STATUS REPORT
June 1, 1992 - November 30, 1992

THE DYNAMICS OF HYDROPONIC CROPS FOR SIMULATION STUDIES OF THE CELSS INITIAL REFERENCE CONFIGURATIONS

NASA-AMES Research Grant No. NCC2-608

Principal Investigator
Tyler Volk

NEW YORK UNIVERSITY
FACULTY OF ARTS AND SCIENCE
DEPARTMENT OF APPLIED SCIENCE

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Principal Investigator: Tyler Volk

Institution: Department of Applied Science, New York University, 26 Stuyvesant Street, New York, NY 10003

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The goal of this research is to develop a progressive series of mathematical models for the CELSS hydroponic crops. These models will systematize the experimental findings from the crop researchers in the CELSS Program into a form useful to investigate system-level considerations, for example, dynamic studies of the CELSS Initial Reference Configurations. The crop models will organize data from different crops into a common modeling framework.

This is the fifth semiannual report for this project. (The PI was on academic sabbatical during the 1991-1992 academic year) The following sections are discussed:

1) Use of field crop models to explore phasic control of CELSS crops for optimizing yield.

2) Seminar presented at Purdue CELSS NSCORT.

3) Paper submitted on analysis of bioprocessing of inedible plant materials.

Before beginning discussions of these items, I would like to mention several meetings attended during this time period:

Science and Technology Working Group for NASA Space Station CELSS Test Facility, Carmel, CA, 21-24 July 1992.

American Society of Agronomy, Minneapolis, Minnesota, 1-6 November, 1992.

Science and Technology Working Group for NASA Space Station CELSS Test Facility, Burlingame, CA, 17-19 November 1992.

1) Use of field crop models to explore phasic control of CELSS crops for optimizing yield:

Through careful study of the factors that control the development rates of field crop, from the specific viewpoint of modeling (Hanks and Ritchie, *Modeling Plant and Soil Systems*, ASA, 1991) I have become convinced that analyses with the existing field crop models could provide ideas foe the CELSS crops in the area of phasic control. Phasic control means changing environmental conditions at different stages in the crop's development to maximum yield.

I have obtained the following models and am in contact with the following people.

CERES WHEAT and CERES MAIZE. Contact: Walter Bowen, International Fertilizer Development Center, Muscle Shoals, AL (205) 381-6600.

SOYGRO. Contact: Office of Jim Jones, University of Florida (904) 392-8535.

SUBSTOR for POTATO. Pre-formal release version. Contact: Brian Baer, Michigan State, (517) 353-8537.

I plan on reporting at this work in a talk and poster at the CELSS PI meeting in Washington in early March 1993.

2) Seminar presented at Purdue CELSS NSCORT:

At the invitation of Cary Mitchell, I presented an overview of the role of crop modeling in CELSS system design on 26 October 1992. I met individually with many of the NSCORT investigators, including Phillip Nelson, Louis Sherman, Michael Ladisch, Suzanne Nielson, Paul Hasegawa, and Tom Hodges.

On the following two pages are the seminar announcement with abstract and one key figure that summarizes the areas I discussed in the seminar.

NSCORT SEMINAR

NASA Specialized Center of Research and Training in Bioregenerative Life Support

"Impact of Crop Modeling on CELSS System Design"

Dr. Tyler Volk
Associate Professor of Applied Science
Earth Systems Group
New York University

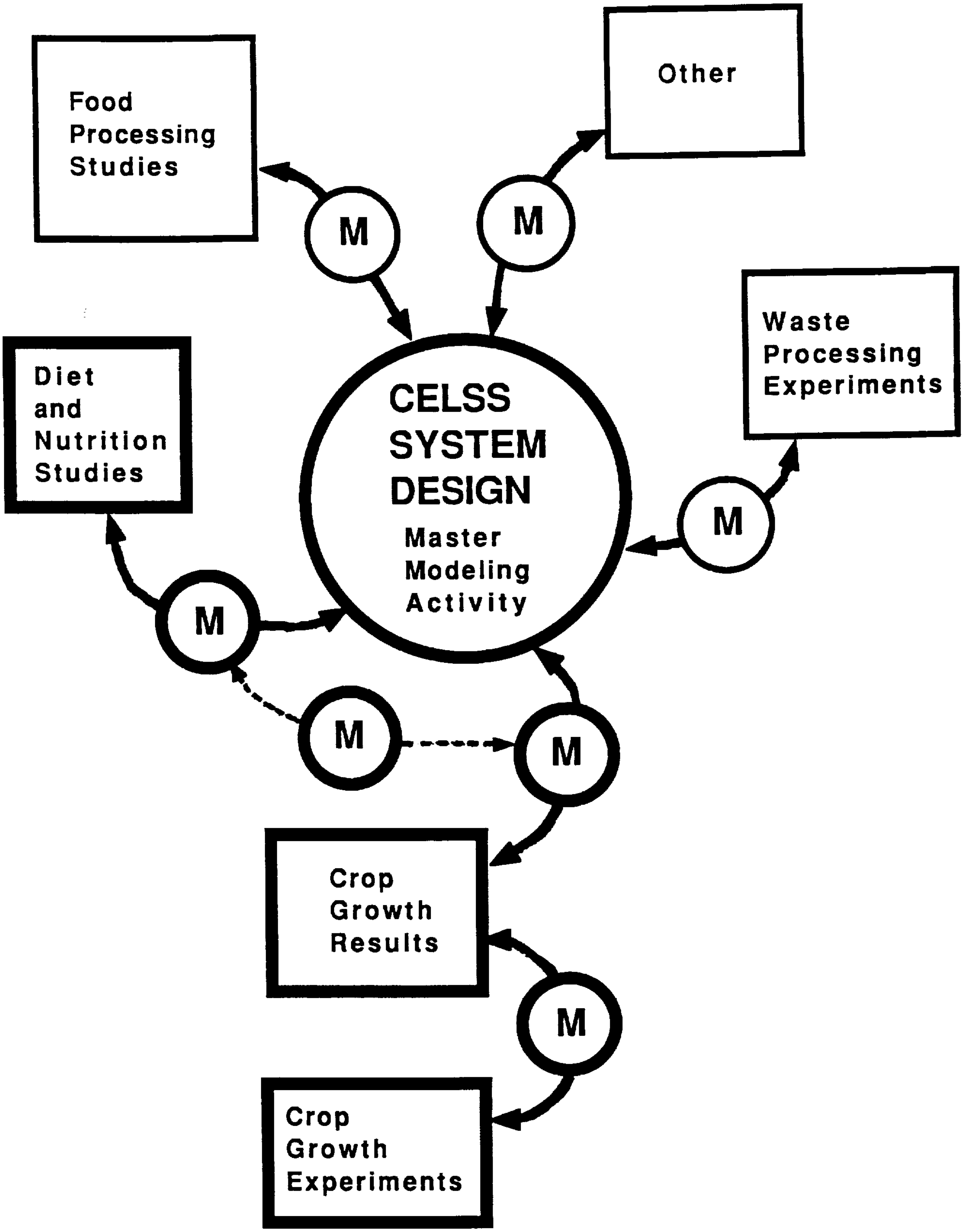
After humans, plants are the key components of a CELSS. Much of the design of a CELSS will revolve around the needs of the crops and the processes to which they contribute. Progressing toward a preliminary design for a CELSS and performing first-order trade-offs among, for example, efficiency, size, and diet variation, requires crop models suited for the system design task. I have been working toward addressing some of these issues.

I will cover the following: (1) stoichiometries of crop growth for CO_2, O_2, and nutrient exchange, (2) multiple drop configurations for matching dietary requirements, (3) use of an energy cascade concept for linking crops into an engineering energy balance along with material fluxes, and as a way of targeting questions during crop experiments relevant to overall system needs, and (4) phasic development in field crop models compared to CELSS experiments.

I hope this survey will stimulate interest in these topics that can be pursued in more detail during my stay at Purdue.

3:30 pm - 4:20 pm
2-102 Lilly Hall of Life Sciences
Monday, October 26, 1992

*Please contact Lynn Warble at 46533 for a special appointment.



M = Modeling tasks and opportunities
(bold outlines = seminar focus areas)

3) Paper submitted on analysis of bioprocessing of inedible plant materials.

The remainder of this report includes a paper recently submitted from work completed during the period of this report. I discussed the calculations with Cary Mitchell during the CTF STWG meeting in November and verified the general approach and conclusions:

Comments on "Bioprocessing in Space"

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submitted to *Enzyme and Microbial Technology*

An analysis developed by Westgate et al. (ref 1) for the digestible energy of edible and inedible biomass, including hydrolysis and fermentation, is re-examined with state-of-the-art values for the harvest index of hydroponic crops.

Westgate et al. formalized an important consideration for the design of a Controlled Ecological Life Support System (CELSS) for space exploration and habitation. Namely, since a portion of a crop is inedible, savings can be derived from bioprocessing this otherwise inedible portion into additional food. In their example, bioprocessing reduced the crop growth area from 49 m^2/person-day to 33 m^2/person-d. This comment focuses on the role of the harvest index for these savings.

Harvest index is the ratio of the edible to total biomass at crop maturity. For their example, Westgate et al. took a value for the harvest index of hydroponic wheat of $h = 0.2$, derived from hydroponic wheat experiments in which the harvest index failed to reach typical field values. However, as they noted, "If the relatively low edible fraction of the fast-growing hydroponic plants is increased, the amount of biomass requiring bioregenerative processing will be reduced." Subsequent experiments by the wheat investigators have succeeded in raising the harvest index of hydroponic wheat under high light conditions to about 0.45 (ref 2). This number has also been achieved under optimal CO_2 by hydroponic soybeans (ref 3). Another important candidate crop for CELSS is potatoes, which have been grown hydroponically with a harvest index of 0.8 (ref 4). Given the variety of values for the harvest index, and the analytical framework for bioprocessing spearheaded by Westgate et al., it is valuable to generalize this framework as a potential design element for CELSS.

Westgate et al. established the dietary energy values of edible biomass and inedible biomass (after bioprocessing). Combining several of their terms and definitions to get to the heart of the issue, we can write

$$E_e = h \; v_e \; M \tag{1}$$

$$E_i = (1 - h) \; v_i \; M \tag{2}$$

$$E_e + E_i = E_t \tag{3}$$

where

E_e , E_i = respective daily energies obtained from edible and inedible harvested biomass, kcal/person-day

h = harvest index, g edible/ g total

v_e , v_i = respective specific digestible energy values of edible and inedible biomass, respectively, kcal/g

M = total biomass required to be grown, g/person-day

E_t = total daily energy requirements, kcal/person-day

To compare the value of M with waste biomass processing (v_i, $E_i > 0$) to its value without such processing (v_i, $E_i = 0$), compute M for these two conditions from equations (1-3) and set the two values for M in a ratio of biomass production, r. Analytically, r is therefore

$$r \equiv \frac{M_{v_i>0}}{M_{v_i=0}} = \frac{h\ v_e}{h\ v_e + (1 - h)\ v_i} \tag{4}$$

Using the review by Westgate et al. for the sequence of losses that enter into the v's, the values for v_e and v_i are, respectively, 3.4 and 0.4 kcal/g. The relatively low value for v_i comes from a sequence of conversion efficiencies, which include fractional recoveries for hydrolysis, fermentation, sugars used to make edible material, and final digestibility. While none of the terms alone is exceptionally low, their cumulative product results in the above value.

In Figure 1, r is plotted as a function of h. For the case of $h = 0.2$ presented by Westgate et al., $r = 0.67$ (i.e. 33 m^2/49m^2), demonstrating substantial savings possible with bioprocessing. For higher values of h, the value of r increases and the savings concomitantly decrease. For example, when $h = 0.45$, currently possible with soybeans and wheat in the CELSS experiments, $r = 0.87$. In this case the savings in crop biomass production by using biomass processing (which translates directly into savings in the all-important design constraints of growth area and power for lighting) is about 13%. For values of $h = 0.8$ achieved with potatoes, $r = 0.97$, implying perhaps nearly negligible savings. A second curve for r—assuming that the digestible energy potential from bioprocessing the inedible biomass could be doubled from the typical value reported by Westgate et al.—is shown for comparison in Figure 1. The values of r for soybeans-wheat and potatoes, respectively, are 0.78 and 0.94.

The overall system of analysis presented by Westgate et al. is the kind of tool CELSS design engineers need to make tradeoffs among available options. It is clearly an ongoing research priority in the crop growth experiments to maximize the harvest index. Although the processes that may limit such improvements are not well-established, a high harvest index will always be a design goal since, as Westgate et al. point out, additional equipment, volume, and power would be required for the procedures of separation, hydrolysis, and fermentation in processing the inedible biomass. The current crop values for *h* in Figure 1 limit the potential savings by biomass processing. Further improvements of *h* that would limit these saving even more could be balanced, however, by improvements in the yields along the various steps of the bioprocessing sequence (see ref 1 for details of these steps). The simplified system presented here may help focus issues about options for CELSS design.

Acknowledgements

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References

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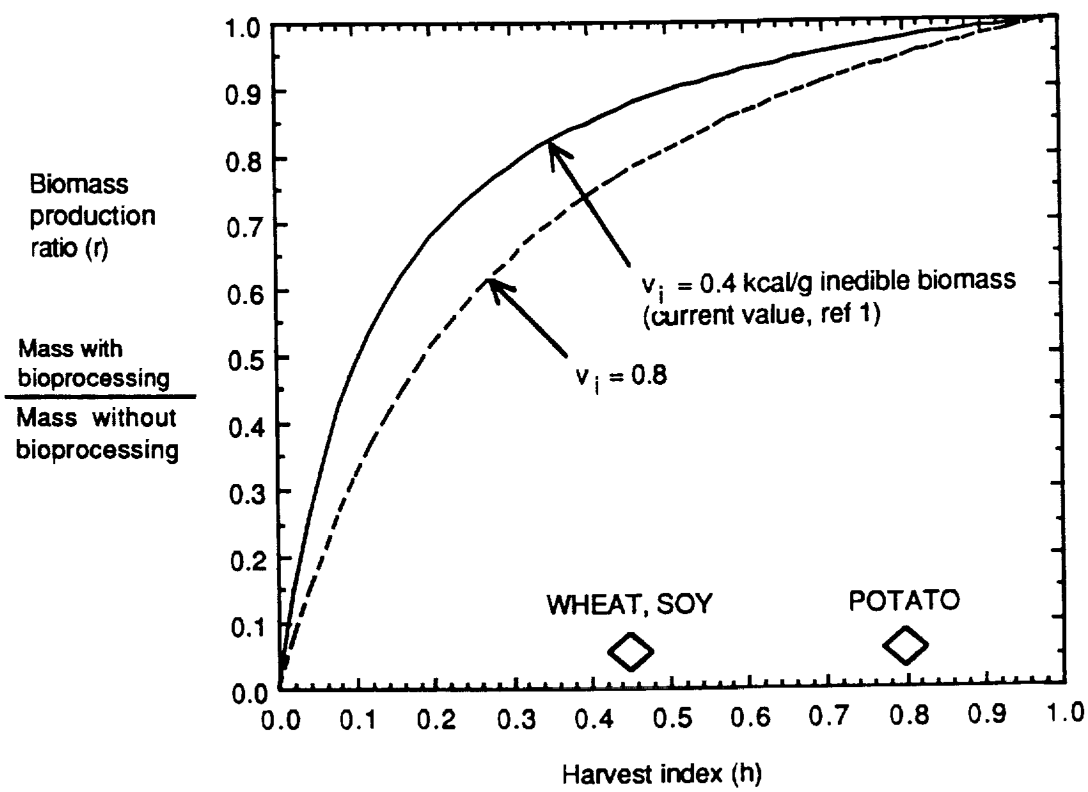
2 Bugbee, B. G. and Salisbury, F. B. Exploring the limits of crop productivity. *Plant Physiol.* 1988, **88**, 869-878.

3 Wheeler, R. M., Mackowiak, C. L, Sager, J. C. Proximate composition of seed and biomass from soybean plants grown at different carbon dioxide (CO_2) concentrations. *NASA Tech. Memorandum 103496* 1990, 28 pp.

4 Wheeler, R. M., Mackowiak, C. L, Sager, J. C., Knott, W. M. and Hinkle, C. R. Potato growth and yield using nutrient film technique (NFT). *Am. Potato J.* 1990, **67**, 177-187.

Figure 1


Biomass production ratio (r)
Mass with bioprocessing
Mass without bioprocessing
v_i = 0.4 kcal/g inedible biomass (current value, ref 1)
v_i = 0.8
WHEAT, SOY
POTATO
Harvest index (h)
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0