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An Ecological Engineering Project for Combined Undergraduate and Graduate Classes*

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As interest develops in ecological engineering, there is a need for the development of projects suitable for teaching. Ecological engineers must learn how to deal with ecological relationships on both a quantitative and qualitative level. This paper describes a project that takes advantage of the synergy possible between graduate students and undergraduate students. The project focuses on the design and implementation of both physical and virtual models of a sealed aquatic microcosm.

INTRODUCTION

IN GENERAL, engineering programs are based on a specific science. For example, biomedical engineering can be seen as based on biomedical sciences, chemical engineering as based on chemistry, and materials engineering as based on materials science. Similarly, ecological engineering is an emerging discipline founded on the principles of ecology. Ecological engineering has been defined as the 'design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both [1]'. Typical ecological engineering curricula include science courses, such as plant or wildlife ecology and water quality, engineering mathematics supplemented with statistics, and engineering courses, such as biological systems controls and groundwater hydrology.

As part of this development, programs that include ecological engineering must meet the same criteria as other engineering programs. However, as with many emerging disciplines, there are not many examples of student projects. The project described below is one example. It is intended as an integrative project, applying knowledge from multiple technical disciplines, and supports the following ABET Program Outcomes and Assessment criteria [2]:

- an ability to apply knowledge of mathematics, science, and engineering;
- an ability to design and conduct experiments, as well as to analyze and interpret data; and
- an ability to design a system, component, or process to meet desired needs.

In addition to meeting these programmatic requirements, the project had several specific educational goals unique to ecological engineering. First, the project was intended to teach students the concepts of self-organization and homeostasis. Ecological systems have a tendency to organize in such a way that, in the short term, homeostasis appears, but, in the long term, change is inevitable. Thus, deviation from the initial design is not failure but rather to be expected [1].

Second, the project was intended to teach students a systems approach to understanding and designing ecological systems. Even in intentionally simplified mesocosms such as this one, ecological systems contain a large number of variables with complex interactions. Therefore, there are multiple possible outcomes to any ecological process. The outcomes include a range of stable ecosystems, periodic processes such as limit cycles, and death. If a specific outcome is desired, the initial conditions must be chosen near the desired point of homeostasis, since the mesocosm is more likely to organize towards a similar state [3].

Finally, the project was intended to teach students the properties and limits of biosystems models. While the project uses a model to predict the outcome of student designs, biological systems continue to self-organize to surprising and successful outcomes.

The mesocosm under consideration consisted of a sealed (air-tight, water-tight and food-tight) 10-gallon aquarium. The primary contents of the aquarium were several crayfish, *Procambarus* (*Scapulicambarus*) *clarkii*, dechlorinated water, air, gravel, and submerged aquatic plants. While the graduate students created a virtual aquatic ecosystem of the mesocosm, the undergraduates created a physical model of the same system.

The undergraduates' project was to approximate an ecosystem by balancing primary production,

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waste production and degradation, food consumption, and respiration. The undergraduate students were challenged to construct self-sustaining closed aquatic ecosystems through an iterative design process and frequent monitoring of water quality parameters. It was possible to maintain the equilibrium in the ecosystem for a duration of up to one month.

Concurrent with the undergraduates' efforts, the graduate students in the class constructed and calibrated a computer simulation model of the physical ecosystem. It is expected that this computer model, after successive iterations of the graduate/undergraduate partnership in future classes, will become an increasingly accurate representation of the ecosystem. The graduate students' computer model was based on a series of sub-models describing crayfish growth and oxygen consumption, biodegradation of submerged plants, nitrogenous component degradation by bacteria, and the chemical reactions that take place in photosynthesis and respiration. The parameters required for these sub-models were extracted from the physical ecosystems and from the literature. Both literature and experimentation were used to determine the relationships between the sub-models. The graduate students' mathematical model was used by all of the students as an aid to understanding the components and interactions that make up a complex system and by the undergraduate students to plan their ecosystems.

Because of their complexity, both the mathematical and physical models were developed through an iterative sequence of (1) conceptualization, (2) implementation, and (3) calibration. The main goal of the iterative sequence was to ensure that the model would accurately reflect both the self-organizational behavior and outcome of the physical system.

PROJECT DEVELOPMENT

The project of creating an ecosystem was divided into two components: physical modeling and computer modeling. This paper emphasizes the system development underlying the project, since the undergraduate project emphasized system design and measurement and the graduate course emphasized system analysis and modeling.

Model conceptualization

Within the first few days of the semester, the students (both graduates and undergraduates) were asked to apply their knowledge of chemistry and biology to identify the necessary components of a stable ecosystem. The relationships between the components were then added and the result was used to develop a conceptual model. The conceptual model, described below, provided a framework on which the students implemented their models.

Whether physical or virtual, the models of ecological systems focused on the flux of matter and energy through consumer pathways composed of the individual organisms in the ecosystem. It was important to both recognize and quantify the trophic relationships of the organisms within the ecosystem, since these are the primary variables that can be controlled in the design. The major trophic categories in an ecosystem include the primary producers, consumers, and decomposers. The organisms within these subgroups form the basis for the rates of material and energy transfer within the ecosystem. Therefore, the modeling effort was directed along defining the relationships between the three primary trophic levels in the ecosystem.

Superimposed onto these relationships were three physico-chemical pathways. On a global scale, these pathways are effectively closed and form the major material cycles involved in sustaining the global biosphere. In constructing the physical and virtual mesocosms, additional attention was paid to establishing these cycles—particularly the oxygen, carbon, and nitrogen cycles—at adequate rates to sustain the various biota in the ecosystem. Fig. 1 shows the relationships between the three trophic categories (on the perimeter of the schematic) and the three physico-chemical cycles (in the center of the schematic).

Primary producers. The primary producers generate the organic material that supports all biological activity in freshwater ecosystems. Phytoplankton (algae) and higher aquatic plants generate this material through photosynthesis. Primary production is the process by which inorganic carbon (in the form of carbon dioxide) is fixed into organic forms in biomass, producing the oxygen used in respiration. The energy and matter in this biomass is transferred to other trophic levels within the ecosystem by routes initiated by herbivores that graze on live plant biomass or by detritivores that consume waste of organic matter after the senescence and death of the producer [4]. Only anacharis was considered for the initial modeling efforts, although the modular nature of both models will allow the incorporation of other producer species modules developed in future classes. The choice to use anacharis was based on its easy availability at pet stores, its applicability as a food source for crayfish, its easy experimental manipulation, and the significant literature documenting its life cycle.

Consumers. The consumers in the system play a pivotal role in the conceptualization process, since the overall goal of the project was to sustain the crayfish. The rates of feeding, respiration, and waste production (both respiratory and metabolic) for the crayfish were incorporated in the models. Additionally, crayfish growth can become an important factor in organism metabolic rates over the long term, thus rates of growth were considered for incorporation in the models. The

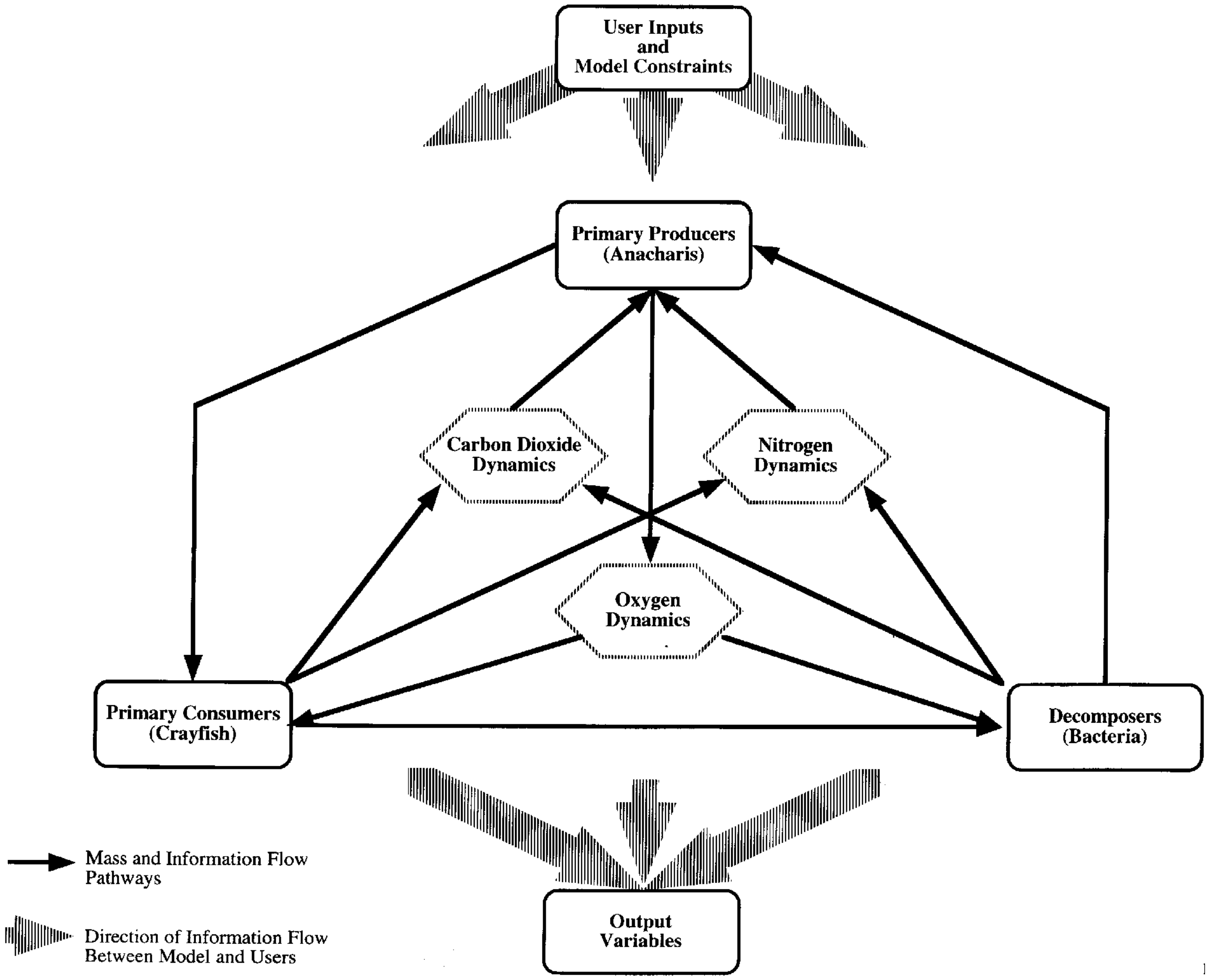

Fig. 1. A schematic of the model structure showing the six primary elements and the mass and information flows between them. The overall direction of information flow between the students and the models is shown.

choice of crayfish for this role was based on two features. Firstly, crayfish are invertebrates. This minimizes the regulations concerning their use. The use of vertebrate animals requires extensive oversight and approvals [5]. Secondly, it was a practical animal for use in student mesocosms. It was inexpensive, small, robust, and readily available [6].

Decomposers. Organisms in the sealed ecosystem generate waste as organic and nitrogen compounds, particularly ammonia (NH_{4^+}) [7]. Microorganisms oxidize the organic wastes as part of their metabolism, consuming oxygen and producing carbon dioxide in the process. Balancing the ecosystem models relied on the quantification of the bacterial component of ecosystem production. Particular attention was focused on the cycle of nitrogen within the ecosystem, following the processes of nitrification and denitrification. The oxidation of many nitrogenous compounds (particularly ammonia in nitrification) can consume large quantities of oxygen. It was recognized that NH_{4^+}-nitrogen was a potential source of oxygen depletion in water [8]. In addition, microbial nutrient cycling may act as a material sink for many biomass constituents [4]. This was of particular importance in modeling the closed ecosystem, since there are no geological material sinks or transport processes that can replace lost material.

Model implementation

The virtual and the physical mesocosms were implemented so that their processes complemented each other. For instance, the parameters were selected to dovetail the data collected by the undergraduate groups into the graduate students' model. This relationship turned out to be beneficial to both groups of students. The undergraduate students developed an understanding of data gathering, not just to evaluate the health of their systems but also for model development. The graduate students obtained experience in designing experiments for numerical simulation and in leading project groups. The graduate students also developed an understanding of the limitations of experimental data gathered by others.

Project team organization

Six research teams were formed, with undergraduates making up five of the teams and graduate students making up the remaining team. The goals and responsibilities of the two types of teams were as follows:

Undergraduate students. Each group had to construct an aquatic ecosystem with given aquarium materials and three crayfish (*Procambarus clarkii*), with the ultimate goal of keeping the crayfish alive in a sealed ecosystem for a month. One person from each group was assigned the task of checking on the aquarium each day and measuring specific water quality parameters throughout the duration of the project. Choosing what were the 'important' water quality parameters was a class decision that was updated as the students' understanding of the system grew. Ecosystems were designed by first dividing the sealed tanks into aquatic and terrestrial portions, and then by selecting among various plants and invertebrate species in appropriate proportions to balance the various biochemical cycles to maintain crayfish vitality. Candidate plant species included the following submerged aquatics: anacharis (genus *Elodea*), java moss (genus *Vesicularia*), java fern (genus *Microsorium*), floating water hyacinth (genus *Eichhornia*), and terrestrial philodendron (genus *Philodendron*). However, due to cost considerations, anacharis was chosen as the primary aquatic plant species. Experimental measurements were available from the physical models. The bacterial, plant, and crayfish biomasses were measured initially and as a function of time. The water quality parameters that were experimentally determined included dissolved oxygen, dissolved carbon dioxide, ammonia concentration, nitrite concentration, and nitrate concentration, since these parameters could influence the health and vitality of the biological constituents. The additional parameters observed in the models included temperature, pH, and alkalinity. These data sets were used to calibrate and validate the graduate students' model.

Graduate students. The graduate group met weekly with the goal of developing a virtual ecosystem to mimic the undergraduate tanks. In doing so, the graduate students worked with the undergraduates to obtain the data they required. To approach the modeling process, the group conceptually divided the ecosystem into primary ecological components. In order to simplify the initial modeling effort, certain components were omitted from consideration. Thus, the model from the beginning of the project included the principal biological components in the ecosystems such as crayfish, anacharis, heterotrophic bacteria, as well as the dynamics of the major biochemical elements, such as carbon, oxygen, and nitrogen cycling. Initial conditions for the model were determined through close association with the data collection efforts of the undergraduate groups. Most model parameters, such as rate constants for various chemical and biochemical reactions, were obtained from the literature [9–11]. Certain parameters, such as specific growth rate of the plants or crayfish respiration rate, were not readily available in the literature. Therefore, simple experiments were designed and performed by the graduate students to discover these data.

Model structure

The models in this project, whether physical or virtual, were treated as having two sections. The first section included the three primary trophic elements. The second section contained the three primary geochemical cycles within the models. In essence, the students were able to control the initial conditions of both sections, but did not have control of the system thereafter.

State variables. In general, models contain state variables acted upon by input and output flows. The rates at which the state variables changed were described as first-order differential equations. The solution to the model was obtained by simultaneously solving these coupled differential equations. A variety of tools were available to solve these equations. The graphical programming language STELLA was chosen for the graduate students' project, since it emphasized an understanding of system structure rather than numerical methods [12]. In STELLA, the state variables are referred to as *Stocks*, with *Flows* entering and leaving the stocks. The rates of the flows are modified by *Converters.* The converters contain information on flow rate coefficients, equations, etc. [13]. Information, such as rates of material flow or material generation, was in turn input into the converters. All of the required inputs for this model were entered using a graphical user interface. The program itself generated a matrix of first order differential equations for the time rate of change of each state variable, which it then solved by using numerical integration algorithms.

The state variables that were selected for the trophic portion of the STELLA model ecosystem included the anacharis, crayfish, and bacterial biomasses. The state variables for the cycle portion of the model were nitrogen (partitioned into elemental nitrogen, ammonia, nitrite, and nitrate), oxygen, and carbon dioxide.

Linkages between the state variables. Each of the trophic levels and cycles was programmed as an independent sector. The sectors were, in turn, linked by the various flows (determined by their ecological and biochemical relationships). For example, biomass of the crayfish altered its growth rate, its food and oxygen consumption, and its ammonia production. Specific formula and functional descriptions were all integrated into the model programming.

Similarly, anacharis' biomass was tracked as a state variable with both plant growth and its consumption by crayfish treated as flows. It was assumed that the chemical makeup of the anacharis biomass followed the molar ratios of 106:46:16 for carbon, oxygen, and nitrogen found in phytoplankton [14, 15]. These ratios were used to calculate the molar uptake of these constituents from the water as the anacharis grew. The growth of the anacharis was modeled as a first-order process linked to the rate of ammonia production from the crayfish waste.

An alternate set of paths linked the crayfishes' waste, through the bacteria, to the nitrogen cycle. Within the cycle, the partitioning between ammonia, nitrite, nitrate, and elemental nitrogen was computed treating each partition as a state variable with Michaelis-Menten reaction kinetics controlling the flow rates between the partitions [11]. To determine relative rates of nitrification and denitrification, calculations were performed based on the bacterial biomass, determined empirically from the five physical crayfish mesocosms. Variations on the steady-state bacterial biomass were linked to the surface area of the gravel substrate.

The gaseous chemicals tracked in the ecosystem model were carbon dioxide, nitrogen, and oxygen. Initial conditions for each of the gases were calculated via the application of physical chemistry laws. The partitioning of the gases between the aquatic and atmospheric portions of the closed ecosystem was determined using the initial conditions, the mass in the appropriate state variable, and Henry's law constants [16].

Model assumptions and specified operating conditions. The model solutions were simplified in two ways. Firstly, the operating conditions for the mesocosms were specified. These simplifications included:

- A constant water level in the tank.
- A constant light level throughout the 24 hours of the day.
- A constant temperature of 22°C.
- The air pressure was atmospheric when the mesocosms were sealed.
- Calcium carbonate (present in the gravel) was present in excess and was, therefore, not limiting to crayfish growth.
- The pH remained constant due to the excess of calcium carbonate present in the system.
- The second set of simplifications was made within the computer model. These assumptions significantly simplified the model, without significantly altering the behavior of the model.
- Cannibalistic behavior between crayfish did not

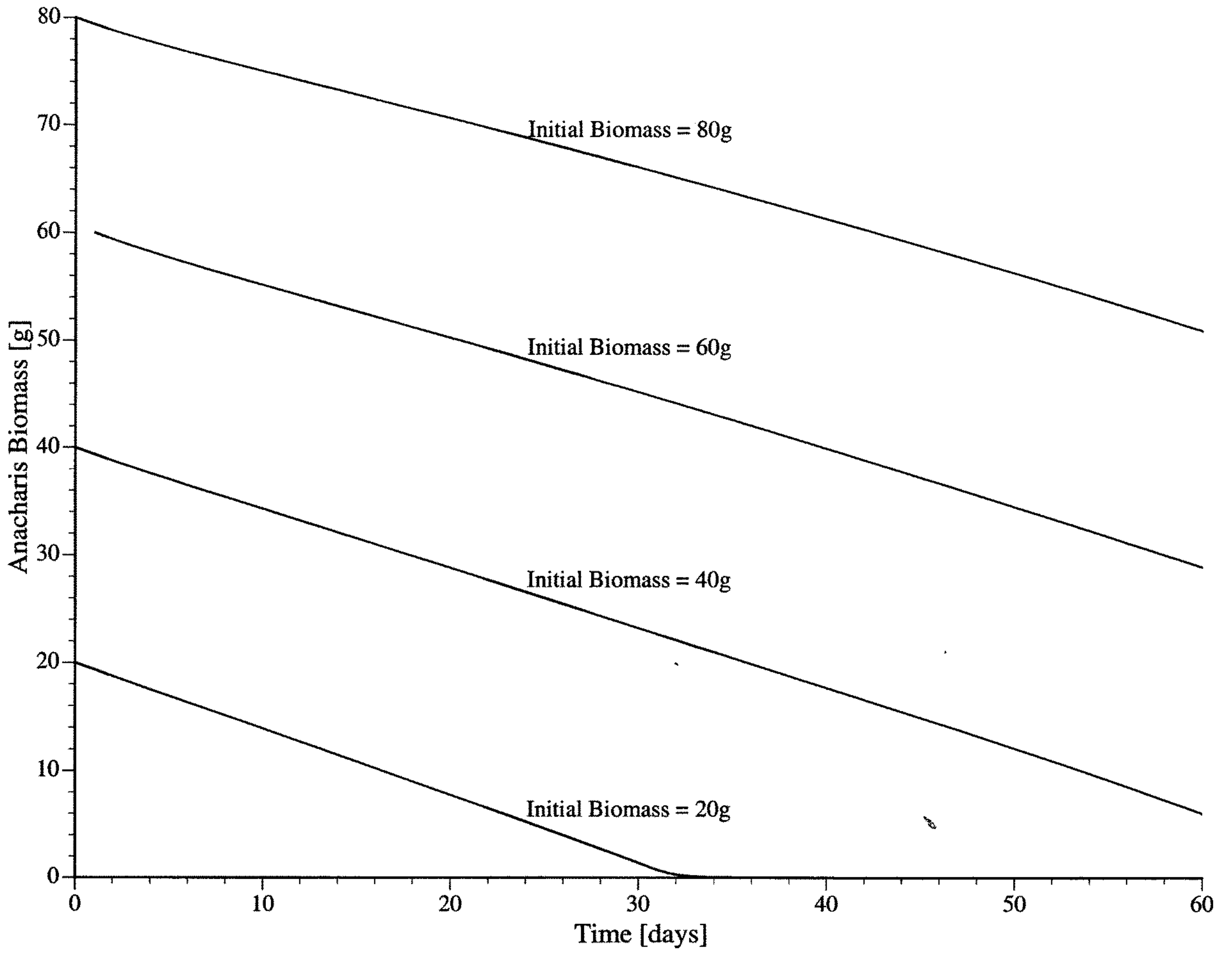

Fig. 2. The mass of anacharis (in g) over 60 days, integrating growth and consumption. Note that, for 20 g of initial biomass, the anacharis was completely consumed by around day 31.

occur unless the supply of anacharis was depleted.

- The gaseous ammonia released to the air above the water surface was neglected.
- The crayfish consumed food at a constant rate per unit crayfish biomass as long as food was available.
- The crayfish grew logistically to a maximum size.
- The growth of algae was not considered in the model.
- Only nitrifying and denitrifying bacteria were considered in bacterial biomass calculations.
- The gravel substrate had a spherical shape and was uniformly covered by bacterial biofilm.
- The biofilm mimicked ocean sediments regarding bacteria content and behavior.
- Bacteria and anacharis had a biomass composition that resembled the chemical composition of algae.

Design of the user interface. Because the computer model was intended as a tool for studies of closed aquatic ecosystems, certain parameters were set aside as user inputs to allow the exploration of various scenarios. In the model, a separate sector was established to house all of the user inputs. Based on the experimental variables available for alteration by the undergraduates, the following parameters were chosen as user inputs: tank length, width, and height (the model assumes a rectangular aquarium tank); height of water in the tank; gravel weight; initial anacharis biomass; and initial crayfish biomass. From this information, the model calculated the initial volumes of the water and air in the tank, and the initial concentration of each of the main gases in the system.

Model calibration

In addition to the student-initiated changes in the both the virtual and physical mesocosms, the composition and structure of the physical mesocosms continued to change as they self-organized. While these changes made finalization of the models' calibration impossible, it required that calibration of the models actively occur throughout the semester.

Thus, students reinforced their understanding of the cycle of model conceptualization, implementation and analysis, and calibration. This understanding was further reinforced through incremental progress reports designed to focus on

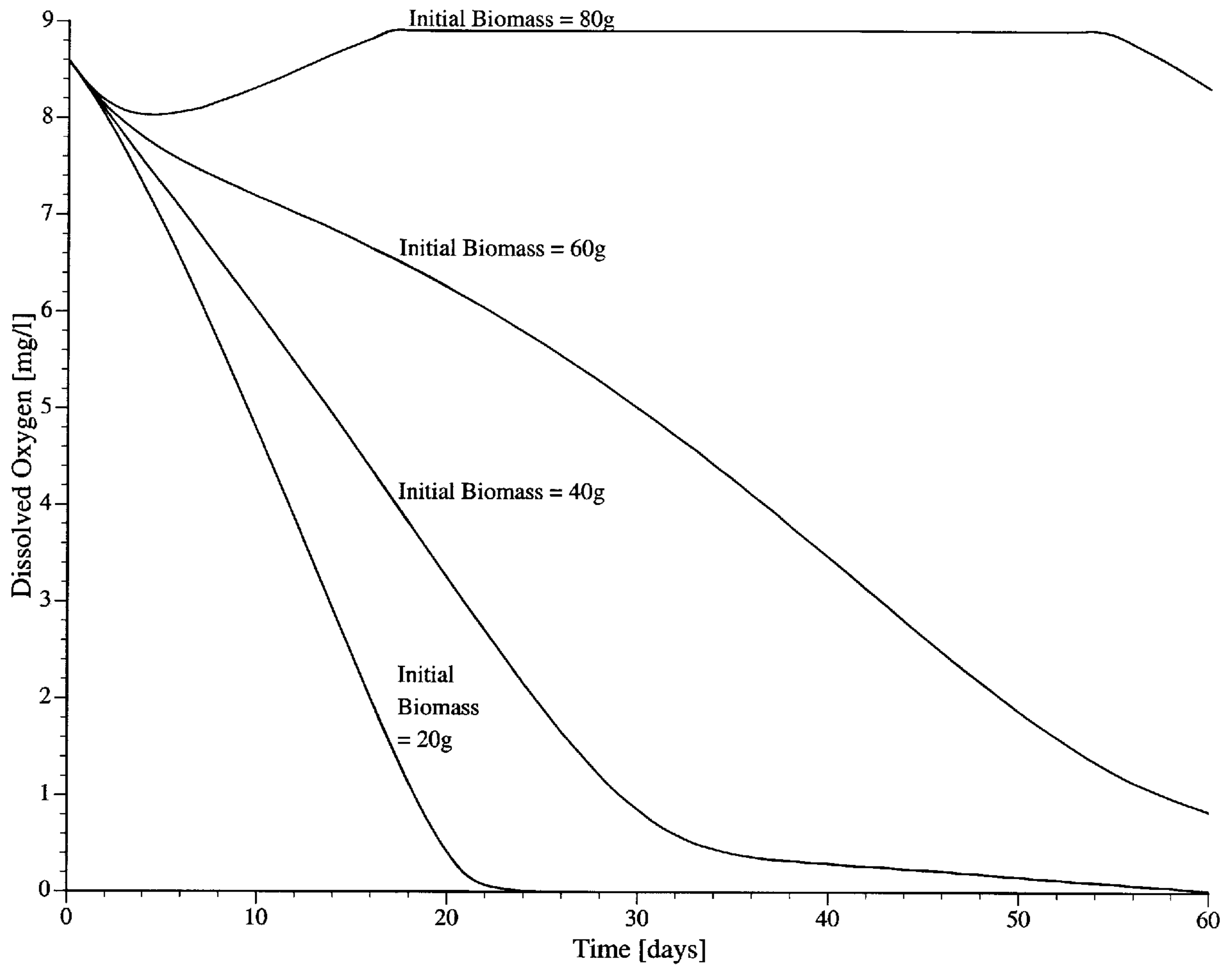

Fig. 3. Variation in oxygen concentration (in mg/l) over 60 days for various initial anacharis masses. As the anacharis in the system decreased, so did the dissolved oxygen. Note that for 80 g of initial anacharis biomass, the water became saturated with oxygen.

the iterative nature of the ecosystems' design. The project culminated in a journal style paper and an oral presentation of the results to the class.

RESULTS

Many parameters contributed to the balancing act of the ecosystem. From the STELLA model, several sensitivity analyses were generated by figures representing different parts of the system. The user input initial conditions were changed to observe the different impacts on the system. Overall, the model behaved correctly where expected, with trend rates of the various accumulators following the results obtained from the physical models. For example, as illustrated in Fig. 2, the growth rate of the anacharis was less than its rate of consumption by the crayfish. Thus, the anacharis biomass continuously decreased.

A variation of oxygen was observed when the mass of anacharis was varied (Fig. 3). The trends in the oxygen variation followed the expected results: at low plant biomasses, the rate of oxygen production would be slower relative to the oxygen consumption by crayfish and bacterial respiration. Stability of oxygen in the system would be exhibited at higher initial plant biomass values. These trends indeed occurred in the model.

The initial mass of anacharis affected certain water quality parameters. For example, at low initial anacharis biomass, ammonia concentrations reached dangerously high levels, as shown in Fig. 4. Because the crayfish consumption was greater than the growth rate of anacharis, there was not enough anacharis to absorb the ammonia. Additionally, when oxygen concentration was low due to a higher respiration rate than photosynthesis rate, the nitrification rate slowed or stopped, and ammonia continued to accumulate in the system. At a higher initial anacharis biomass (40 g), the ammonia stayed fairly constant for 45 days. At 60 and 80 grams of anacharis, the ammonia levels remained constant after an initial two-week rise.

Reaction rates, such as nitrification or ammonia uptake by anacharis, were computed using literature values [9, 10], many of which are approximated from a statistical range of possible values. Fine calibration of the model may correct this problem. Secondly, one major simplifying assumption for the construction of the model was the removal of algae from consideration, on the

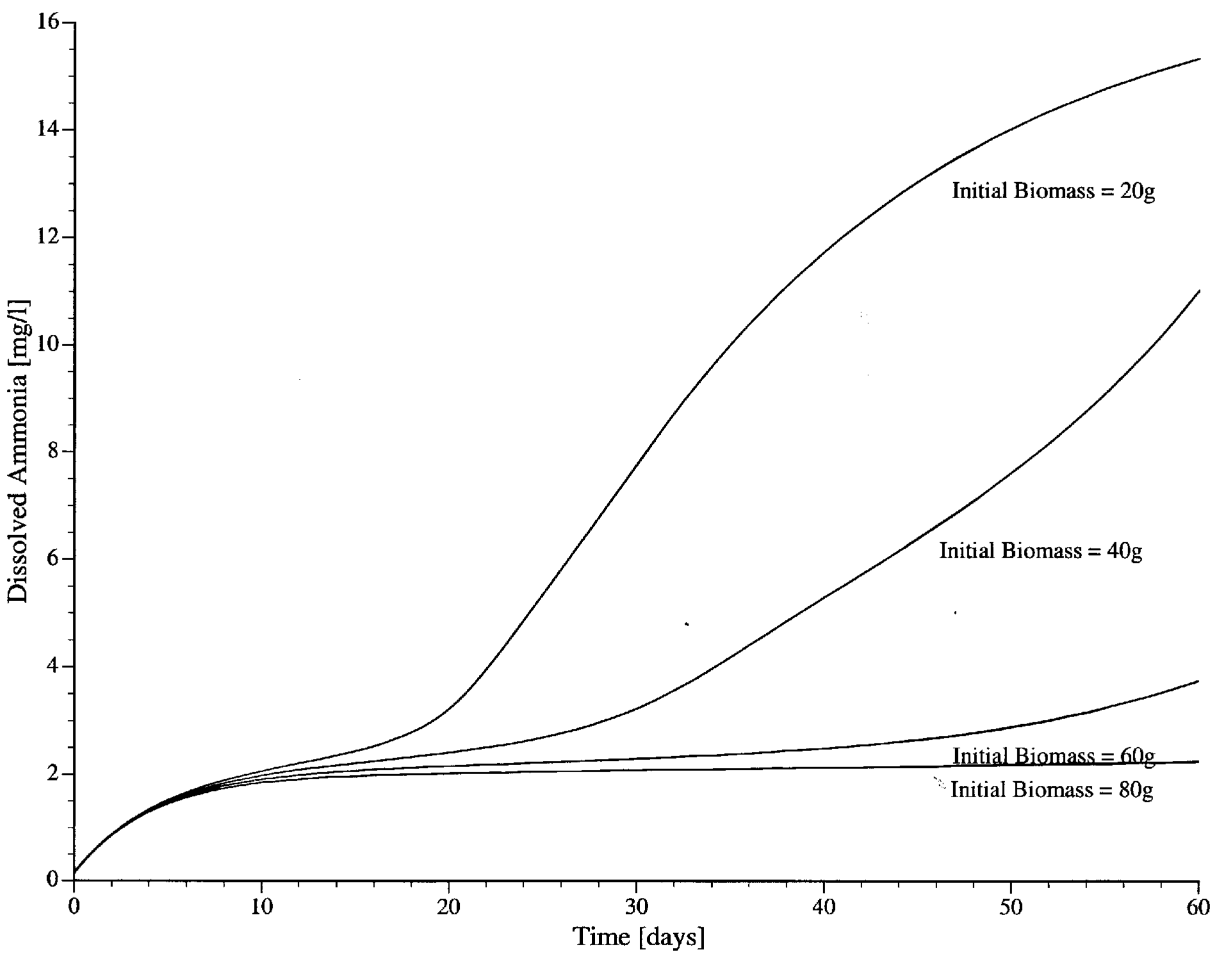

Fig. 4. The figures show how ammonia decreased with an increased mass of anacharis. For 20 g of initial anacharis, the system accumulated ammonia to high levels, while the levels remained more constant at initial anacharis masses of 40 to 80 g.

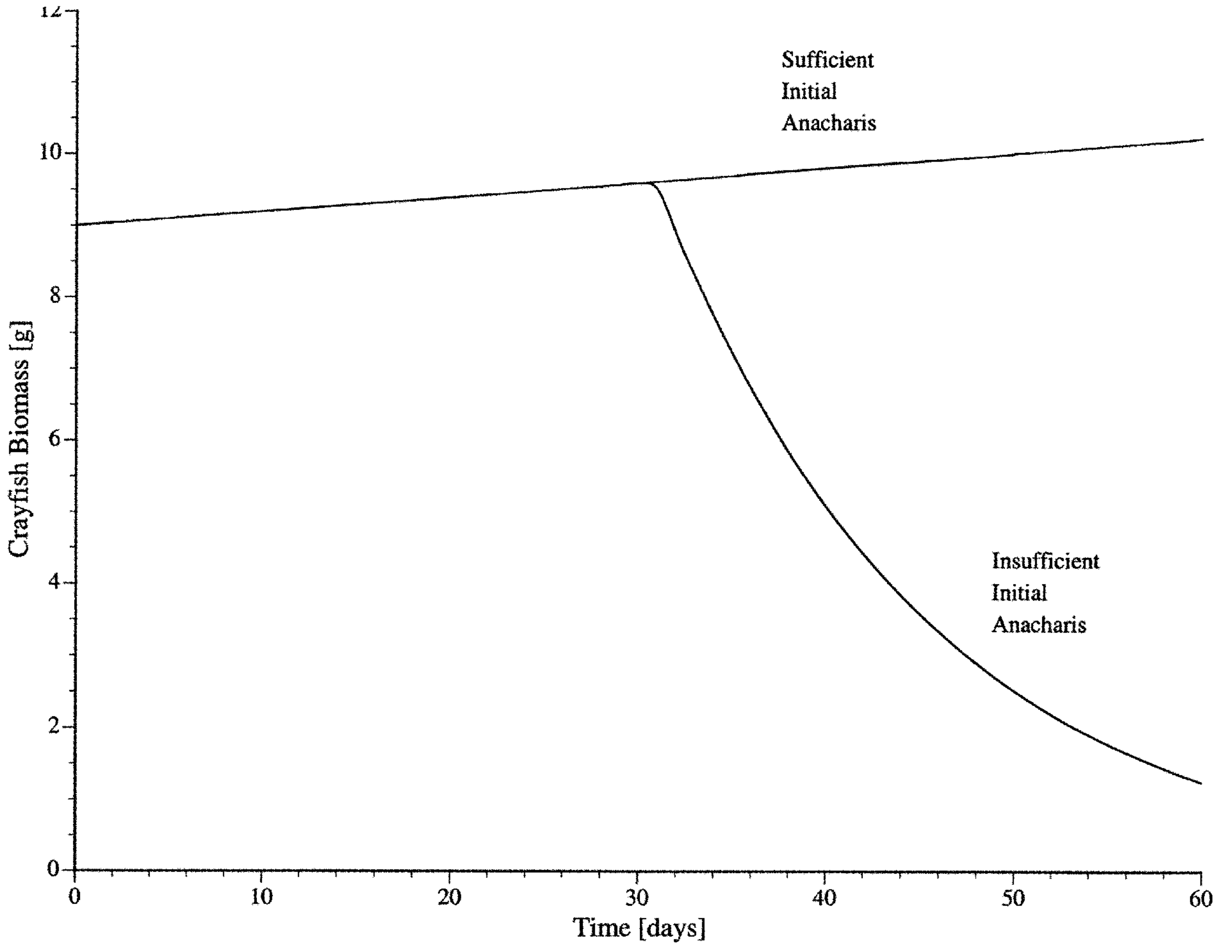

Fig. 5. Crayfish biomass (in g) over time for 20, 40, 60, and 80 g of initial anacharis biomass. Although programmed as a logistic relationship, the growth of crayfish up to 60 days appeared linear as long as anacharis was available for consumption. If there was insufficient initial mass of anacharis (20 g), cannibalism occurred.

assumption that the majority of the primary productivity in the tanks would be from the macrophytic species. However, algal productivity can be significant under proper conditions and was often a major mechanism of nutrient uptake [4]. A well-constructed sub-model concerning algal growth was therefore more necessary than was initially anticipated.

Cannibalism was observed only when there was no mass of anacharis remaining (Fig. 5). The model showed that cannibalism was not a factor until over 60 days. As depicted in Figure 5, the model did not vary the rate of crayfish growth under stressed water quality conditions. Additionally, the crayfish molting process makes the crayfish growth deviate from linearity. However, the system remained stable as long as the crayfish mass was below 9 grams and 20 grams of anacharis was initially present.

CONCLUSIONS

An ecosystem is a complex set of interactions. Thus, development of a model of an ecosystem is a difficult and iterative task. During the development of the computer simulation, the magnitudes of certain components were larger than expected. These deviations were examined by the graduate students, were used to make recommendations for measurements by the undergraduate students, and further analyzed to identify weaknesses in the model (either in conception or in implementation). This iterative process of model and experiment design was of significant benefit to the students [17], since much of their previous experience was either purely theoretical (in classes) or single pass (in course laboratories). Overall, the physical and mathematical models provide students with significant benefits that are not found in a classroom experience alone.

Further, the project presents a unique opportunity to combine graduates and undergraduates in the same class, with both groups contributing to the same goal. The project was also easily adaptable to use over multiple classes, since minor changes in the operating conditions of the mesocosms can result in significant changes in the results of the project. For instance, alterations in temperature will alter the rate kinetics of the biological processes, alterations in the light levels will alter both the growth rate and photosynthesis rates of the anacharis, or the substitution of the species of primary producers or consumers will alter the characteristics of the entire system.

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