depicted in Figure 4a show production in the system over a 100 day period. Lettuce tops and roots were harvested every 7 days along with the attached biofilm. Fish biomass was shown to increase steadily at a rate that was similar to the observed growth. Since the plant area and production rate were held constant and fish were growing and being fed more, the biofilm compartment increases rapidly around day 85. Based on observaton, fish wastes and waste feed which compose the substrate for the biological film began to accumulate not only on the roots but also as suspended solids in the tank. Figure 4b shows a simulation where the lettuce biomass on the system was doubled which allowed it to run 110 days before the biofilm began its rapid increase. The increase in the biofilm component was slowed by the additional harvest of lettuce roots and biofilm. The response of fish biomass to biweekly harvest can be seen in this simulation. Fish production with harvest remains fairly constant.

CONCLUSIONS AND RECOMMENDATIONS

After 5 months of system operation it was concluded that nitrogen accumulated in the solution, and therefore the plant growth area needs to be increased. This concept was also supported in the simulation model runs. A larger plant growth area should allow for more production and better biofiltration. Fish growth rates and productivity should also increase with improved water quality resulting from better filtration, and by operating the system at a higher temperature. In addition, system improvements such as oxygen injection and foam fractionation to remove organics, biological oxygen demand (BOD), and solids could also improve production. The simulation model will continue to be developed and tested and used for system management. The revised model will incorporate not only biomass but also energy, and nutrient dynamics.

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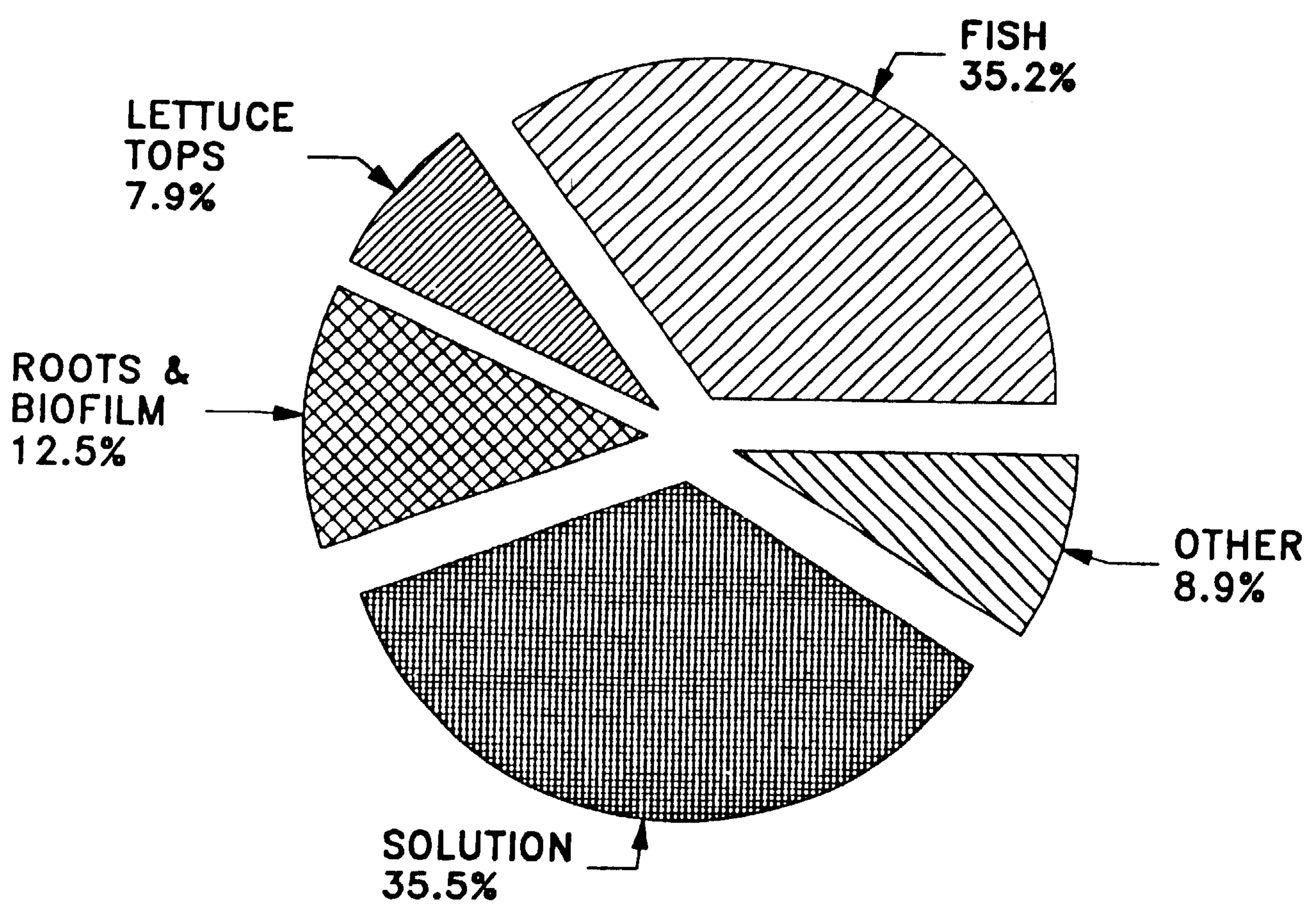


Figure 1. Partitioning of nitrogen added to the system during 5 months of operation.

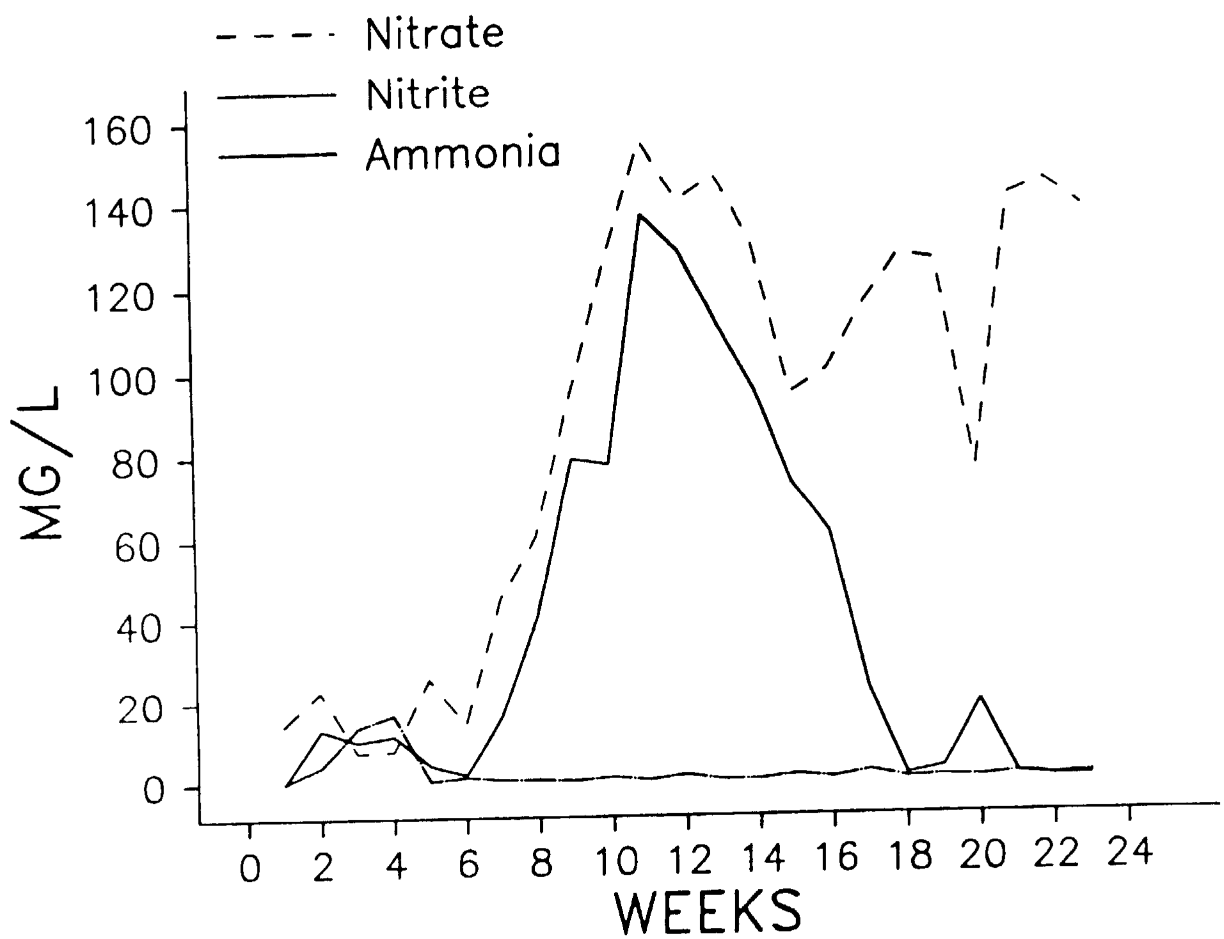


Figure 2. Nitrate (NO_3), nitrite (NO_2), and ammonia (NH_4) dynamics in solution over time.

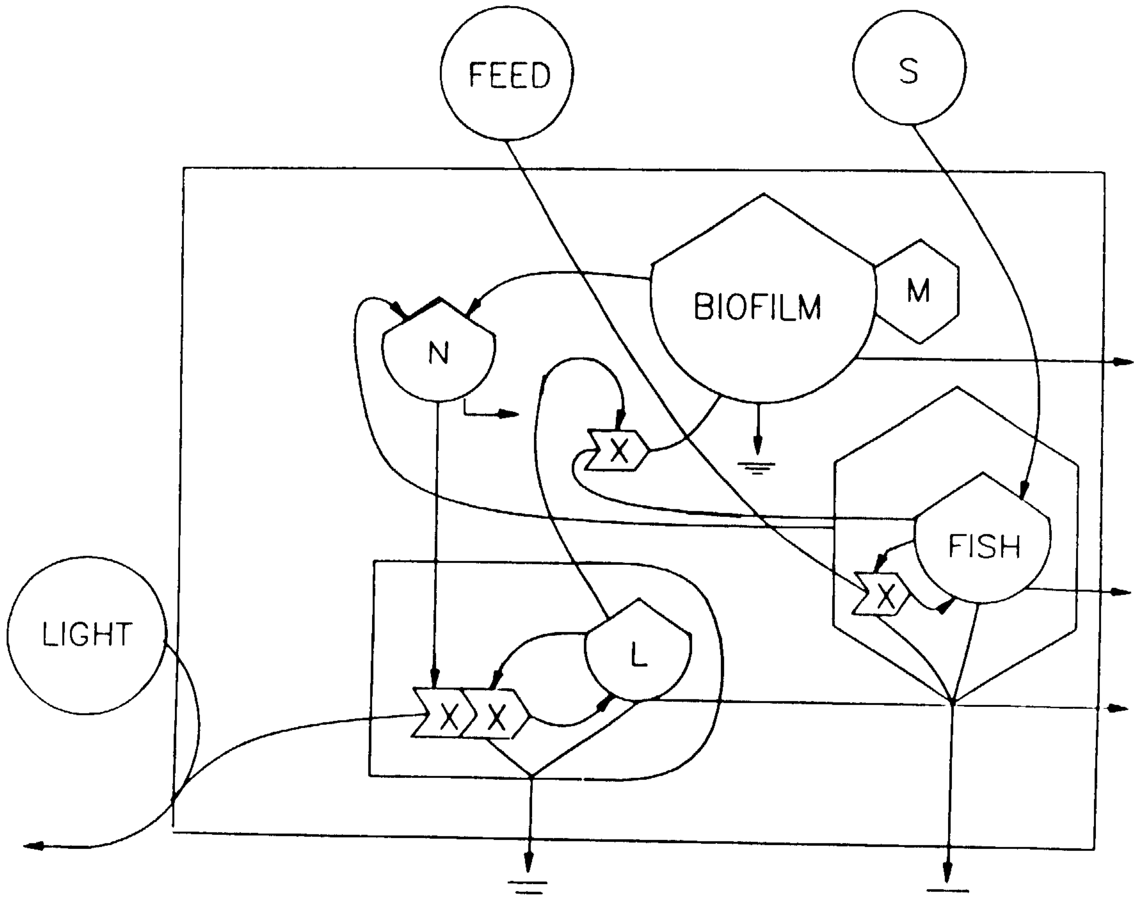
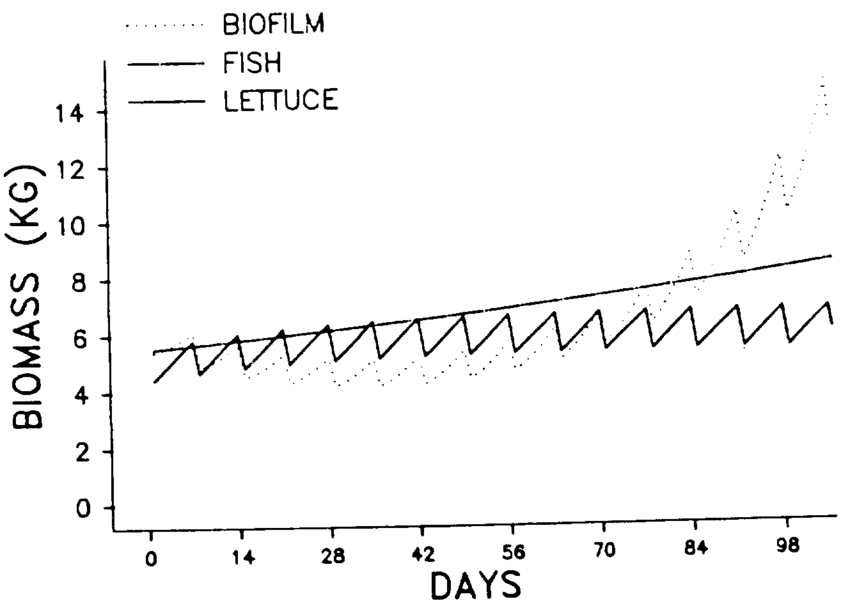


Figure 3. Diagram of the integrated aquaculture/agriculture system biomass production simulation model. (N=nitrogen, L=lettuce, M=microbes, and S=stock, for fish replacement)

a



b

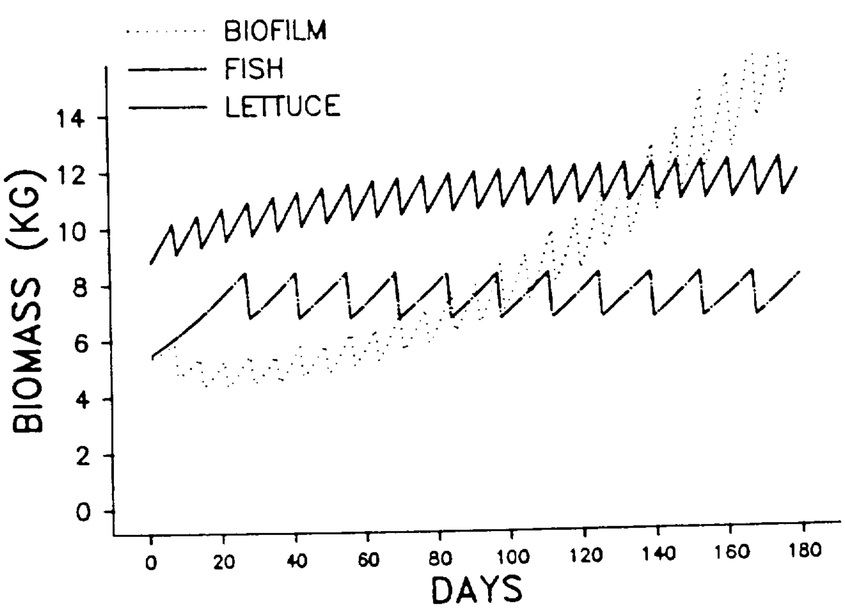


Figure 4. a. Initial model simulation run showing biofilm, fish, and lettuce production over 100 days. b. Model simulation run with increased lettuce biomass, and biweekly fish harvest over 180 days.