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MODELING THE GROWTH DYNAMICS OF FOUR CANDIDATE CROPS FOR CONTROLLED ECOLOGICAL LIFE SUPPORT SYSTEMS (CELSS)

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ABSTRACT

The production of food for human life support for advanced space missions, such as the lunar and Mars bases, will require the management of many different crops. The research to design these food production capabilities along with the waste management to recycle human metabolic wastes and inedible plant components are parts of the NASA program in Controlled Ecological Life Support Systems (CELSS). Since complete operating CELSS have not yet been built, a useful adjunct to the research developing the various pieces of a CELSS are system simulation models that can examine what we currently know about the possible assembly of subsystems into a full CELSS. This report examines the growth dynamics of four crops--wheat, soybeans, potatoes, and lettuce--for their general similarities and differences within the context some of their important effects upon the dynamics of the gases, liquids, and solids in the CELSS.

Data for the four crops currently under active research in the CELSS program using high-production hydroponics are shown. Two differential equations, one each for the inedible and edible protions of the crop's biomass, are developed and applied to the general characteristics of each crop's growth pattern. Model parameters, such as ultimate sizes and growth rates, are determined by closely approximating each crop's data. These parameters are constant here for each crop, in order to demonstrate the capability for a relatively simple generic model to reproduce the overall characteristics of growth of different crops that can serve as a basis for including these crops in a model of a complete CELSS. In actuality these parameters are functions of environmental qualities, such as photosynthetic photon flux, photoperiod, atmospheric pCO_2 -- therefore further development along the lines based upon principles of photosynthesis and plant physiology is indicated. Models such as these can aid the engineering conceptual design of CELSS by providing flux rates of substances going into and leaving the plants. Flux rates for CO_2, H_2O, HNO_3, and O_2 are shown for the models developed here.

INTRODUCTION

The NASA CELSS program is developing Controlled Ecological Life Support Systems for advanced space missions involving long duration stays by humans (see CELSS, 1986). Simulation models help in the conceptual and preliminary engineering design of such systems by assembling the components as presently understood into a mathematical framework for asking and answering particular

Previous work along these lines by this author and John Rummel considered a CELSS that grows wheat as the sole crop (Volk and Rummel, Rummel and Volk, 1987). The model in these works used stoichiometries for various substances, such as plant protein and human urine, to develop balances to trace the flow of carbon, hydrogen, oxygen, and nitrigen through the various pathways. The model can grow wheat in a variety of planting schemes, between the end-points of a single batch (planting and harvesting once every fifty-five days) to much smaller plantings every day (yielding the same integrated amount of food production). Different planting schemes create different magnitudes of fluctuations in the standing biomass and in the buffer reservoirs of CO_2, H_2O, HNO_3, and O_2.

Eventually we need to extend such modeling efforts to crops other than wheat, to mimic what--due to human nutritional requirements--must be a mutliple-crop system. Several crops are undergoing tests in hydroponic systems to determine their growth characteristics in high-production systems with relatively high photosynthetic photon fluxes (PPF), atmospheric pCO_2 levels, optimized nutrient supply, controlled temperature and humidity, etc. Wheat is one of these crops; others include potatoes, soybeans, and lettuce. Questions regarding the differences in growth characteristics would affect the design of CELSS, such as how different will the growth environments have to be for different crops? This would affect the hardware design. Will each crop require a highly-customized system? Also of interest and a focus of this study is the comparative growth dynamics of the crops. How similar or how different are they? What do these similarities and differences mean for formulating the crops into a model of a CELSS?

FINDINGS

The study began with development of a questionnaire each crop researcher was asked to complete to provide a common set of characteristics for each crop. Answers were received both over the mail and by phone for each of the four crops requested: wheat, soybeans, potatoes, and lettuce. Examples of the information gathered included environmental conditions under particular high-yield experiments for both the aerial and root parts of the plants, and plant growth through time, food-type composition, planting and harvesting procedures, etc. Interested readers can contact me for more information.

Key data for this report are the growth curves of the four crops. Representative curves are shown in figures 1-5. Figure 1 shows typical soybean growth for the edible seed mass and inedible plant parts (inedible with respect to people), which in this case includes the leaves, stems, and roots. A division into edible and inedible biomasses is of fundamental importance in a CELLS because of the separation of material flow that would occur because of this division. The growth curves for edible and inedible portions of wheat (again the seeds as edible vs. all other plant parts as inedible) is shown in figures 2 and 3, with figure 2 showing the growth of dry biomass for different light levels and figure 3 the growth of the fresh (wet) biomass and cumulative transpiration. Figure 4 shows the growth of tubers (the edible biomass) and the stems and leaves (the inedible biomass) for potatoes, both fresh and dry masses and for two diffferent photoperiods. Figure 5 shows several growth curves for lettuce.

The intention here is not to evaluate in any way the suitability for these crops for future CELSS. In fact, the assumption is that all these crops--indeed many more--would need to be grown for physically- and psycologically-satisfactory support of life. I have not attempted to provide all the environmental data for each crop; see me for more details. Note that some growth data is in grams per square meter and some in grams per plant. The goal at hand is to begin looking at these crops as a system, and what effects their various and special characteristics may have on the dynamics of a CELSS.

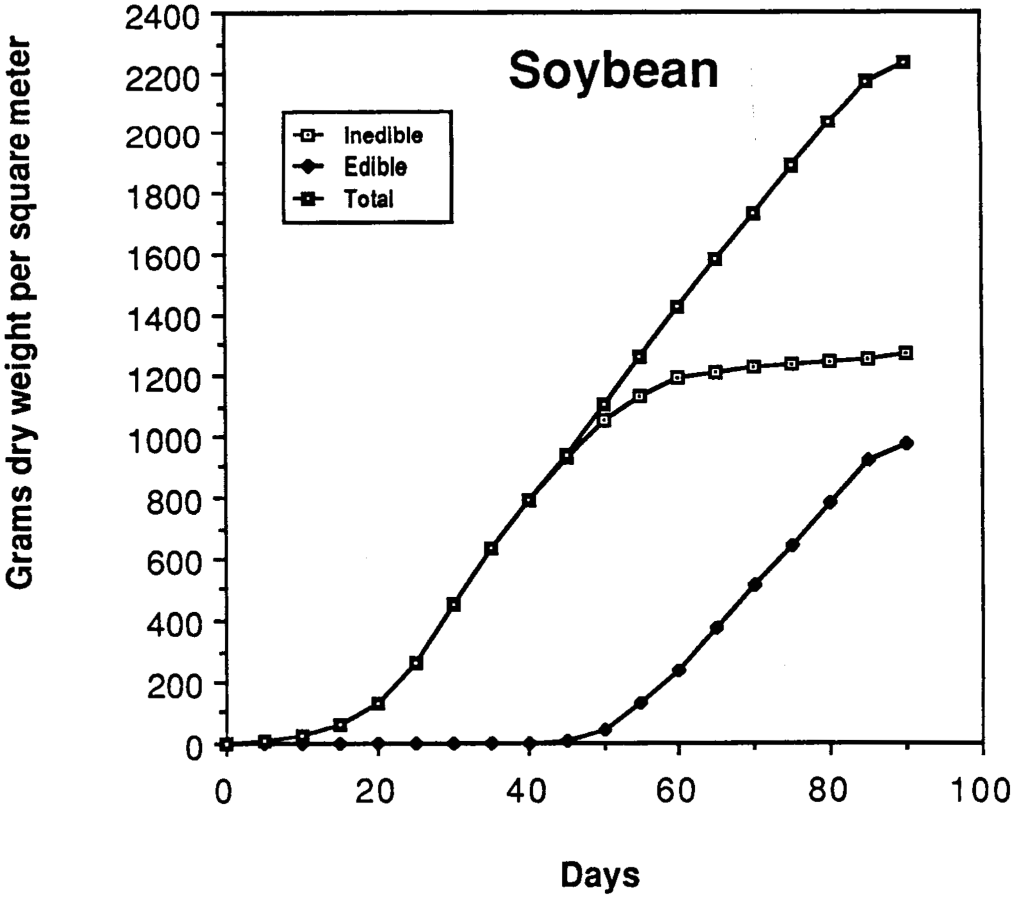

Figure 1. Soybean growth from data provided by D. Raper.

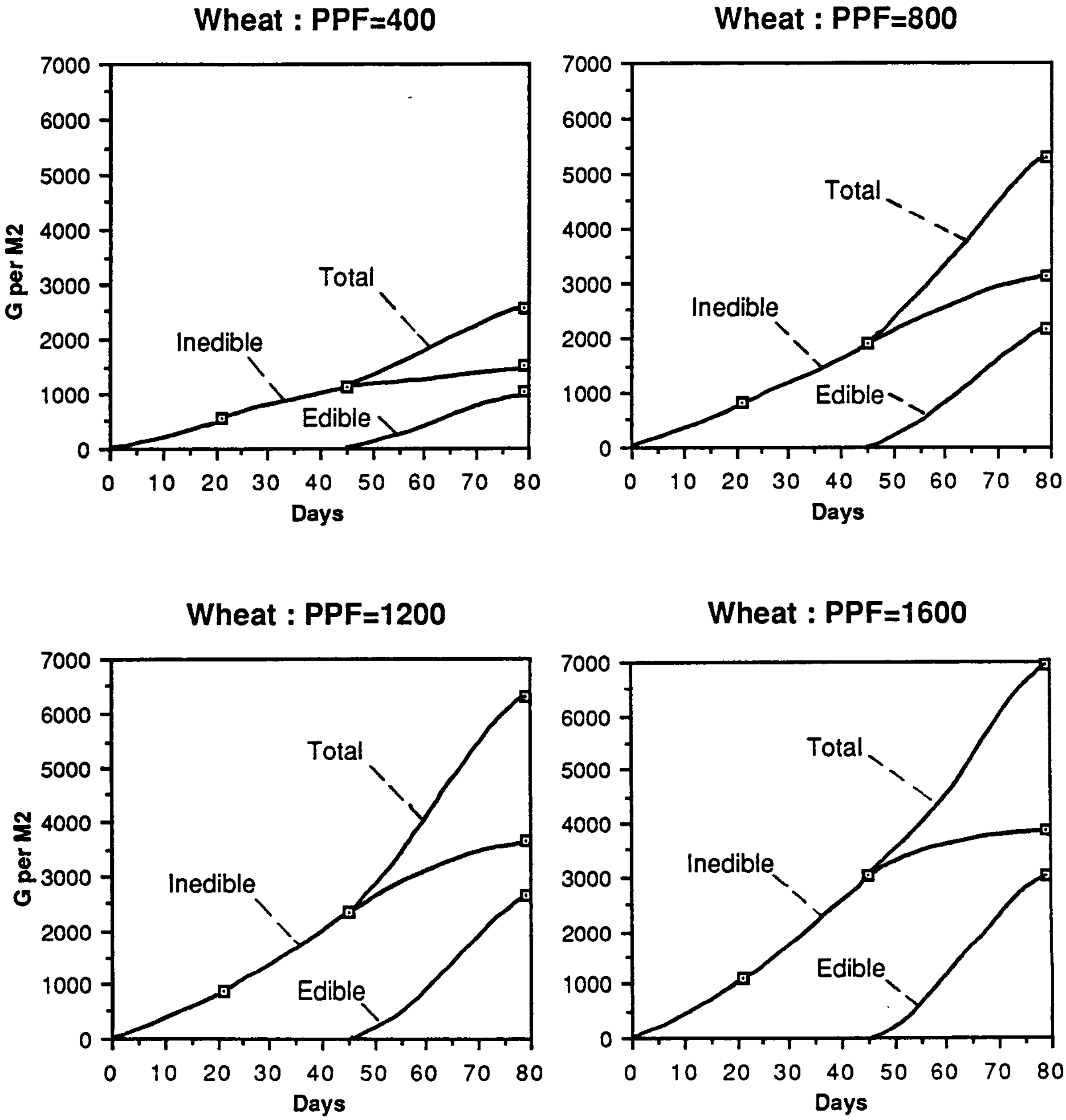

Figure 2. Wheat growth from data provided by B. Bugbee. See also Bugbee and Salisbury (1987). Some data points were modified by T. Volk in collaboration with B. Bugbee. Curves drawn by T. Volk. The photosynthetic photon flux (PPF) is in μmol/m^2-s.

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ARC WHEAT GROWTH DATA

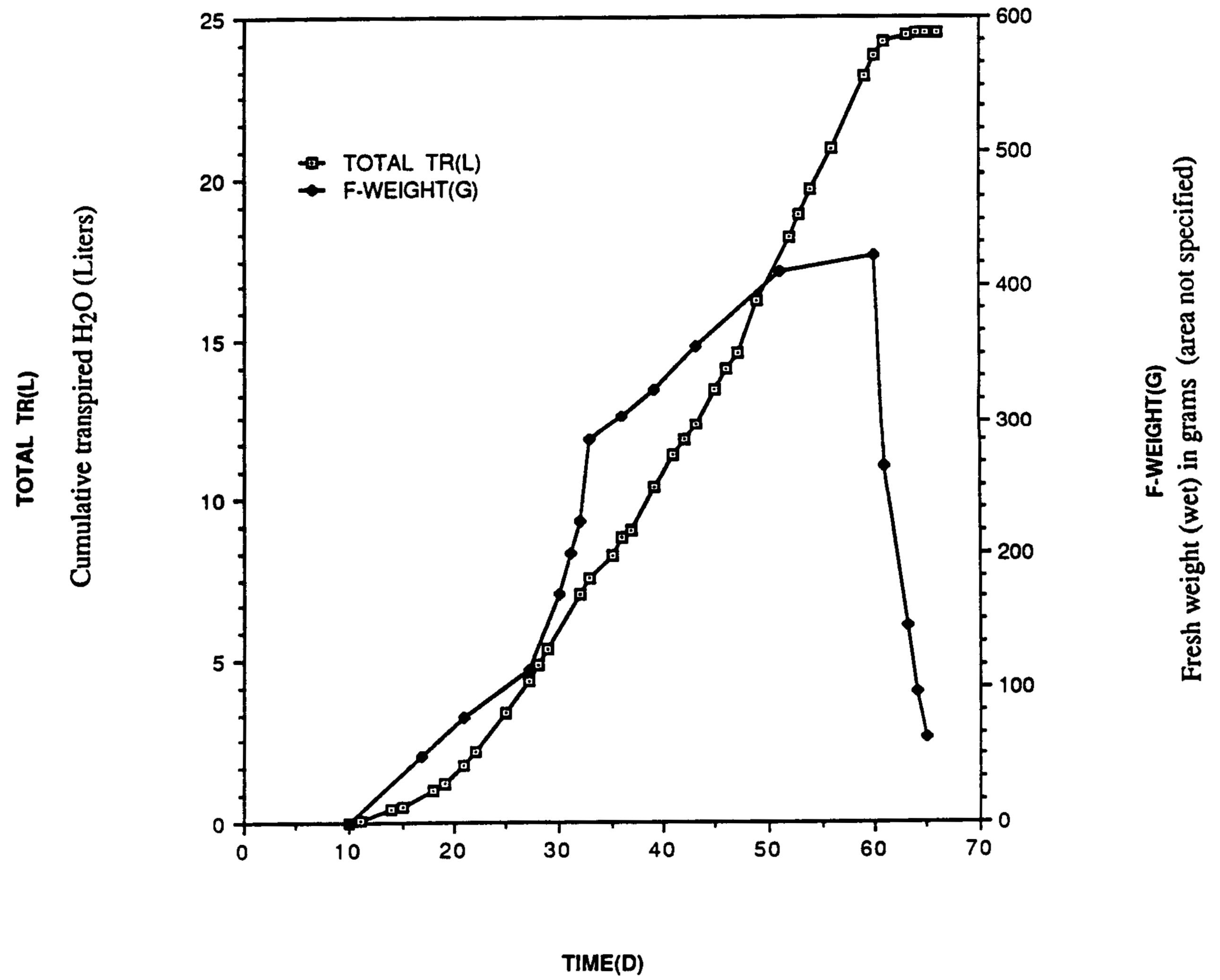

Figure 3. Wheat growth data from S. Schwartzkopf for cumulative transpiration and fresh-weight biomass.

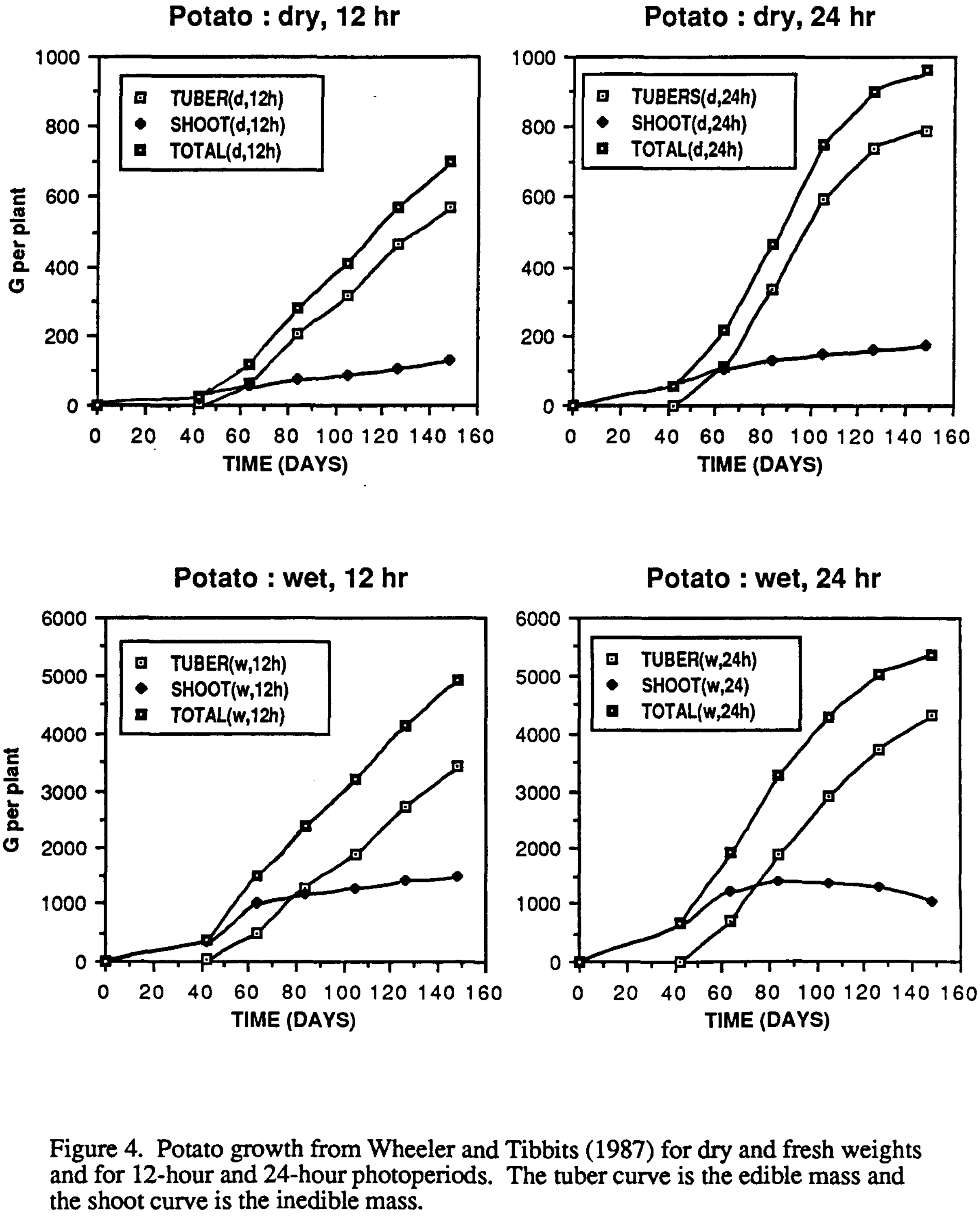

Figure 4. Potato growth from Wheeler and Tibbits (1987) for dry and fresh weights and for 12-hour and 24-hour photoperiods. The tuber curve is the edible mass and the shoot curve is the inedible mass.

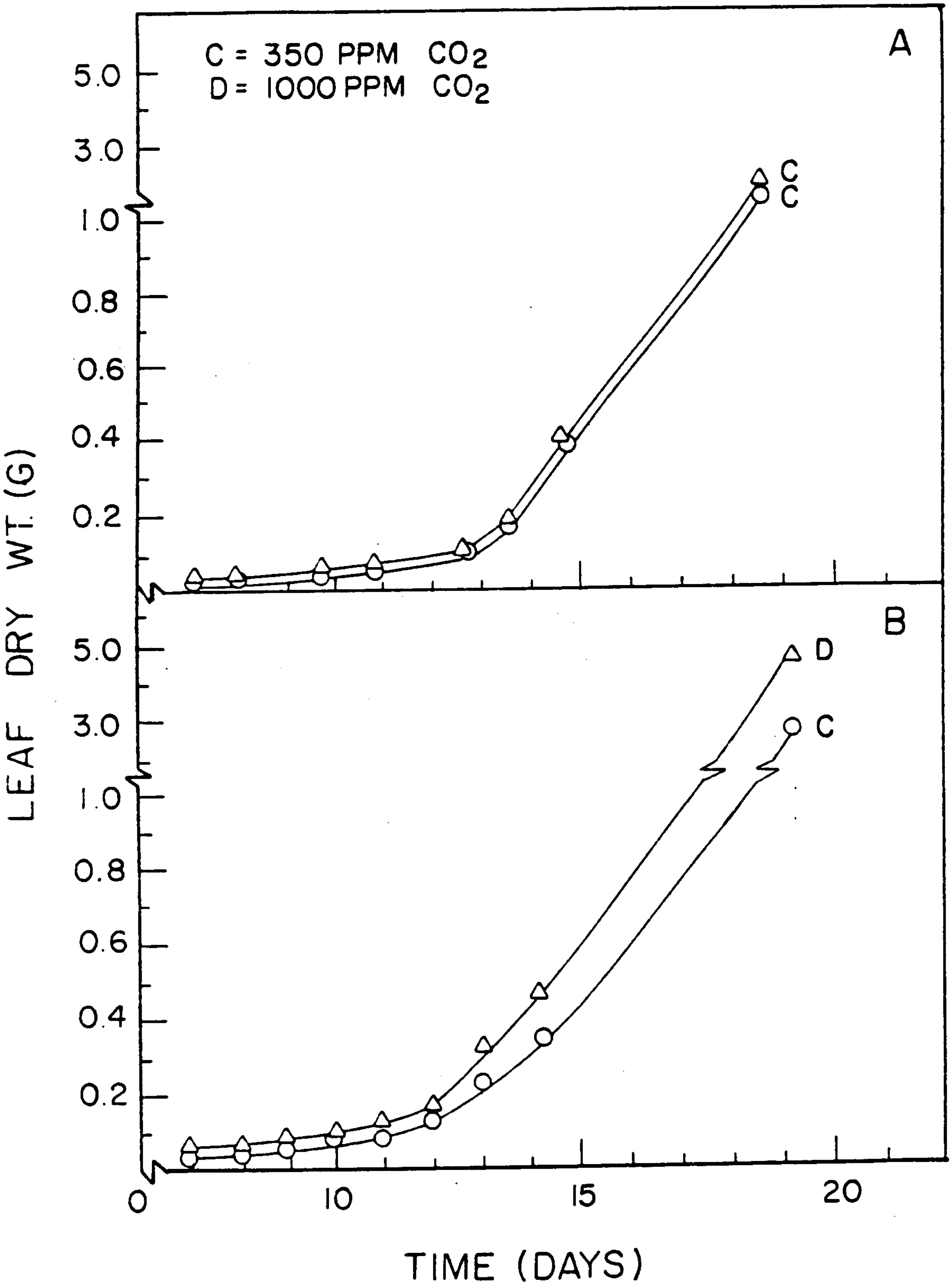

Figure 5. Growth profile of 'Waldmann's Green' leaf lettuce at 450 µmol/m^2-s of PAR + 350 µl/l CO_2 in 2 separate Minitron II chambers (top), and at 1000 µl/l CO_2 in one chamber and at 350 in another, both at the same PPFD (bottom). [Figure and figure description from Mitchell et al, 1986]

Many of the growth curves prominantly show the S-shaped or sigmoidal curve typical of biological systems. The logistic differential equation's solution imitates this S-shape of exponential growth followed by a leveling-off. In the logistic equation, $dC/dt = rC(1-C/K)$, where C is the biomass and t is time, two parameters appear: r and K. The r is the growth rate for the purely exponential part of the system. K, the carrying-capacity in a ecological system, in this case is the maximum biomass reached by the crop. I think of it as a "negative feedback from the lifetime", a environmentally-modifiable but inherently genetically-based slowing of the total growth rate (the dC/dt) by the approach of the crop to its mature size. The logistic equation, while about as simple as one could conceive to derive the S-curve, contains some biologically-meaningful parameters. This equation will be used for the growth of the inedible plant parts.

The equation for the edible plant parts must be somewhat differently structured. Like the inedible cells, the edible cells reproduce and total edible growth must contain a proportionality to the edible mass. But since the edible parts (except for lettuce--see below) are not producing their growing mass through photosynthesis, but rather receive products from photosynthesis of the inedible parts (the leaf mass), one would require the inedible biomass to also appear in the edible equation. Furthermore, as evident from the data in figures 1-5, the edible may begin substantially after the beginning of the inedible growth, and so a turning-on time (t^*) is placed into the edible equation. In addition, since before t^*, the edible mass is assumed equal to zero, an initial growth-spurt of edible is provided to ensure proper behavior (the term E_{min}). For further discussion of these equations, contact me

$$\frac{dM_{ined}}{dt} = r_{ined} M_{ined}\left(1 - \frac{M_{ined}}{K_{ined}}\right) \tag{1a}$$

$$t < t^*: \quad \frac{dM_{ed}}{dt} = 0 \tag{1b}$$

$$t > t^*: \quad \frac{dM_{ed}}{dt} = r_{ed} M_{ined}\left(\frac{E_{min} + M_{ed}}{K_{ed}}\right)\left(1 - \frac{M_{ed}}{K_{ed}}\right) \tag{1c}$$

The parameters t and t^* are in units of time; r_{ined} and r_{ed} are in units of $time^{-1}$, and all other parameters are in consistent mass units. The system of eqns (1a-c) above was used for wheat, soybean, and potato. For lettuce the system was modified to be (with t^* having a different meaning):

$$t < t^*: \quad \frac{dM_{ed}}{dt} = r_{ed,1} M_{ed}\left(1 - \frac{M_{ed}}{K_{ed}}\right) \tag{2a}$$

$$t > t^* : \frac{dM_{ed}}{dt} = r_{ed,2}\, M_{ed}\left(1 - \frac{M_{ed}}{K_{ed}}\right) \tag{2b}$$

$$\frac{dM_{ined}}{dt} = \frac{dM_{ed}}{dt}\,\frac{K_{ined}}{K_{ed}} \tag{2c}$$

These systems of equations (1a-c) and (2a-c) were placed into the STELLA modeling program for the MacIntosh computer (see figure 6). STELLA is useful for relatively simple dynamic models for the user creates a digram in the program that corresponds to the model equations, and a hierarchical structure allows one to "open-up", examine, and change the various components at will. The graphic quality allows the user to recall the model structure after not using the model for a period of time, facilitating a very flexible interaction. I envision such modeling systems as STELLA to be very useful to models at the stage of CELSS when large-scale design differences need to be explored and analyzed by a number of different types of people.

The program was run and graphic output of edible and inedible biomass through time generated with the same scales as the crop data. I shifted parameters in ways that made sense to me until the model generated approximately what the data showed. No attempt was made to optimize the fit--there is little to be gained by this at this point. The parameters used for each crop is listed in Table 1 and the model outputs shown in figure 7.

Note that the crop data imitated by the figure 7 models for wheat was the figure 2 (PPF=1200) case and for potatoes was the figure 4 (dry, 24 hour) case.

The model curves demonstrate that it is relatively easy to imitate the data with a single model whose parameters have some biological meaning in at least a crude sense. Table 1 lists the actual planting masses for the crops, but I need to investigate whether the data at t=0 actual means the initiation of the crop from seed or tissue, or is the transplanting time after initial seeding growth. Some further adjustment to account for additional information on the meaning of time t=0 may therefore be necessary.

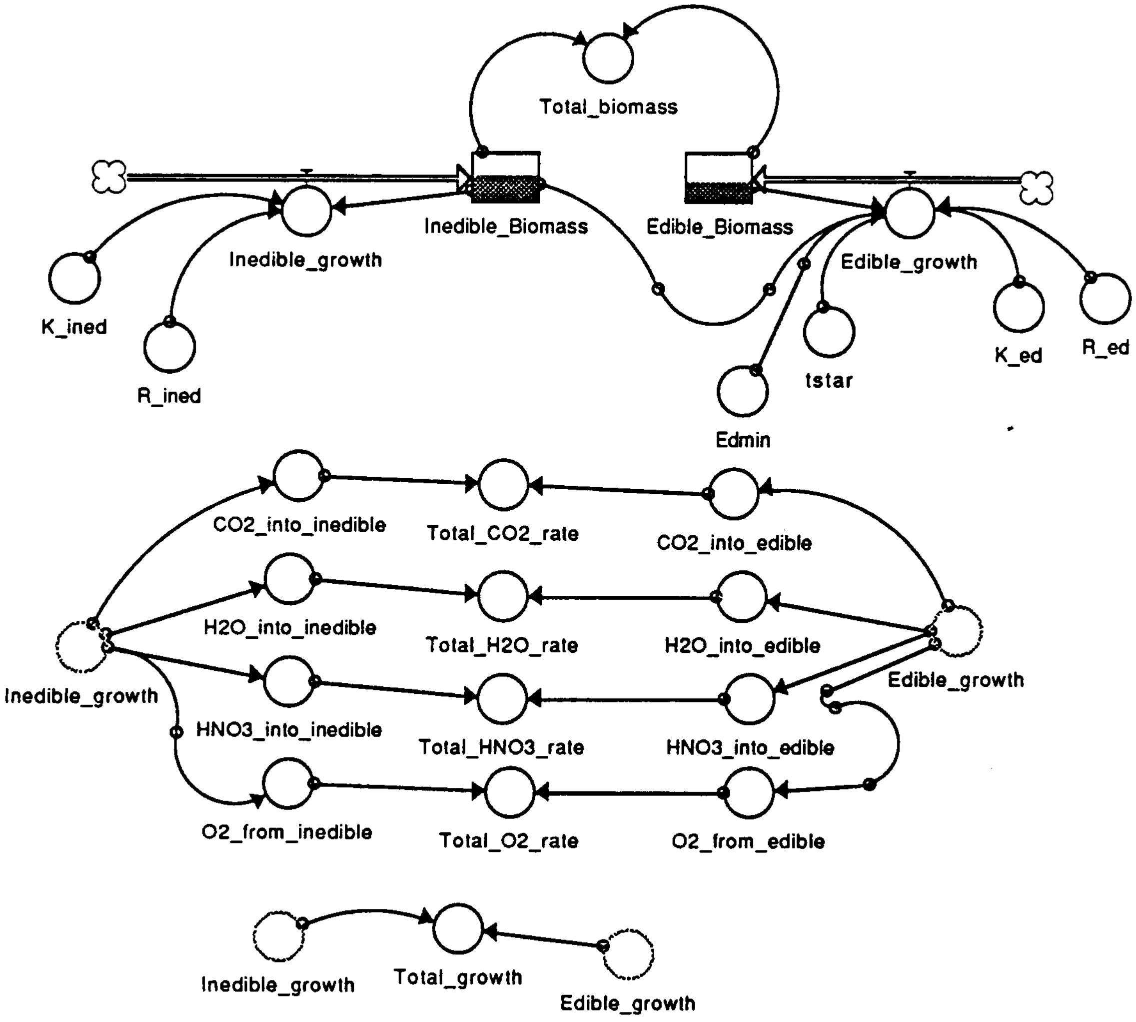

Figure 6. Crop model structure in STELLA programming language. Upper portion of diagram corresponds to eqns (1a-c).

Table 1. Parameters for Crop Models

Parameter	Wheat	Soybean	Potato	Lettuce
r_{ined} (day^{-1})	0.09	0.10	0.06	0.2 r_{ed}
r_{ed} (day^{-1})	0.15	0.10	0.20	0.2 to 0.5
K_{ined}	3700.0	1300.0	200.0	2.0
K_{ed}	3000.0	1100.0	800.0	20.0
E_{min}	80.0	80.0	80.0	X
$M_{ined,o}$	150.0	20.0	5.0	X
$M_{ed,o}$	0.0	0.0	0.0	0.008
t* (days)	45.0	45.0	40.0	11.0 (r_{ed} switch)
[actual $M_{ined,o}$ in seeds or tissue]	70.0	2.0	0.15*	0.008**

* not certain whether wet or dry
**not certain whether 0.008 or 0.0008

Note different units between crops for K_{ined} ; K_{ed} ; K_{ined} ; $M_{ined,o}$; $M_{ed,o}$
For wheat and soybean all are in grams dry mass per square meter.
For potato and lettuce all are in grams dry mass per plant (approx. 5 plants per square meter for potato).

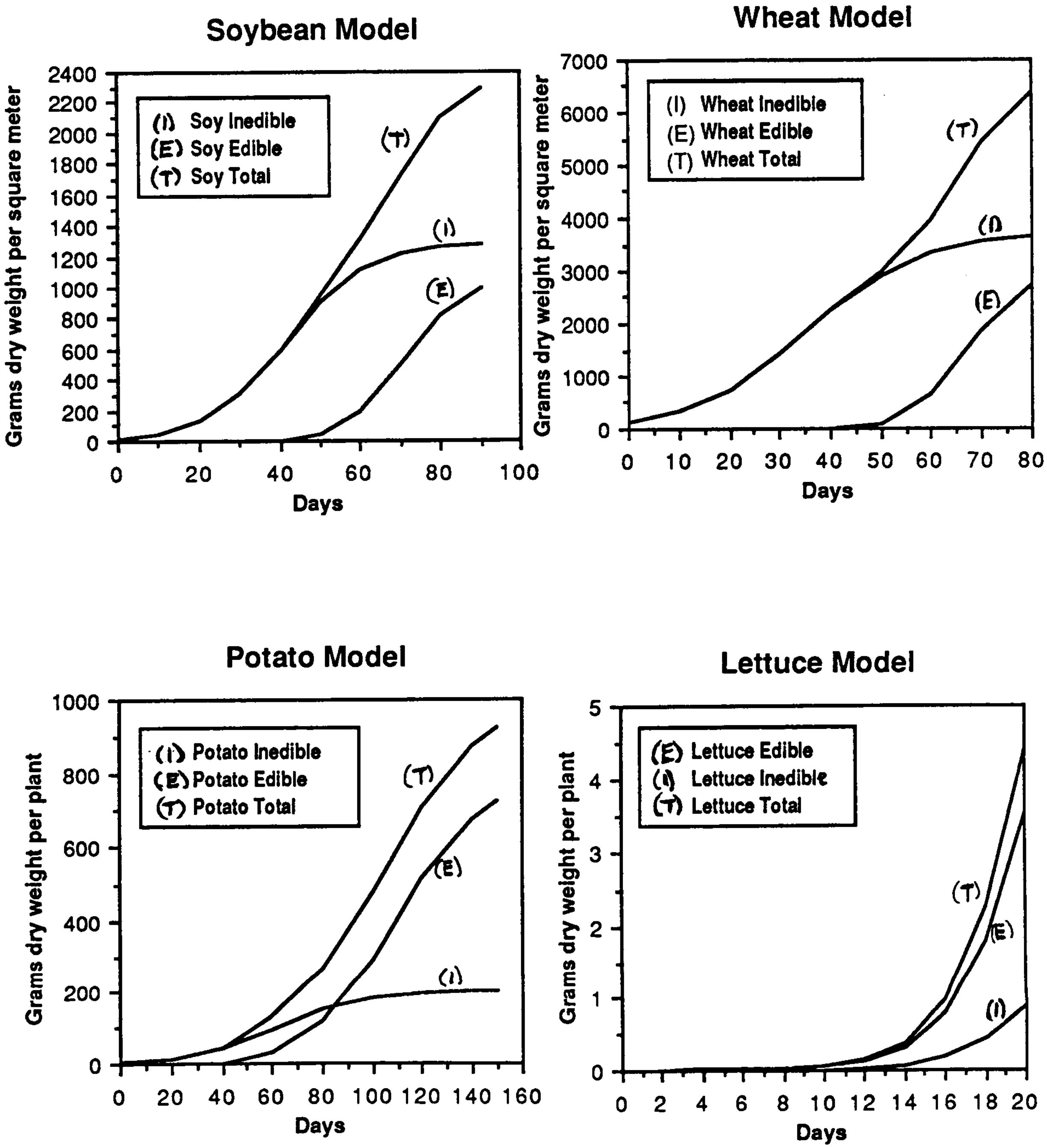

Figure 7. Models for the four crops. Eqns (1a-c) were used for soybean, wheat, and potato models. Eqns (2a-c) were used for lettuce. Parameters are in Table 2. (Curves are smoother than shown here.) The wheat parameters were adjusted to obtain curves close to those of the data with "PPF=1200" in Figure 2. The potato parameters were adjusted to obtain curves close to those of the data with "dry, 24 hr" in Figure 4. Closer fits are obviously possible; but the purpose at hand is to demonstrate the potentials of a generic crop model.

Volk and Rummel (1987) list formulas for protein, carbohydrate, lipid, fiber, and lignin that can be placed into balanced equations for carbon, hydrogen, oxygen, and nitrogen. It is therefore possible to calculate the uptake of CO_2, H_2O, and HNO_3, and the production of O_2 by the crops. Per unit mass of biomass, these compounds vary as a function of the biomass's fractional distribution of protein, carbohydrate, lipid, fiber, and lignin. The details of the calculation is not shown here; please contact me if interested. Table 2 shows the mass balances for the four crop models. Note the substantial differences betweeen, for example, the CO_2 required and O_2 produced per gram of edible soybean vs. per gram of edible wheat. This difference is due primarily to the difference in lipid content. Such differences represent differences in the fluxes of these materials between the crops and their environments, and will presumably be important in the engineered hardware designs with respect to how similar or different the hardware must be for the various crops.

The balances in table 2 were used with the crop growth models (see program diagram in figure 6) to calculate the fluxes of CO_2, H_2O, HNO_3, and O_2 during growth; these fluxes are shown in figure 8. Note the different shapes for the crops. Such actual curves will be known during the operation of a CELSS (for example, since CO_2 will be monitored and maintained at desired levels in the crop's atmosphere, the amount of CO_2 injected to maintain these levels will be known). Due to the characteristic patterns of these fluxes, it may be possible to tie this knowledge into monitoring systems of state of the whole crop. Note that these curves assume a constant percentage of protein, carbohydrate, lipid, fiber, and lignin for the edible and inedible during their respective growths. This is clearly not the case as seen in the decrease in leaf nitrogen in the hydroponic wheat during seed growth (Bugbee and Salisbury, 1987). Obviously the next step is to let this nitrogen difference represent a decrease in the edible parts' protein in the late stage of growth, and it would be informative to see how much this affects the CO_2, H_2O, HNO_3, and O_2 fluxes. We could tell how much uncertainty in composition over time affects the fluxes, and therefore if we know how accurately the fluxes need to be predicted, this would give requirements for the data.

Table 2. Mass Balances for Crop Models

Mass Types	Wheat	Soybean	Potato	Lettuce
Edible Mass Fractions				
protein	0.21	0.45	0.13	0.26
digest. carbo.	0.74	0.30	0.84	0.12
lipid	0.02	0.25	0.00	0.06
fiber	0.03	*	0.03	0.56
lignin	0.00	*	0.00	0.00
Edible Mass Balances (g/g-dry-biomass)				
CO_2 (in)	1.651	2.102	1.572	1.822
H_2O (in)	0.582	0.662	0.585	0.570
HNO_3 (in)	0.160	0.343	0.099	0.198
O_2 (out)	1.393	2.107	1.256	1.590
Inedible Mass Fractions				
protein	0.09	0.17	0.19	0.11**
digest. carbo.	0.14	0.80	0.30	0.11**
lipid	0.00	0.03	0.00	0.00**
fiber	0.72	*	0.45	0.78**
lignin	0.05	*	0.06	0.00**
Inedible Mass Balances (g/g-dry-biomass)				
CO_2 (in)	1.720	1.632	1.755	1.681
H_2O (in)	0.561	0.595	0.556	0.554
HNO_3 (in)	0.068	0.129	0.144	0.084
O_2 (out)	1.349	1.356	1.455	1.319

* fiber and lignin were included in the soybean carbohydrate data
** values were assumed by T. Volk

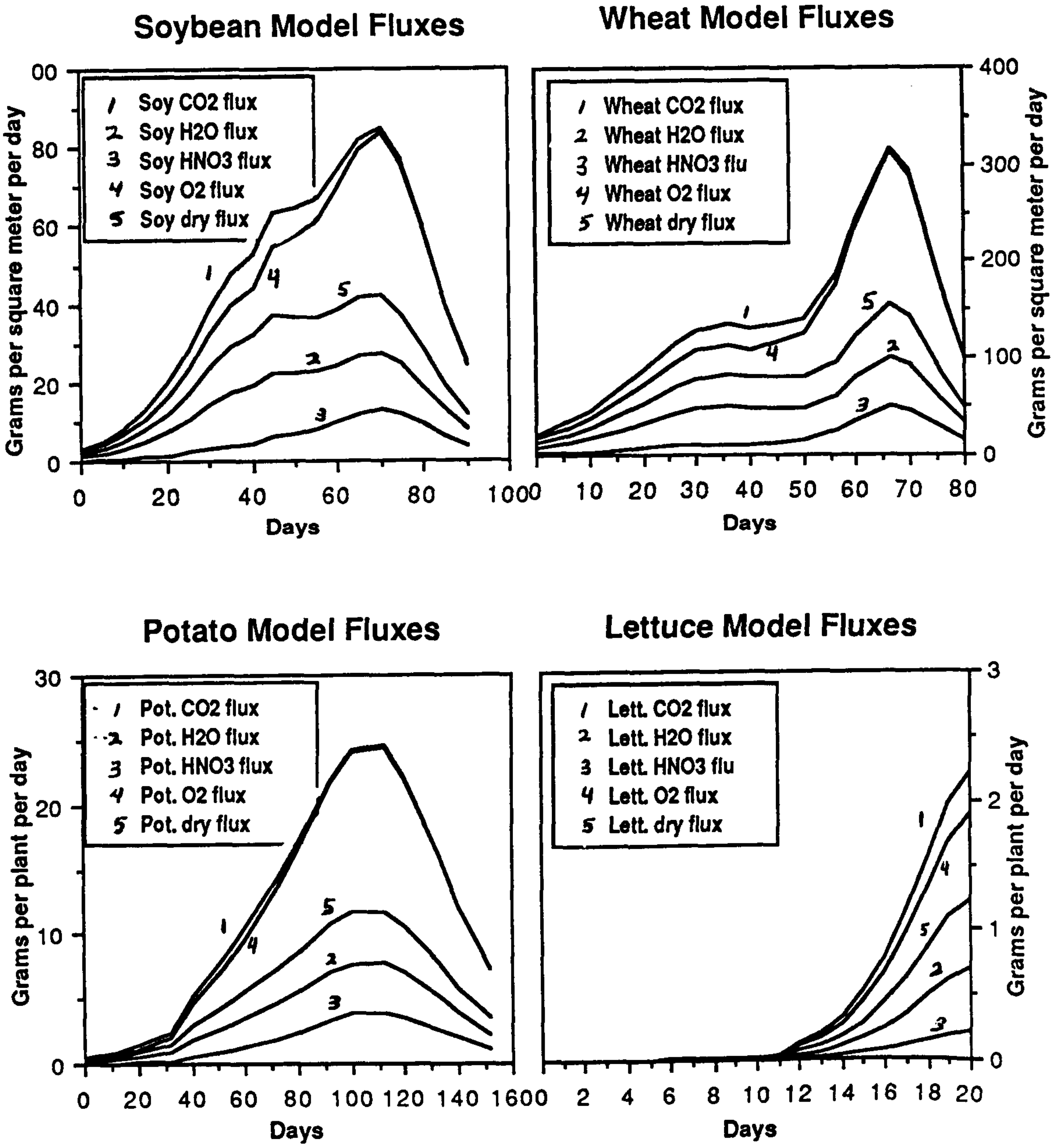

Figure 8. Fluxes for the four crop models: CO_2, metabolic H_2O, nutrient HNO_3, O_2 produced, and total dry weight biomass (edible plus inedible). Note different units for the different crops. Fluxes are from the models of Figure 7 using the stoichiometries of Table 2.

CONCLUSION

A simple generic model has been demonstrated that can emulate the growth dynamics of four different candidate crops for Controlled Ecological Life Support Systems and provide mass fluxes associated with these growing crops for incorporation into a whole-system CELSS model . That the model at this stage is simple is significant; an initial simplicity is desirable because the model will tend to quickly become more complex when it incorporates additional refinements, particularly sensitivities to environmental variables. There is every reason to expect that a generic model like the one demonstrated here will be useful in constructing a model system for studying the dynamics of a space farm. Combining the crops into such a farm could be a subsequent step from this study.

Another next step is to incorporate the above-mentioned refinements. It is obvious that by adjusting the parameters in eqns (1a-c), fits to the other growth curves shown for wheat and potatoes in Figures 2 and 3 could be obtained. The model parameters, such as growth rates, r_i's, and ultimate biomasses, K_i's, are not constant, but must be functions of environmental conditions. A reasonable approach would be to develop the environmental functionality of these parameters along lines of classical mathematical treatments of photosynthesis, such as in Gates (1980), wherever possible. That way the data--for example, the variation of growth with light shown in figures 2 and 4 for wheat and potatoes--would not be used for fitting, but rather for model validation. Transpiration submodels and the relationship between atmospheric pCO2, humidity, nutrient uptake, and growth, need to be developed in order for the various design tradeoffs between energy, volume, etc. to be investigated. The model shown here could serve as a basis for further development.

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