SCENARIOS FOR OPTIMIZING POTATO PRODUCTIVITY IN A LUNAR CELSS

N93-13997

R. M. Wheeler

NASA Biomedical Operations and Research
Kennedy Space Center FL 32899

R. C. Morrow, T. W. Tibbitts, and R. J. Bula

Wisconsin Center for Space Automation and Robotics
University of Wisconsin
Madison WI 53715

The use of controlled ecological life support systems (CELSS) in the development and growth of large-scale bases on the Moon will reduce the expense of supplying life support materials from Earth. Such systems would use plants to produce food and oxygen, remove carbon dioxide, and recycle water and minerals. In a lunar CELSS, several factors are likely to be limiting to plant productivity, including the availability of growing area, electrical power, and lamp/ballast weight for lighting systems. Several management scenarios are outlined in this discussion for the production of potatoes based on their response to irradiance, photoperiod, and carbon dioxide concentration. Management scenarios that use 12-hr photoperiods, high carbon dioxide concentrations, and movable lamp banks to alternately irradiate halves of the growing area appear to be the most efficient in terms of growing area, electrical power, and lamp weights. However, the optimal scenario will be dependent upon the relative "costs" of each factor.

INTRODUCTION

The establishment of bases on the surface of the Moon has been identified as one of the primary initiatives to be pursued by NASA (*Ride*, 1987). Potential economic benefits from mining the lunar surface may provide an additional impetus for establishing these bases (*Kulcinski*, 1988). As lunar outposts increase in size, the high cost of resupply from Earth will make it imperative to reduce the quantity of these resources. Controlled ecological life support systems (CELSS), systems that recycle chemical and biological resources necessary to support human life, will therefore come to play a crucial role in the long-term support of these bases (*Ride*, 1987).

Green plants (primarily various algae and higher plants) will play an integral part in a CELSS because the process of photosynthesis utilizes radiant energy (400-700 nm) to convert carbon dioxide and water into carbohydrates and oxygen. In addition to removing carbon dioxide from the atmosphere and producing food and oxygen, higher plants can purify water through the process of transpiration. The gravitational field of the Moon should be sufficient to allow the production of higher plants using systems that have been adapted from the technologies used for controlled-environment plant growth on Earth (*Bula et al.*, 1987).

Several species of higher plants have been selected for study as possible CELSS candidate crops (*Tibbitts and Alford*, 1982). One of these species is the white, or Irish potato (*Solanum tuberosum L.*). Potato exhibits several characteristics that are of value in a CELSS (*Tibbitts and Wheeler*, 1987), including high rates of productivity and a high ratio of edible to inedible biomass (high harvest index). In addition, they are a good quality food source (rich in carbohydrates with adequate protein levels), are easily stored for long periods, and can be prepared in a number of culinary forms. There is also a good information base available on potato culture, and a substantial amount of work has been done in recent years to investigate potato productivity and physiology under controlled environments. In general, high tuber yields (tubers being the edible underground portion of the potato) are promoted by short photoperiods (i.e., diurnal cycles with short days and long nights), moderate to high irradiance (1/4 to 1/2 full sunlight), cool temperatures (<20°C), and high carbon dioxide levels (e.g., 1000 ppm). Certain environmental requirements, however, can be offset or compensated for by altering other factors. For example, tubers will form without any dark periods (i.e., continuous irradiation) provided irradiance is sufficiently high and temperatures are cool (*Wheeler and Tibbitts*, 1987a; *Wheeler et al.*, 1986). Also, high carbon dioxide concentrations can partially substitute for high irradiance. When all factors are optimal, yields as high as 40 g m^{-2} day^{-1} of tuber dry matter have been obtained from controlled environments (*Tibbitts et al.*, 1989). This equates to over 200 metric tons (fresh weight) per hectare, or approximately seven times the average field yield in the United States.

In contrast to most traditional agronomic systems, the goal of maximum production per unit area may not be the major concern in a CELSS. Rather, the primary goal will likely be to optimize productivity based on the relative costs of various factors. Thus, it is important to assess various ways in which the growing environment of potatoes might be manipulated to optimize production in relation to the factors that are most likely to be limiting in a lunar CELSS. These include the growing area (or volume) available, electrical power (or possible total energy) availability, and launch weight of the hardware required to support plant growth. The weight of lighting equipment is of particular significance because the cost of transporting lamps for a 30-person CELSS to the lunar surface could run into hundreds of millions of dollars (not including purchase price) at the conservatively estimated launch cost of $10,000 per kilogram (*Koelle*, 1988). Other factors that might be limiting to plant productivity include temperature and humidity control, water and nutrients to support plant growth, inert gases to maintain atmospheric pressure, and reliability and safety considerations.

BASELINE ASSUMPTIONS

To evaluate the tradeoffs between various CELSS environments in terms of growing area, energy efficiency, and initial payload weight, a "baseline" situation needs to be defined. The following assumptions will be made for the purpose of this discussion:

1. ***Potatoes will be the sole biomass producing crop.*** In reality, a true CELSS diet would consist of several different plant species, matched to provide a balanced and interesting diet (*Hoff et al.*, 1982). Eventually, various production scenarios will need to be developed that take into account the integration of the different species used for biomass production in a lunar CELSS.

2. ***Temperature and humidity control, water and nutrients, inert gases, and reliability and safety will be considered nonlimiting.*** More detailed concepts of an actual lunar CELSS are required before the impact of these factors can be evaluated.

3. ***The base will have 30 inhabitants.*** A lunar base with 30 inhabitants has been projected for the year 2010 (*Ride*, 1987). Because the caloric requirement for each inhabitant will be approximately 2800 kcal d^{-1} (*NAS*, 1980), the total needs of all the inhabitants would be on the order of 84,000 kcal d^{-1}. Potatoes provide 3.73 kcal g^{-1} of tuber dry weight (*Watt and Merril*, 1963), so 30 inhabitants would require about 22,5000 g (dry weight) of tubers per day, or about 112 kg (250 lb) of fresh tubers.

4. ***Electrical lamps will be used in a lunar CELSS.*** Although the possibility exists that direct solar radiation can be utilized for plant growth in a lunar CELSS, lamps will still be necessary to provide irradiance during the two-week-long lunar "nights." Currently, one of the most efficient irradiation sources for photosynthetic lighting is the 1000-W high-pressure sodium lamp (*Tibbitts*, 1987). The relationship between lamp input power and the photosynthetically active radiation (PAR) produced can be conservatively estimated at 1 W m^{-2} of lamp input power for each μmol sec^{-1} m^{-2} of PAR produced (The Phytofarm, DeKalb, IL, personal communication, 1987), which is approximately equivalent to a 20% conversion of electricity to PAR. The weight of a 1000-W high pressure sodium lamp (bulb, ballast, and reflector) has been estimated at 20 kg (W. W. Grainger, Inc., 1987 catalog).

5. ***Tuber productivity will follow trends shown in Fig. 1.*** Approximate tuber productivity values in response to various combinations of irradiance, photoperiod, and carbon dioxide level are shown in Fig. 1. These curves are derived from experimental data (*Wheeler and Tibbitts*, 1987a; R. M. Wheeler and T. W. Tibbitts, unpublished data, 1988), though productivity at high and low levels of irradiance are estimations based on related work and past experience.

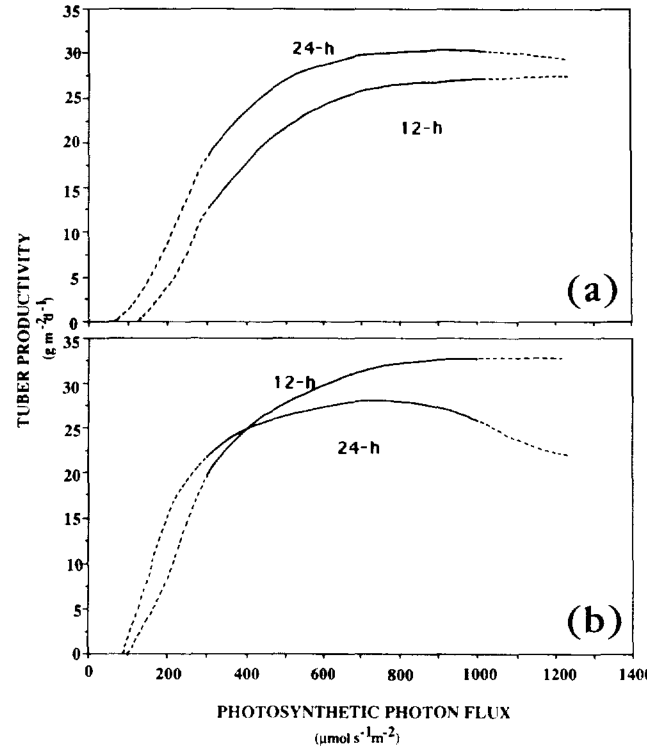

Fig. 1. Potato productivity curves for **(a)** low and **(b)** high carbon dioxide concentrations at various photosynthetic photon flux (irradiance) levels (*Wheeler and Tibbitts*, 1987a; R. M. Wheeler and T. W. Tibbitts, unpublished data, 1988). Productivities at high and low photosynthetic photon flux (broken lines) have been estimated based on related work.

MANAGEMENT SCENARIOS

Fixed Lamps, Low Carbon Dioxide Concentrations

The first set of scenarios involves a fixed lamp arrangement to provide irradiance at 400 and 800 μmol sec^{-1} m^{-2}, 12-hr and 24-hr photoperiods, and "Earth" ambient (350 ppm) or low carbon dioxide levels (Table 1). Those scenarios that utilize high irradiance levels (scenarios 1 and 2) require the least growing area to provide daily caloric requirements, but scenarios utilizing 12-hr photoperiods (scenarios 2 and 4) are most efficient in terms of energy required. Use of continuous, low-level irradiance (scenario 3) requires the least initial lamp weight. Although scenario 1 is the most efficient on an area basis, it is the least efficient on any energy basis and its lamp weight is high. This would be of use in situations where area is limited, but energy and lamp weight are of minimum concern. Scenarios 2 and 3 are equivalent in terms of area and energy efficiency, but the lamp weight for scenario 3 is half that for scenario 2. Scenario 3 would provide a good compromise if all three potentially limiting factors were of equal concern. Scenario 4 is most efficient in terms of energy and is moderate in terms of weight, but it requires a large growing area. This scenario would be useful if growing area were of minimum concern.

Fixed Lamps, High Carbon Dioxide Concentrations

The next set of possible scenarios again assumes fixed lamps but is based on the use of carbon dioxide enrichment to increase the productivity of potato plants under the 12-hr photoperiods to levels nearly equivalent to those observed under the 24-hr photoperiods, essentially substituting for increased irradiance. However, increasing carbon dioxide concentrations has only a small effect on plants grown for 24 hr at 400 μmol sec^{-1} m^{-2}, and no effect on those grown at 800 μmol sec^{-1} m^{-2} (R. M. Wheeler and T. W. Tibbitts, unpublished data, 1988). Using carbon dioxide enrichment, scenario 6 (Table 1) now becomes the most efficient on an area basis, while scenario 8 becomes the most efficient on an energy basis. In addition, carbon dioxide enrichment results in a substantial decrease in the number of lamps required for growing plants under a 12-hr photoperiod. With the use of carbon dioxide enrichment, 12-hr photoperiods show a definite advantage in productivity efficiency compared to the use of 24-hr photoperiods regardless of radiation level. If energy, growing area, and lamp weight were of equal concern, scenario 8 would be the best selection of the scenarios thus presented, including all carbon dioxide level scenarios.

Movable Lamp Arrangement

Because the potential cost of transporting lamps to the lunar surface is so great, it might be desirable to utilize movable lamp banks (*Wheeler and Tibbitts,* 1987b). By breaking the growing area into segments, half the segments could then be irradiated during the first 12-hr period (out of 24 hr) and the other half irradiated during the second 12-hr period. This reduces the number of lamps required by half while maintaining desired productivity levels (Tables 1 and 2, scenarios 10 vs. 4 and 12 vs. 8), and allows continuous use of available power. Alternatively, lamps could be positioned twice as densely to obtain irradiance (with a 12-hr photoperiod) twice that possible by lighting the entire area with the same number of lamps over a 24-hr photoperiod (Tables 1 and 2, scenarios 9 vs. 3 and 11 vs. 7). In fact, if mobility of the lamp bank is not in itself a limiting factor and carbon dioxide can be maintained at high concentrations, it would always be better to double lamp density (~doubling PAR) over half of the growing area (Table 3, column 2 vs. column 1). If area is not as limiting as power or lamps, it would again be better to use alternate 12-hr photoperiods (with movable lamps) but with twice the planted area (Table 3, column 3 vs. column 1). This would provide a productivity level equivalent to two 12-hr yields as compared to one 24-hr yield. If potatoes can be successfully grown under an 8-hr:16-hr light:dark cycle without serious reductions in productivity, three 8-hr photoperiods during each 24 hr might provide even greater increases in growing efficiency. It is noteworthy that if lamp and ballast weights could be reduced (e.g., through the development of small, energy efficient, solid state ballasts), the initial payload weight of lamps might be removed as a primary limiting factor in a lunar CELSS. However, the equipment required to make the lamp banks movable adds an unknown increment of weight that needs to be taken into consideration.

TABLE 1. Management scenarios for optimizing production of the 22,500 g day^{-1} of potato tubers required to satisfy caloric needs for 30 inhabitants in a lunar CELSS using an arrangement of fixed lamps.

Scenario	Irradiance	Photoperiod	Area Requirement	Energy Requirement	Area Efficiency*	Energy Efficiency	Lighting System Weight†
	(μmol sec^{-1}m^{-2})	(hr)	(m^2)	(kWhr d^{-1})	(g m^{-2} d^{-1})	(g kWhr^{-1})	(kg)
Low Carbon Dioxide Concentration (350 ppm)							
1	800	24	776	14,900	29	1.51	12,400
2	800	12	900	8,640	25	2.60	14,400
3	400	24	938	9,005	24	2.50	7,504
4	400	12	1184	5,683	19	3.96	9,472
High Carbon Dioxide Concentration (1000 ppm)							
5	800	24	776	14,900	29	1.51	12,400
6	800	12	726	6,970	31	3.23	11,616
7	400	24	900	8,640	25	2.61	7,200
8	400	12	882	4,234	25.5	5.31	7,056

*Also termed productivity. Adapted from *Wheeler and Tibbitts,* 1987a and Wheeler and Tibbitts, unpublished data, 1988. Values based on the average of 2 cultivars, Denali and Norland.

† Including ballast, bulb, and reflector.

TABLE 2. Management scenarios for optimizing production of the 22,500 g day^{-1} of potato tubers required to satisfy caloric needs for 30 inhabitants in a lunar CELSS using an arrangement of movable lamps.

Scenario	Irradiance	Photoperiod	Area Requirement	Energy Requirement	Area Efficiency*	Energy Efficiency	Lighting System Weight †
	(μmol sec^{-1}m^{-2})	(hr)	(m^2)	(kWhr d^{-1})	(g m^{-2} d^{-1})	(g kWhr^{-1})	(kg)
Low Carbon Dioxide Concentration (350 ppm)							
9	800	alt. 12‡	900	8640	25	2.60	7200
10	400	alt. 12	1184	5683	19	3.96	4736
High Carbon Dioxide Concentrations (1000 ppm)							
11	800	alt. 12	726	6970	31	3.23	5808
12	400	alt. 12	882	4234	25.5	5.31	3528

*Also termed productivity. Adapted from *Wheeler and Tibbitts,* 1987a; and Wheeler and Tibbitts, unpublished data, 1988. Values based on the average of 2 cultivars, Denali and Norland.

† Including ballast, bulb, and reflector.

‡ Alternate 12-hr photoperiods—half the growing area irradiated during the first 12-hr period, half irradiated during the second 12-hr period.

TABLE 3. Comparisons of fixed and movable lamp configurations based on an equal energy input.

Fixed lamp configuration		Movable lamp configurations			
1		2		3	
1 × area*		1 × area†		2 × area‡	
Irradiance	Yield	Irradiance	Yield	Irradiance	Yield
(μmol sec^{-1}m^{-2})	(g m^{-2}d^{-1})	(μmol sec^{-1}m^{-2})	(g m^{-2}d^{-1})	(μmol sec^{-1}m^{-2})	(g m^{-2}d^{-1})
300	18	600	26	2 × 300	30(2 × 15)
400	25	800	28	2 × 400	44(2 × 22)
500	27	1000	29	2 × 500	50(2 × 25)
600	28	1200	30	2 × 600	52(2 × 26)

*Lamps covering entire growing area (1 × density), 24-hr photoperiod.
† Lamps covering 1/2 of the growing area (2 × density). After a 12-hr photoperiod, lamps are moved to other 1/2 of growing area for another 12-hr photoperiod.
‡ Lamps covering 1/2 of the growing area (1 × density), except growing area is *doubled* in size. Therefore, lamps are spaced identically to those in column 1, but are alternated between each half of the growing area as for column 2.

Yield data are averaged over high and low carbon dioxide concentrations and for two potato cultivars, Denali and Norland (*Wheeler and Tibbitts*, 1987a; Wheeler and Tibbitts, unpublished data, 1988).

Other Scenarios

The management scenarios above, while simplified for the purpose of discussion, provide a framework within which additional scenarios can be generated by the manipulation of various factors and then evaluated and compared. For example, some of the lamps used could be placed within the plant canopy to improve the efficiency of irradiation absorption by the plants. This might result in an increase in productivity without a corresponding increase in required power inputs. Another possibility would be to utilize the growing area more efficiently (i.e., reduce the amount of open space between plants during early growth). This could be done by using a variable spacing mechanism, but the complexity of such a system might negate any increase in area-use efficiency obtained. An alternative would be to use an intercropping management system. At the per plant spacing used to determine productivity factors in this discussion (0.2 m^2), potatoes do not form a closed canopy until five to six weeks after planting (*Tibbitts and Wheeler,* 1987). A short season crop, such as lettuce, could be planted in the culture unit between the young potato plants and harvested before the canopy closes. Again, this would increase productivity of the CELSS with minimal additional input.

CONCLUSION

The crop management scenario that is ultimately chosen for a lunar CELSS will depend upon the factor or factors that are most limiting in terms of cost. A lunar base will likely evolve and assume several configurations depending on the stage of development of the base. Therefore, biomass production in the CELSS will be a dynamic process, changing with prevailing base configurations to optimize productivity. For example, as a lunar base expands, the area available for plant growth may become less limiting, thereby favoring those management scenarios that are energy efficient at the expense of area efficiency. However, the increase in growing area might result in factors such as carbon dioxide or lamp weight becoming limiting. Likewise, development of an energy intensive industrial process (i.e., lunar oxygen processing) might require cutbacks in the power available to the plant growing unit. Such a situation would favor a mangement scenario that is very energy efficient.

In any CELSS, maximum crop yield probably will not be the main objective. Rather, obtaining efficient production based on system limitations will be the primary concern. The management scenarios discussed represent an attempt to address crop production in a lunar CELSS from a limiting factor perspective. More detailed evaluation of these and other factors will be needed in order to determine break-even points between development of a CELSS and resupply of life support requirements from Earth. Similar system analyses for all potentially useful CELSS crops will enable the integration of these crops into an overall management program for the lunar CELSS.

REFERENCES

Bula R. J., Corey R. B., Volkweiss S. J., and Tibbitts T. W. (1987) *Concepts for a Commercial Space-based Plant Growth Unit.* WCSAR Tech. Rpt., AR2-8704-1, Madison. 6 pp.

Hoff J. E., Howe J. M., and Mitchell C. A. (1982) *Nutritional and Cultural Aspects of Plant Species Selected for a Controlled Ecological Life Support System.* NASA CR-166324, NASA Ames Research Center, Moffett Field. 125 pp.

Koelle H. H. (1992) The influence of lunar propellant production on the cost-effectiveness of cis-lunar transportation systems. In *The Second Conference on Lunar Bases and Space Activities of the 21st Century,* this volume.

Kulcinski G. L. (1988) Commercial attractiveness of D-He3 fusion reactors. *UWFDM-55,* Univ. of Wisconsin, Madison. 49 pp.

National Academy of Sciences (1980) *Recommended Dietary Allowances,* 9th edition. Natl. Acad. Sci.—Natl. Res. Coun. Publ. No. 2941, Washington, DC. 185 pp.

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.

Tibbitts T. W. (1987) Greenhouse lighting systems: An overview. In *Proc. Natl. Plug Prod. Conf.* (N. H. Agnew, ed.), pp. 61-69. Iowa State University Research Foundation, Inc., Ames.

Tibbitts T. W. and Alford D. K., eds. (1982) *Controlled Ecological Life Support System—Use of Higher Plants.* NASA CP-2231, NASA Ames Research Center, Moffett Field. 84 pp.

Tibbitts T. W. and Wheeler R. M. (1987) Utilization of potatoes in bioregenerative life support systems. *Adv. Space Res., 7,* 115-122.

Tibbitts T. W., Bennett S. M., Morrow R. C., and Bula R. J. (1989) Utilization of white potatoes in CELSS. *Adv. Space Res., 9,* 53-59.

Watt B. K. and Merril A. L. (1963) *Composition of Foods.* USDA-ARS Agric. Handbook No. 8, Washington, DC. 147 pp.

Wheeler R. M. and Tibbitts T. W. (1987a) 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.

Wheeler R. M. and Tibbitts T. W. (1987b) Productivity and cost tradeoffs of various environments for growing potatoes in a CELSS. In *Space Life Sciences Symposium: Three Decades of Life Science Research in Space,* pp. 26-27. NASA, Washington, DC.

Wheeler R. M., Steffen K. L., Tibbitts T. W., and Palta J. P. (1986) Utilization of potatoes for life support systems. II. The effects of temperature under 24-h and 12-h photoperiods. *Am. Potato J., 63,* 639-647.