CROP GROWTH AND ASSOCIATED LIFE SUPPORT FOR A LUNAR FARM

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Supporting human life on a lunar base will require growing many different food crops. This paper investigates the growth dynamics of four crops (wheat, soybeans, potatoes, and lettuce) for general similarities and differences, along with associated material flows of the gases, liquids, and solids in a lunar farm. The human dietary requirements are compared with the protein, carbohydrate, and lipid contents of these hydroponically grown, high-productivity crops to derive a lunar farm diet. A simple and general analytical model is used to calculate the mass fluxes of CO_2, H_2O, HNO_3, and O_2 during the life cycle of each of the four crops. The resulting farm crop areas and corresponding biomass production rates are given. One significant conclusion of this study is that there is a "lipid problem" associated with the incorporation of these four crops into a viable diet.

INTRODUCTION

Following the return of our astronauts to the lunar surface around the turn of the twenty-first century, an outpost for temporary habitation could evolve into a permanently occupied base on the Moon (*Ride*, 1987). The major human life support needs will have to be met at increasingly self-sufficient rates during this evolution. The pathways leading to a lunar farm are yet to be defined in the habitat development scenarios.

Human diets for a lunar base can be provided with hundreds of foods. Here, however, we will focus on four crops studied in the NASA Controlled Ecological Life Support Systems (CELSS) Program: lettuce, potatoes, soybeans, and wheat. Substantial data have been generated on the response of these crops to variables important in future space agriculture such as near-maximally achievable planting density, light intensities and schedules, and atmospheric CO_2 levels. Additional experimental data for these crops were received in 1987 through personal communication with CELSS researchers B. Bugbee, C. Mitchell, D. Raper, R. Wheeler, and S. Schwartzkopf. Information received included environmental conditions for both the aerial and root plant parts in particular high-yield experiments. Figure 1a shows the composition of the edible portions of lettuce, potatoes, soybeans, and wheat in terms of the three major food types, protein, carbohydrate, and lipid.

To incorporate these crops into a farm, we consider the dietary needs that must be met by the candidate crops. Figure 1b shows the protein, carbohydrate, and lipid requirements of two standard satisfactory diets. More detailed dietary breakdowns, such as essential amino acids, fatty acids, and vitamins are beyond the scope of this study. Even though each diet provides 2700 kcal per day per person, the relative fractions of calories obtained from proteins and lipids are different. By comparing the compositions of the crops (Fig. 1a) with those of the diets (Fig. 1b), a lipid problem becomes evident.

The lipid problem arises because both standard diets contain more lipid than protein. Diets with lower lipid than those used here might be desirable (*Roberts*, 1988). Because none of the four crops contains more lipid than protein, any allotment we make using these crops to fulfill the total lipid requirements will concomitantly have an excess of protein. Waste such as this would be detrimental to a space agriculture prescribed by energy and mass constraints.

CROP MODEL DEVELOPMENT

Simulation models help us conceptualize and design new systems by using a mathematical framework to assemble components for investigating specific system-level issues. Previous work along these lines developed a model (called BLSS) for a CELSS that grows wheat as the sole crop (*Volk and Rummel*, 1987; *Rummel and Volk*, 1987). BLSS can be used to track the flow of carbon, hydrogen, oxygen, and nitrogen through the various processes in a CELSS because it contains the stoichiometries for various compounds such as plant protein and human urine. The model grows wheat in a variety of planting schemes, with different numbers and sizes of simultaneous batches. Different schemes produce different magnitudes of fluctuations in the standing biomass and in the buffer mass reservoirs of CO_2, H_2O, HNO_3, and O_2.

Here we extend this approach to include lettuce, potatoes, and soybeans also. Figure 2, along with the model results still to be discussed, shows selected and typical data for the growth of the edible and inedible parts (to humans) of each crop. A breakdown of biomass into edible and inedible parts is fundamental in a CELSS because of the consequent separation of material flows.

Many crop growth curves prominently show an S-shaped or sigmoidal curve typical of biological systems. The logistic differential equation $dC/dt = rC(1\text{-}C/K)$ imitates this S-shape of exponential growth followed by a leveling off. The term C is biomass, t is time, r is growth rate for the purely exponential part of the system, and K is a "negative feedback" from the growth process itself, an environmentally modifiable but inherent (genetically based) slowing of the total growth rate (dC/dt) by the approach of the crop to its mature size. The logistic equation thus contains some biologically meaningful parameters and is chosen to represent the growth of the inedible crop parts.

The equation for the edible crop parts must be somewhat differently structured. The edible cells, like the inedible ones, reproduce, so the total edible growth is set proportional to the edible mass. Furthermore, the nonphotosynthesizing edible parts (except for lettuce; see below) grow using products from photosynthesis by the inedible parts (the leaf mass); therefore, the inedible biomass (M_{ined}) should also appear in the edible equation. Also, the edible growth occurs substantially after the beginning of the inedible growth (see Fig. 2), so a switch-on time (t^*) is used in the formulation for edible growth. The edible biomass (M_{ed}) is assumed to be equal to zero before t^* and to start its growth at t^* with minimum edible mass (E_{min}). With these considerations we write

$$\text{all } t: \quad \frac{dM_{ined}}{dt} = r_{ined}\, M_{ined}\left(1 - \frac{M_{ined}}{K_{ined}}\right) \tag{1a}$$

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

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

The parameters t and t^* are in units of time, while r_{ined} and r_{ed} in time^{-1} and the remainder in mass (see Table 1). For wheat, soybean, and potato we use equations (1a) to (1c). Because the edible and inedible parts develop together, the parameter t^* is defined differently for lettuce. *Mitchell et al.* (1986) found that the growth rate increases by more than a factor of two at about 11 days; therefore we define $r_{ed,2}$ and $r_{ed,1}$ for $t > t^*$ and $t < t^*$, respectively. The equations become for lettuce

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

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

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

These models were run in a computer program and the results generated were compared to the experimental crop data. Adjustments were made to the parameters until the models agreed reasonably with the data. The parameters used for each crop are listed in Table 1, while the model outputs are shown in Fig. 2.

The output curves demonstrate that it is relatively easy to represent the data with a model whose parameters have some fundamental biological meaning. Table 1 lists the actual planting mass for the crops, but we need to investigate further the data at t = 0 to determine whether they correspond to the initiation of the crop from seed or tissue or to the transplanting time after initial seeding growth. Some further adjustment might be necessary to account for the physical meaning of time t = 0.

Additional refinements are possible. Better fits to the growth curves shown for wheat and potatoes in Fig. 2 are obtainable. More importantly, the model parameters, such as growth rates

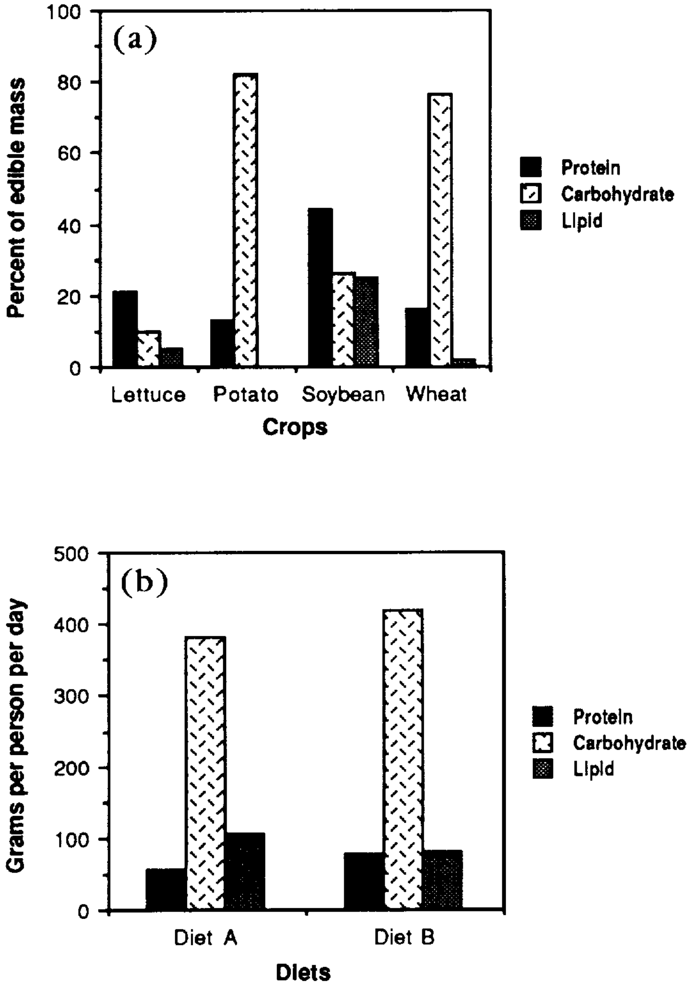

Fig. 1. (a) Compositions of lettuce leaves, potato tubers, soybeans, and wheat berries for typical high-yield hydroponic growth experiments. Data provided by CELSS researchers C. Mitchell (lettuce), R. Wheeler (potatoes), D. Raper (soybeans), and from *Bugbee and Salisbury* (1988, wheat). The balancing components of fiber and ash are not shown. (b) Compositions of two possible diets. Diet A is from the 1980 Recommended Dietary Allowances and Estimated Safe and Adequate Daily Dietary Intake, using American Heart Association recommendations of 35% of food kcal from fat (*Krause and Mahan*, 1980). Diet B uses the NIH recommendations (C. Mitchell, personal communication, 1988) of 0.5 g protein per day per lb of body mass and using lower value of the recommended 30-50% of nonprotein food kcal as lipid to give lower lipid, higher protein diet to contrast with diet A. Both diets are approximately for a 155-lb individual having 2700 kcal per day.

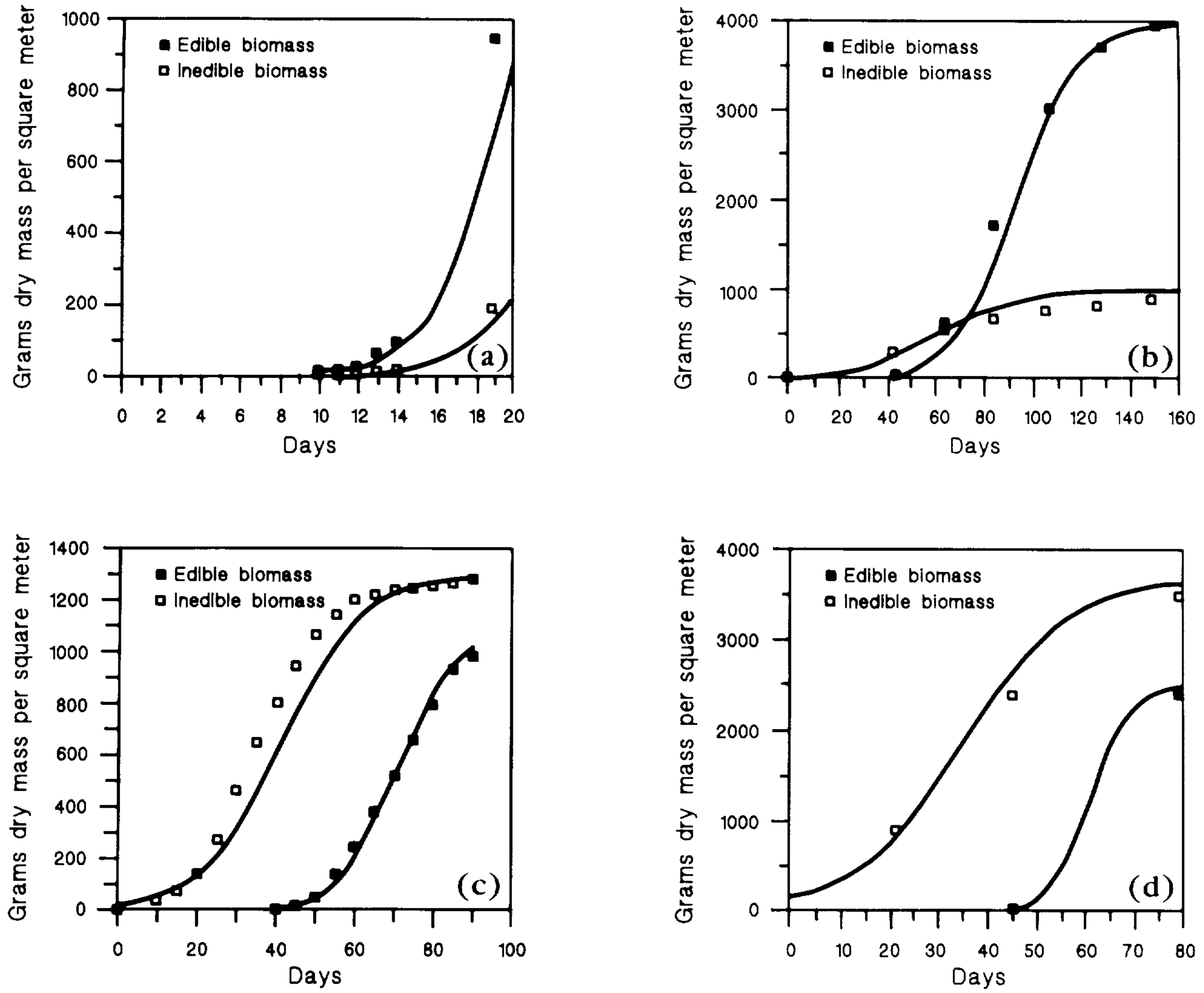

Fig. 2. Models of crop growth using parameters from Table 1, compared to crop growth data. **(a)** Lettuce data are from *Mitchell et al.* (1986) at 1000 ppm CO_2 and 450 $\mu mol/m^2$-sec of PPF [data were given per plant and adjusted here to yield leaf production of 60 g/m^2-d (C. Mitchell, personal communication, 1987)]. **(b)** Potato data are from *Wheeler and Tibbitts* (1987) for dry mass production under 24-hour continuous light at 300 $\mu mol/m^2$-sec PPF (assume 5 plants per m^2). **(c)** Soybean data are from D. Raper (personal communication, 1987) grown at 700 $\mu mol/m^2$-sec PPF and 400 ppm CO_2 (data were interpolated by D. Raper to be in equal time intervals). **(d)** Wheat data are from B. Bugbee (personal communication, 1987) for plants grown at 1200 $\mu mol/m^2$-sec and 1200 ppm CO_2 (see also *Bugbee and Salisbury,* 1988). Data represent individual growth experiments, not necessarily the maximum yields ever obtained. Model parameters were not adjusted to achieve exact fits to growth data, rather to demonstrate the utility of equations (1) and (2) in providing a relatively simple method of generating growth curves to determine gas and fluid fluxes applicable for including plants in systems models.

TABLE 1. Parameters for crop models.

Parameter	Wheat	Soybean	Potato	Lettuce
r_{ined} (day^{-1})	0.09	0.10	0.06	same as r_{ed}
r_{ed} (day^{-1})	0.17	0.10	0.30	$r_{ed,1} = 0.2$, $r_{ed,2} = 0.5$
K_{ined}	3700.0	1300.0	1000.0	1000.0
K_{ed}	2500.0	1100.0	4000.0	5000.0
E_{min}	80.0	80.0	400.0	X
$M_{ined,o}$	150.0	20.0	25.0	X
$M_{ed,o}$	0.0	0.0	0.0	2.0
t^* (days)	45.0	45.0	40.0	11.0

Units for K_{ined}, K_{ed}, E_{min}, $M_{ined,o}$, $M_{ed,o}$ are g dry mass m^{-2}.

(r_is) and ultimate biomass (K_is), are not constant, but are functions of environmental conditions. A reasonable approach could be to develop these parameters along the lines of classical mathematical treatments of photosynthesis, such as in *Gates* (1980), wherever possible. That way the data would not be used for fitting, but rather for model validation. Transpiration submodels and the relationships between atmospheric pCO_2, humidity, nutrient uptake, and biomass growth need to be developed for investigation of the various design tradeoffs between energy, mass, and volume. The models shown here would serve as a basis for further developments.

Volk and Rummell (1987) listed formulas for protein, carbohydrate, lipid, fiber, and lignin that can be placed into

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balances equations containing 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. These compounds vary as a function of fractional distribution of protein, carbohydrate, lipid, fiber, and lignin in the biomass. Table 2 shows the mass balances for the four crop models. For example, note the substantial differences between soybean and wheat in the CO_2 required and the O_2 produced per gram of edible biomass produced. This difference is due primarily to the difference in lipid content. There are corresponding differences in the fluxes of these materials between the crops and their environments. These fluxes are important in the design of engineered hardware for the various crops.

The balances in Table 2 were used with the crop growth models to calculate the fluxes of CO_2, H_2O, HNO_3, and O_2 during growth; these fluxes are shown in Fig. 3. Note the different curves for the crops. Such curves will be produced during the actual operation of a CELSS (e.g., if 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 is possible to relate this information to the monitoring system for the state of the whole crop. Note that these curves assume a constant percentage of protein, carbohydrate, lipid, fiber, and lignin for the edible and

TABLE 2. Mass balances for crop models.

Mass Types	Wheat	Soybean	Potato	Lettuce
Edible Mass Fractions				
Protein	0.17	0.45	0.13	0.26
Digestible Carbohydrate	0.78	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
Fluxes During Edible Biomass Production (g per g dry biomass)				
CO_2 (in)	1.62	2.10	1.57	1.82
H_2O (in)	0.59	0.66	0.58	0.57
HNO_3 (in)	0.13	0.34	0.10	0.20
O_2 (out)	1.34	2.11	1.26	1.59
Inedible Mass Fractions				
Protein	0.09	0.17	0.19	0.11†
Digestible Carbohydrate	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†
Fluxes During Inedible Biomass Production (g per g dry biomass)				
CO_2 (in)	1.72	1.63	1.75	1.68
H_2O (in)	0.56	0.59	0.56	0.55
HNO_3(in)	0.07	0.13	0.14	0.08
O_2 (out)	1.35	1.36	1.45	1.32

* Fiber and lignin were included in the soybean carbohydrate data.

† Values assumed by T. Volk.

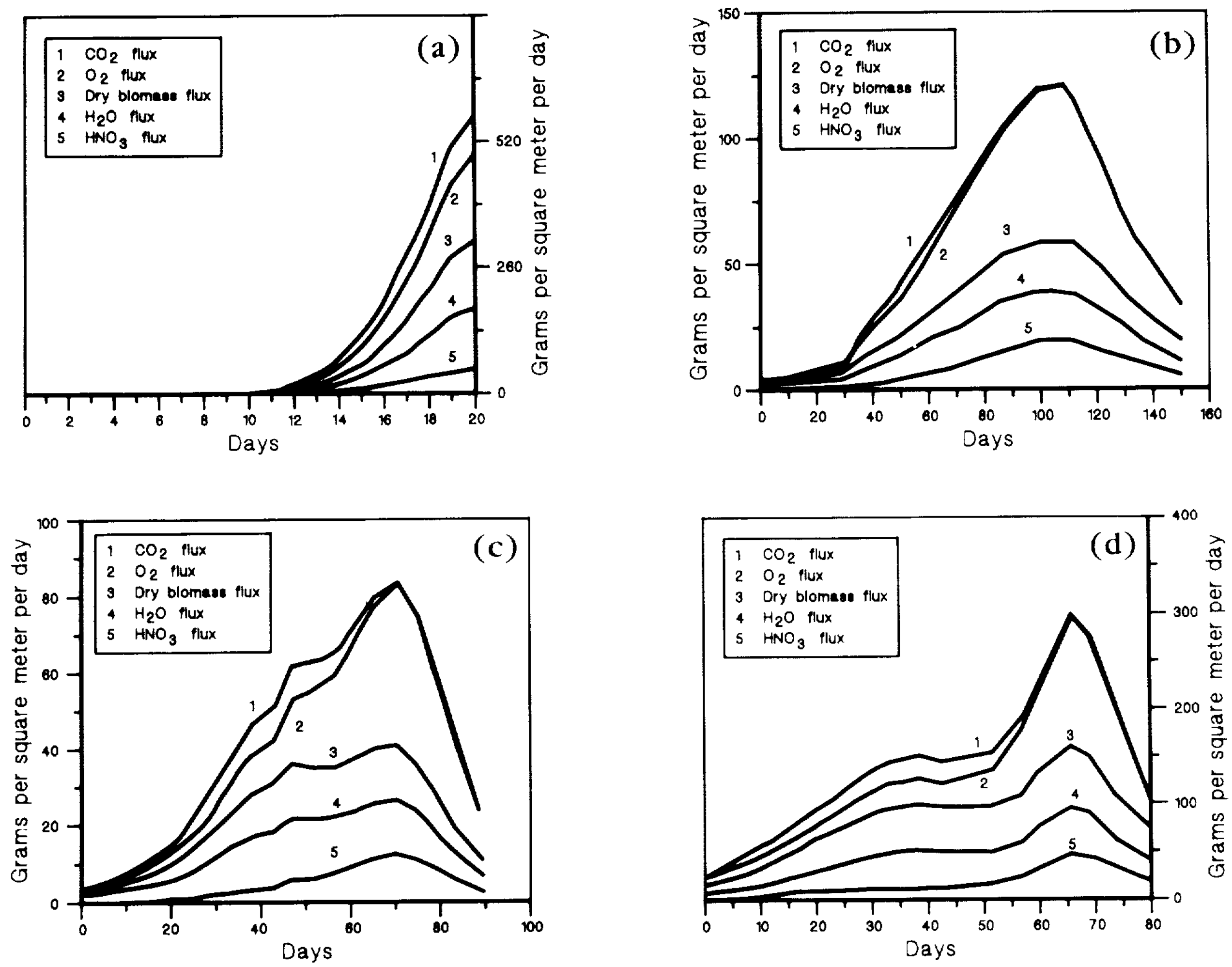

Fig. 3. Fluxes of CO_2, metabolic H_2O, nutrient HNO_3, O_2 produced, and total dry weight biomass (edible plus inedible) for the four crop models: **(a)** lettuce; **(b)** potato; **(c)** soybean; and **(d)** wheat. Note different units for the different crops. Fluxes are from the models of Fig. 2 using the stoichiometries of Table 2.

inedible during their respective growths. That this is clearly not the case is seen in the decrease in leaf N during the seed growth in the hydroponic wheat (*Bugbee and Salisbury,* 1988). A next step here would be to let this N change represent a decrease in the protein of the edible parts during the late state of growth and to see how much this decrease affects the CO_2, H_2O, HNO_3, and O_2 fluxes.

LUNAR FARM DISCUSSION

The crops can be incorporated into a collective model for the entire farm, assuming the relative areas and volumes for each crop are known. We now assemble the four crops into a diet following a particular logic. We first assume that a person could consume 10 g of dry biomass of lettuce leaf per day. Furthermore, to use all four crops and take advantage of the complete protein created by the combination of grains (wheat) and legumes (soybean), we assume equal contributions from potatoes, wheat, and soybean to meet the daily protein requirements. After satisfying the protein requirements, the next critical component is lipid. The only crop with substantial lipid is soybean, so additional soybean is added to bring the total lipid up to the target values for the two diets. All these results are summarized in Table 3.

The protein and lipid requirements are now satisfied, but carbohydrate is still short. Potatoes have a significant fraction of carbohydrate, with a ratio of carbohydrate to protein approximately the value required by the diets. The final step in forming the diet, therefore, is to add potatoes until the target value for carbohydrate is reached; but this adds still more protein. As seen in Table 3, the mix of crops to yield 100% of the target values for protein and lipid results in an excess of protein, with total protein now about 400% and 250% of the respective requirements for diets A and B.

By considering the areas required to grow each crop, the total farm area for the life support system can be estimated (see Table 4). The per-area productivity for each crop used in this computation was taken from the data used in Fig. 2. Note that some of these crops have been grown at higher productivities; wheat, for example, has been grown at double the productivity shown by increasing the light level (*Bugbee and Salisbury,* 1988). Thus higher light levels might yield still higher productivities. Light will probably be a useful control parameter for temporarily increasing the yields following crop failure or equipment downtime when storage reservoirs need increased rates of replenishment. Thus the productivities shown in Table 4 were deliberately chosen not to be the maxima. For one thing, the

TABLE 3. Assembly of a lunar farm diet with four crops.

Crop	Diet A				Diet B				Rationale
	Protein	Carbohydrate	Lipid	Dry Mass	Protein	Carbohydrate	Lipid	Dry Mass	
Lettuce	2.1	1.0	0.5	10.0	2.1	1.0	0.5	10.0	Assume 10 g dry mass person^{-1} day^{-1}
Potato	18.7	118.0	0.0	143.8	25.8	162.8	0.0	198.5	Assume 1/3 target protein[*] supplied
Soybean	18.7	11.0	10.6	42.5	25.8	15.2	14.7	58.6	Assume 1/3 target protein supplied
Wheat	18.7	87.7	2.2	114.7	25.8	121.0	3.1	158.3	Assume 1/3 target protein supplied
Soybean	160.9	94.9	91.7	365.7	107.7	63.6	61.4	244.8	Add soy until lipid target[†]
Potato	11.1	70.4	0.0	85.4	8.6	54.4	0.0	73.8	Add potato until carbohydrate target[‡]
Total	230.2	383.0	105.0	762.1	195.8	418.0	79.7	744.0	
% target	411	100	100		253	100	100		

[*] Target values for protein are 56 g day^{-1} for diet A and 77.5 g day^{-1} for diet B (see Fig. 1).
[†] Target values for lipid are 105 g day^{-1} for diet A and 79.7 g day^{-1} for diet B (see Fig. 1).
[‡] Target values for carbohydrate are 383 g day^{-1} for diet A and 418 g day^{-1} for diet B (see Fig. 1).
All values except percentages are in g person^{-1} day^{-1}.

TABLE 4. Illustrative crop areas for the lunar farm.

Crop	Productivity of edible mass[*] g m^{-2} day^{-1}	Diet A			Diet B		
		Required edible production g person^{-1} day^{-1}	Growing area per person m^2	Growing area for 12 people m^2	Required edible production g person^{-1} day^{-1}	Growing area per person m^2	Growing area for 12 people m^2
Lettuce	60	10	0.2	2.4	10	0.2	2.4
Potato	27	229.2	8.5	102.0	272.3	10.1	121.2
Soybean	11	408.2	37.1	445.2	303.4	27.6	331.2
Wheat	30	114.7	3.8	45.6	158.3	5.3	63.6
Total		762.1	49.6	595.2	744.0	43.2	518.4

[*] Productivities are illustrative only, not maximum for each crop. Wheat, for example, has been grown as high as 60 g m^{-2} day^{-1}, but the value of 30 is used here so higher illumination could be used as a control to allow for higher production under unusual circumstances. It will be assumed that the other crops are similar in having higher productivities in conditions still to be investigated.
[†] Note this amount of soybeans creates a wasteful excess of edible protein (see Table 3).

maxima are not yet known. For another, the production rates during normal operations will be less that the maxima to allow the system to be controlled when storage reservoirs need to be readjusted. The productivities used here are representative of hydroponic crop yields that could be accomplished with today's technology.

As apparent in Table 4, using all the preceding calculations with attendant assumptions, most of the area of a lunar farm will be dedicated to soybeans (75% for diet A, 64% for diet B). This is a direct result of using soybeans to match the lipid requirements.

CONCLUSIONS

We have shown that a simple, generic crop model can represent the growth of four different candidate crops for Controlled Ecological Life Support Systems, providing mass fluxes associated with growth for any whole-system CELSS model. 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 new model system for studying the dynamics of a space farm.

An important problem exists in attempting to combine the four crops of lettuce, potatoes, soybeans, and wheat into an adequate diet. Besides being bland, there will be a serious overproduction of protein. Either diets with much lower lipid content than those shown must be designed and approved, or other crops with a higher lipid-to-protein ratio should be included. Rapeseed, for example, is about 50% lipid and about 20% protein; peanuts can be grown with as high as 54% lipid and as low as 21% protein (C. Mitchell, personal communication, 1988). If these crops were used to satisfy the lipid requirements, protein excess could be avoided. Unfortunately, little is known about the behavior of these crops in high production hydroponics. We recommend systematic crop growth experiments aimed at a balanced diet with minimal waste.

REFERENCES

Bugbee B. G. and Salisbury F. B. (1988) Exploring the limits of crop productivity I. Photosynthetic efficiency of wheat in high irradiance environments. *Plant Physiol.*, *88*, 869-878.

Gates D. M. (1980) *Biophysical Ecology.* Springer-Verlag, New York. 611 pp.

Krause M. V. and Mahan L. K. (1980) *Food Nutrition and Diet Therapy: A Textbook of Nutritional Care,* 7th edition. W. B. Saunders, Philadelphia. 525 pp.

Mitchell C. A., Knight S. L., and Fort T. L. (1986) Optimization of controlled environments for hydroponic production of leaf lettuce for human life support in space. In *NASA-TM-88215,* pp. 499-521.

Ride S. K. (1987) *Leadership and America's Future in Space: A Report to the Administrator.* U.S. Govt. Printing Office, Washington, DC. 63 pp.

Roberts L. (1988) Diet and health in China. *Science, 240,* 27.

Rummel J. D. and Volk T. (1987) A modular BLSS simulation model. *Adv. Space Res.*, *7,* (4)49-(4)67.

Volk T. and Rummel J. D. (1987) Mass balances for a biological life support system simulation model. *Adv. Space Res.*, *7,* (4)141-(4)148.

Wheeler R. M. and Tibbitts T. W. (1987) Utilization of potatoes for life support systems in space: III. Productivity at successive harvest dates under 12-h and 24-h photoperiods. *Am. Potato J.*, *64,* 311-320.