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THEORETICAL AND PRACTICAL CONSIDERATIONS FOR STAGGERED PRODUCTION OF CROPS IN A BLSS

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ABSTRACT

A functional Bioregenerative Life Support System (BLSS) will generate oxygen, remove excess carbon dioxide, purify water, and produce food on a continuous basis for long periods of operation. In order to minimize fluctuations in gas exchange, water purification, and yield that are inherent in batch systems, staggered planting and harvesting of the crop is desirable. A 418-d test of staggered production of potato cv. Norland (26-d harvest cycles) using nutrients recovered from inedible biomass was recently completed at Kennedy Space Center. The results indicate that staggered production can be sustained without detrimental effects on life support functions in a CELSS. System yields of H_20, O_2 and food were higher in staggered than batch plantings. Plants growing in staggered production or batch production on "aged" solution initiated tubers earlier, and were shorter than plants grown on "fresh" solution. This morphological response required an increase in planting density to maintain full canopy coverage. Plants grown in staggered production used available light more efficiently than the batch planting due to increased sidelighting.

INTRODUCTION

Crop production tests in the Biomass Production Chamber (BPC) at Kennedy Space Center (KSC) for the past eight years have characterized the growth and yield responses of candidate crops though a single life cycle (Wheeler et al., 1996). These studies have supplied information on crop performance under optimal conditions and permitted the characterization of plant responses to environmental parameters at different stages of development (Wheeler et al., 1996). In an operational Bioregenerative Life Support System (BLSS), production of water, oxygen, and food from a closed recirculating resource stream will be required (Drysdale et al., 1994). Two potential methods of production are a series of "batch" plantings, where an entire compartment is planted and harvested at the same time, and a "staggered" planting, where a portion of a compartment is harvested and replanted at a given time.

The potential advantage of continuous production is that the production of food, water, and oxygen should be at a more uniform rate than from a series of batch plantings, thus reducing the size of storage buffers to maintain a system. However, the impact of different aged plants sharing the same atmosphere and nutrient solution for long periods of time is not known. Recent tests in the BPC have concentrated on determining whether staggered production using recirculating, recycled nutrient solutions will have detrimental effects on crop performance in a closed atmosphere (Mackowiak et al., 1994).

A long-term BPC experiment was initiated in June 1994, with the objective being to determine the effect of staggered cropping of potato using potato bioreactor effluent as a primary source of nutrients. We report on the results of the 418-d staggered production experiment and their relationship to estimated production potential.

MATERIALS AND METHODS

Plant material Potato (*Solanum tuberosum* L. cv. Norland) plantlets were transplanted into the growing trays of the Biomass Production Chamber at Kennedy Space Center, FL. All plants were grown using recirculating nutrient film culture as previously described (Wheeler et al., 1990). The pH of the nutrient solution was controlled to near 5.8+/- 0.2 by additions of dilute (2.5%) HNO_3 and nutrient solution temperature was maintained at 18 C in all levels for the duration of the growout. Solution electrical conductivity was controlled near 1.2 dS m^{-1} by additions of a complete nutrient replenishment solution.

A 12-h light cycle was maintained with high pressure sodium (HPS) lamps for the duration of the experiment. The atmosphere was enriched and controlled to 1200 µmol mol^{-1} CO_2 during the light cycle. No effort was made to suppress CO_2 levels during dark cycles. Relative humidity (RH) was maintained at 85% during the first 10-d of the study, then controlled to 70%. Air temperature was maintained at 20 C during the light cycle and 16 C during the dark cycle.

Gas exchange The population gas exchange characteristics related to various environmental conditions were further characterized. The CO_2 concentration (µmol mol^{-1}), CO_2 added to maintain a setpoint of 1200 µmol mol^{-1} (L), and water collected from condensate system (L) were monitored at five-minute intervals. Population CO_2 exchange rates were calculated from the rate of CO_2 increase during the dark cycle and the rate of CO_2 decrease when the lights were turned on. Net assimilation rates were calculated based on the daily rate of CO_2 utilization, determined by the mass flow of CO_2. Transpiration rates were calculated from the rate of condensate collected from the air handling system.

Harvesting The batch production treatment was in the upper chamber of the BPC. All 32 trays of the compartment were planted and harvested at 104-d cycles. Thus, the plants were all the same age during development. The gas exchange and yield of the initial 104-d harvest was used as a control treatment to estimate CO_2 assimilation under staggered production.

The staggered production treatment was in the lower chamber of the BPC. This treatment involved the harvest of eight trays (25%) at 26-d intervals. The trays was replanted at a density of four plants tray^{-1}. The final density of plants tray^{-1} was determined at time of thinning. The nutrient solution was not changed following the harvests.

Plants were harvested in two-tray units from each shelf in the lower chamber, from random, predetermined positions. Following harvest, the fresh mass of leaves, stems, roots and tubers was determined for each plant. The tissue was either freeze-dried or air-dried in a forced air oven at 70 C. When tubers were present, a 100-g subsample was used to determine percent dry mass. Plant height and canopy coverage were manually determined at 7-d intervals.

Table 1: Summary of the life support capabilities of potatoes cv. Norland grown in staggered production for 418 days

	BWP941 Total	Total Normalized	[z]Human Needs	Area for Human
Water[y]	13,552 L	3.2 L m^{-2} d^{-1}	19.0 L d^{-1}	5.9 m^2
CO_2[x]	173 kg	41.4 g m^{-2} d^{-1}	1.0 kg d^{-1}	24.2 m^2
O_2[w]	126 kg	32.5 g m^{-2} d^{-1}	0.83 kg d^{-1}	24.2 m^2
Food[v]	61 kg	14.5 g m^{-2} d^{-1}	0.62 kg d^{-1}	42.8 m^2

[z]Source: NASA SPP 30262 Space Station ECLSS Architectural Control.
[Y]Water need excludes laundry/dish washing requirement.
[x]CO_2 value is the amount assimilated by photosynthetic tissues.
[w]O_2 value is derived from CO_2 and assumes a 1.00 conversion efficiency.
[v]Food values assume that potato tubers are 17% dry matter.

RESULTS AND DISCUSSION

A summary of the water purification, CO_2 removal, O_2 generation, and food production obtained from a 418-d trial of staggered production of potato using recirculating NFT hydroponics is given in Table 1. Yields of each component were higher in the staggered culture than the batch production (Stutte and Sager, 1995). These results indicate that human requirements for H_20 can be met with 5.9 m^2 of growing area, the atmospheric regeneration component required 24.2 m^2, and food (based on calories) can be achieved with 42.8 m^2 growing area. This is 10% less area than required to achieve food requirement with batch production (42.8 m^2 vs. 47.1 m^2).

Staggered production systems should provide a relatively constant output of O_2, H_20, and food once "steady-state" has been achieved. This is in contrast to batch production systems where an entire crop is harvested at a single time. However, most of the data used to characterize the large scale performance characteristics of CELSS candidate crops have utilized batch production systems.

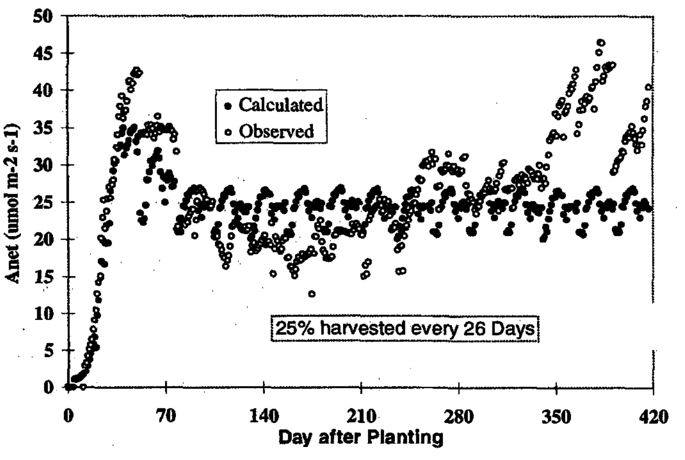

Figure 1: Comparison of calculated and observed CO_2 assimilation rates of potato cv. Norland grown under staggered NFT production.

We attempted to determine whether the information obtained from these batch production tests could be used to the simulate the productivity of crops during staggered production systems. In order to determine the "theoretical" CO_2 removal rates from the atmosphere, the developmental changes in CO_2 fixation obtained from the batch production treatment of BWP941 was assumed to be characteristic of all crops grown in the chamber. The curve was offset at regular 26-d intervals, and appropriate adjustments to planting area were made. The calculated cumulative CO_2 fixation curves were then used as the estimated output of a staggered production system. This "calculated" production curve was compared to the actual results obtained from a 418-d staggered production treatment (Fig. 1). The results indicate that the actual production closely approximated the estimated production rates for most of the growout. During the middle portion of the experiment, the production is reduced because of lower PPF at the canopy level. The reduced PPF is a result of shorter plants that resulted from potatoes sharing a common nutrient solution. Environmental changes which offset this effect were experienced during the final cycle of the experiment, and this is reflected than higher than expected gas exchange rates.

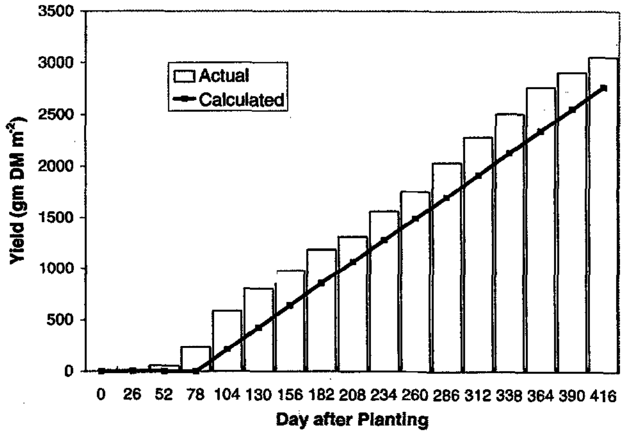

Figure 2: Comparison of calculated and actual cumulative tuber yields, expressed as dry mass, of potato cv. Norland under staggered production.

A similar analysis was conducted with yield, using the initial harvest of the batch production system as the actual data to generate a "theoretical" yield response. As with the gas exchange data, the actual yields exceed the estimates of yield by 8% over the life of the experiment (Fig. 2). This is not to suggest that yields from the batch production were constant, but that the fluctuations tended to balance. Two factors contributed to this increase in yield: The first is that staggered production system opens up the potato canopy, exposing additional leaf area to light. The increase in photosynthetic surface was between 10 and 25% of the total growing area, depending upon height of the plants and height of plants in adjacent trays. This increased light, provides additional energy for fixation of carbon. The second factor is that tubers were initiated earlier on potatoes transplanted into "aged" nutrient solution resulting in a higher harvest index than for plants grown in batch culture on fresh solution for most of the study.

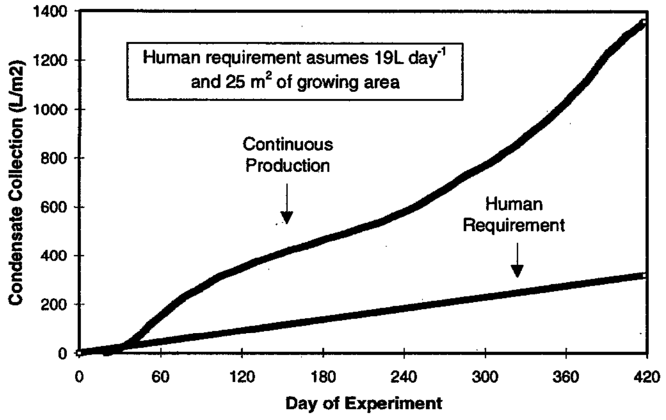

Figure 3: Cumulative water purification capability of potato cv. Norland grown in staggered production for 418-d on an area required to meet human CO_2 removal requirements (See Table 1).

This experiment also indicated that if the atmospheric regeneration requirements are achieved, the human requirement for water purification is exceeded (Fig. 3). The human requirement for water was met early in the production cycle, and exceeded human demand throughout all later stages of experiment. The changes in rate of production reflect differences in cumulative biomass in the chamber. These data suggests that utilization of higher plants for water purification should be carefully evaluated, since the overall area requirement is less than 10% of that required to generate food. The high rate of water cycling (3 L m^{-2} d^{-1}) though the plant system is an important consideration, since water is the greatest weight and mass requirements in a BLSS.

CONCLUSIONS

The BLSS Breadboard Project at KSC has demonstrated that potatoes can be produced continuously using recycled water and nutrients recovered from biological processing of inedible plant residues. The staggered production system has been able to sustain a relatively stable production of fundamental life support activities (CO_2 removal, O_2 production, water purification) that will meet or exceed the requirement for a single individual using 25 m^2 of growing area. These staggered production system conditions have not been optimized. However, the overall yield per unit area has been approximately 8% higher than the best "batch" yields obtained from the BPC to date.

This experiment has demonstrated the feasibility of using higher plants to function as a life support system for an extended period of time. This experiment has indicated that for potato, under these specialized growing conditions, that actual performance of the crop exceeded the estimates based on batch production systems. However, this experiment also revealed interactions with nutrients and plant age which needed to be managed throughout the experiment.

ACKNOWLEDGMENTS

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