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UTILIZATION OF POTATOES IN CELSS: PRODUCTIVITY AND GROWING SYSTEMS

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The potato plant (Solanum tuberosum L.) has been recognized as one of the basic food crops that should be studied for use in NASA's Controlled Ecological Life Support System (CELSS) (Tibbitts and Alford, 1982). It offers high yields per unit area and time, with most of this production in the form of highly digestible carbohydrate (Smith, 1977). Potatoes, like wheat and rice, are particularly useful in human diets because of their nutritional versatility and ease of processing and preparation.

Potatoes can be grown effectively with stem cuttings from plants maintained in sterile culture, thereby eliminating most insect and disease problems and greatly increasing the plant to plant uniformity for research investigations. For our studies, plantlets 10 cm high are grown from the stem cuttings in test tubes on agar under sterile culture and then transplanted into containers of non-sterile peat vermiculite or other media. Upon transplanting, these small plants grow rapidly and after 28 days can attain a diameter exceeding 40 cms. The plants develop vigorous side branches that produces a spreading, vine like plant. As plants enlarge, the leaves orient to effectively intercept all of the incoming irradiation. A canopy with 3 leaf layers per unit ground area (i.e. a leaf area index of 3) absorbs over 95% of the incident radiation (Figure 1).

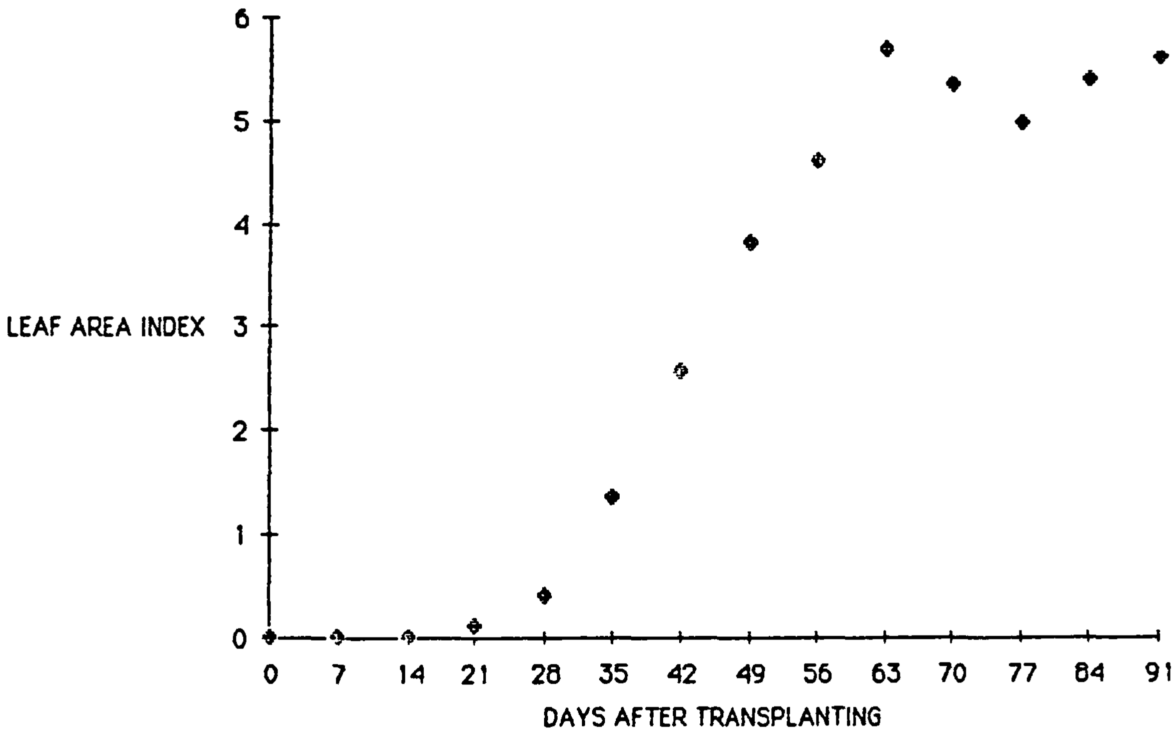

Figure 1. Leaf area index of potato plants spaced 45 cm apart and grown with 400 μmol $s^{-1}m^{-2}$ irradiance with 12-hr photoperiod at $20^{o}C$ and 70% RH.

Tubers form on stolons (underground horizontal stems) that extend from the buried portion of the stem. In some cultivars stolons are very short and tubers form almost sessile to the stem, whereas in other cultivars stolons will extend 0.3 to 0.5 m from the stem and develop tubers along their entire length. Tuber production is regulated to some extent by the volume of media available for root and stolon extension; for example, 38-liter containers provided greater tuber production than 19-liter containers (Figure 2).

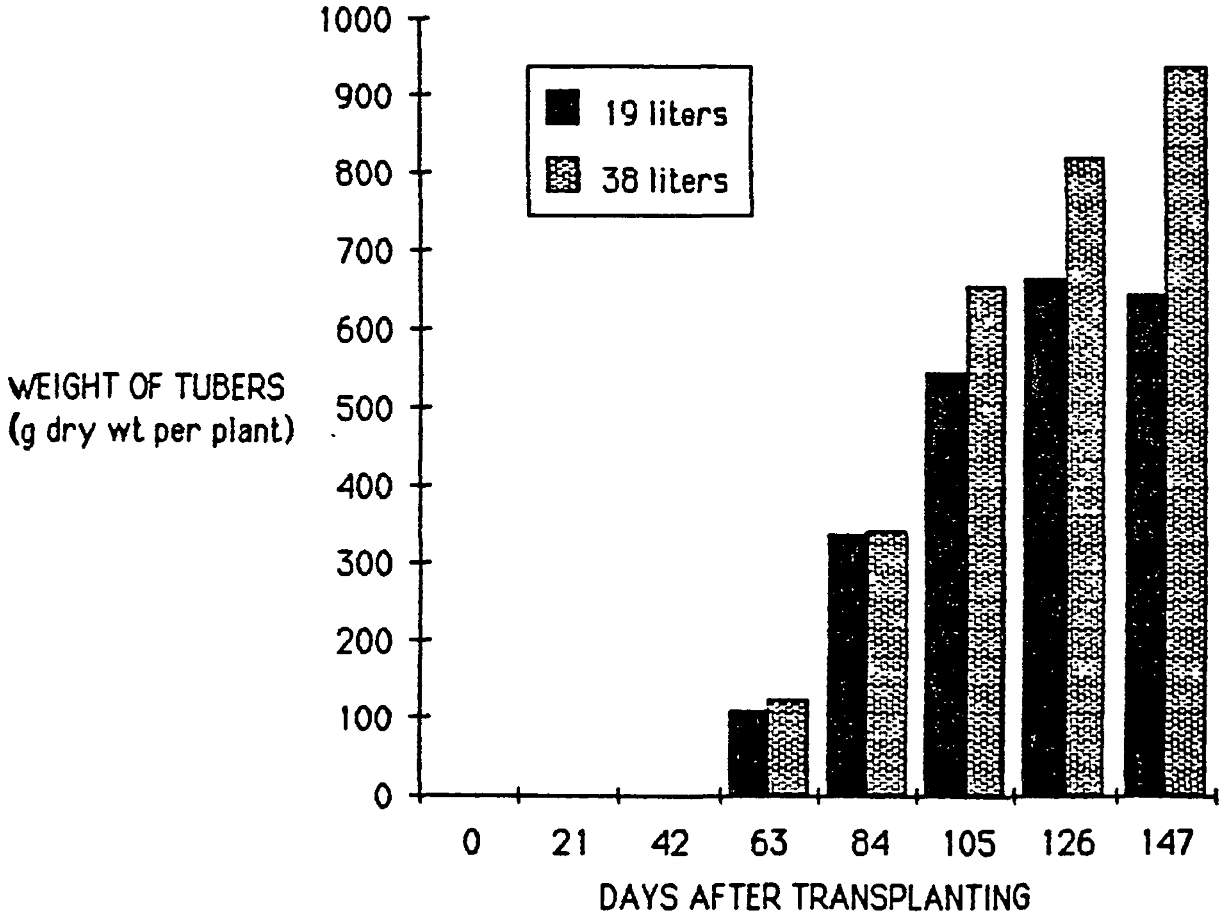

Figure 2. Effect of container size on tuber weight of potatoes at different stages of development. Plants grown with 400 μmol $s^{-1}m^{-2}$ irradiance with 24-hr photoperiod at 16°C and 70% RH.

Plants were larger in the 38-liter containers and accumulated significantly more tubers during final weeks of growth between 105 and 147 days after transplanting.

Tuber production is controlled to a significant extent by many different environmental factors including photoperiod, irradiation level and temperature (Bodlaender, 1963). These factors affect both the total dry matter accumulated per unit time and the allocation of this dry matter between tubers and other vegetative organs of the plant.

Photoperiod has long been recognized to regulate tuberization, with short photoperiods encouraging tuberization and long photoperiods slowing tuberization (Bodlaender, 1963). Our experiments have shown that long photoperiods do decrease the proportion of photosynthates partitioned to the tubers but with increases in total irradiance, tuber production can be obtained despite suppressing effects of the long photoperiods. Thus if irradiance levels are high enough, tuber production can be very large under long photoperiods. A 15-week study of tuber formation of potatoes maintained with 12, 16 and 20-hr of irradiance at 400 $\mu mol\ s^{-1}m^{-2}$ and $20^{o}C$ temperature demonstrated that the highest yields occurred under 20-hr irradiance; with the least under 16 hr (Table 1). However,

Table 1. Tuber production of 15-week-old 'Superior' potatoes grown under different irradiance durations at 400 μmol $s^{-1}m^{-2}$ level and 20°C temperature.

Irradiance period (hrs)	Tuber dry weight per plant (g)	Tuber percentage of total biomass
12	257	61
16	224	43
20	293	43

of the three treatments, the 12 hr plants had the greatest proportion of dry weight in the tubers, i.e. the highest "harvest index". In another study of only 6 weeks duration, we found that continuous irradiance at a level of 400 μmol $s^{-1}m^{-2}$ also produced more tubers than 12 h of irradiance at this same level (Table 2). However continuous irradiance at a level of 200 μmol s^{-1} m^{-2} produced essentially no tubers.

Table 2. Tuber and total biomass production of 'Norland' potatoes grown for 6 weeks under different irradiance treatments and 16°C temperature.

Irradiance		Dry weight per plant (g)	
Duration (hrs)	Level (μmol $s^{-1}m^{-2}$)	Total biomass	Tubers
12	400	53	12.2
24	400	125	19.6
24	200	80	0.4

These data also demonstrated that the efficiency of total dry mass accumulation can be as good or better under continuous irradiance than under 12 hr irradiance, for a doubling of total irradiance with 24 hr irradiance more than doubled the dry matter obtained with 12 hr irradiance. This study also demonstrated that a 200 μmol s^{-1} m^{-2} irradiation level is more photosynthetically effective than 400 μmol $s^{-1}m^{-2}$, for the plants under low irradiance had more total dry weight per unit of irradiance.

It is of particular interest that certain cultivars do not tolerate long photoperiods. This is seen in the stunting of cv. 'Kennebec' plants grown under continuous light. These plants developed to be only 25 cm high and 25 cm in diameter after 8 weeks of growth compared to a healthy cv. 'Norland' plants of which were more than 50 cm high and 100 cm in diameter after 8 weeks of growth. Also, 'Kennebec' was found to be partially stunted under 20 hr irradiation and even slightly stunted under 16 hr irradiation. Another cultivar, 'Superior' was found to be severely stunted under 24 hr irradiance periods but not affected by 20 and 16 hr irradiance. 'Norland' and 'Russet Burbank' cultivars showed no apparent stunting under continuous irradiance.

Temperature has been found to be a very significant variable for regulation of the proportion of dry matter allocated to the tubers and for regulation of the length of the plant stems (Bodlaender, 1963). Reducing the temperature increases the proportion of dry matter allocated to tubers and reduces the stem length. In studies comparing growth at 12°C, 16°C, 20°C, 24°C, and 28°C, maximum tuber production was obtained at 16° (Table 3). Plants at 16° had

Table 3. Development of 'Norland' potatoes grown for 8 wks under different temperature levels.

Temperature (°C)	Tubers (g dry wt) per plant	Total biomass (g dry wt) per plant	Tubers (%)	Stem length (cm)
12	73	123	59	18
16	123	209	59	37
20	96	186	51	48
24	2	151	1	74
28	0	116	-	94

less shoot growth than plants at higher temperatures, indicating that a greater percentage of the photosynthetic production was allocated to the tubers. At high temperatures nearly all dry matter production was allocated to the shoots and essentially none to tuber formation. At 12°C, total growth was slowed but a high proportion of the photosynthates were allocated to tuber formation. The reduction in stem length with cool temperatures is particularly significant with regard to minimizing total plant volume in a CELSS plant growth facility.

We are now involved in study of the interacting effects of carbon dioxide concentration, temperature and irradiance level on tuber formation. We have established a split plot matrix study involving the following levels and combinations:

Carbon Dioxide ($\mu l\ l^{-1}$):	400, 1000, 1600
Temperature (^{o}C):	16, 20, 24
Irradiance ($\mu mol\ s^{-1}m^{-2}$):	250, 400, 550

Only one-half of the matrix treatments have been completed but the data obtained indicate that carbon dioxide additions provide significant growth advantage only at the medium and low irradiance levels. The data also suggest that irradiance levels of 400 $\mu mol\ s^{-1}m^{-2}$ are close to a saturating irradiance level for potatoes and little advantage is obtained with higher irradiance levels. This is particularly important in terms of overall energy efficiency for growing plants in a CELSS. These conclusions are only tentative and must await the completion of all of the matrix combinations.

Our highest tuber production in terms of grams of edible carbohydrate per day has been obtained from the study shown in Figure 3 with plants grown in 38-liter containers for 147 days at 16°C under continuous irradiation. An

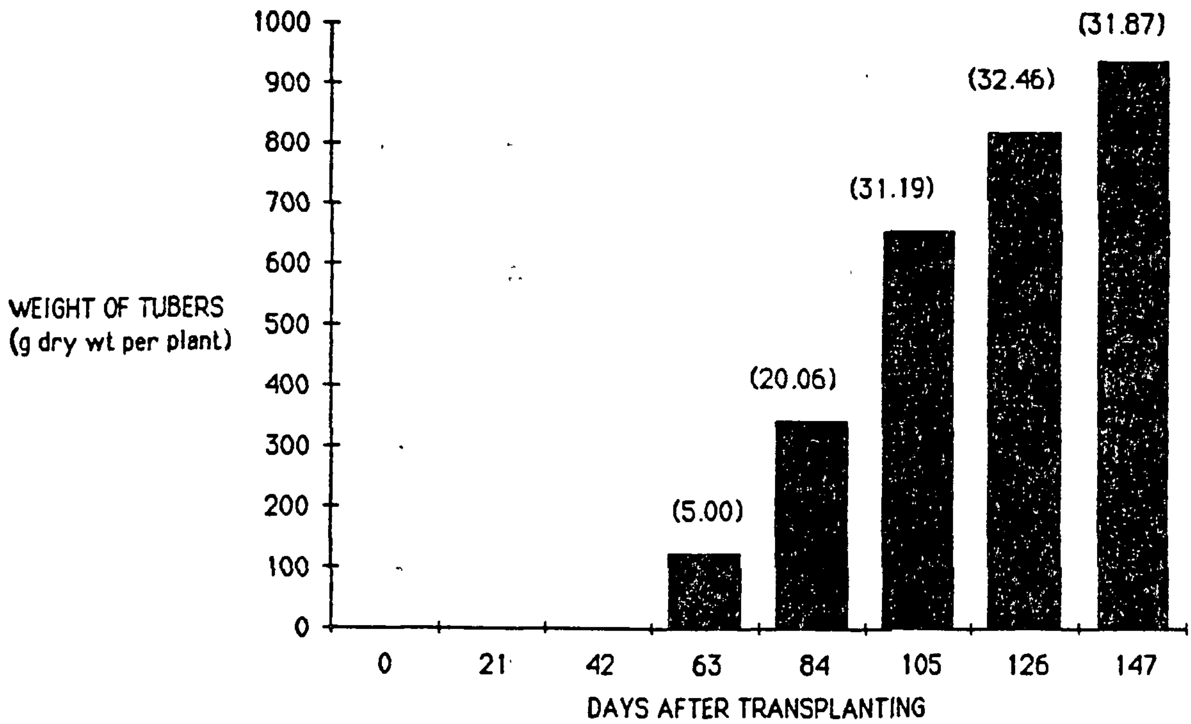

Figure 3. Tuber weight of potatoes at different stages of development. Plants grown with 400 μmol $s^{-1}m^{-2}$ irradiance over 24-hr photoperiod at 16°C and 70% RH. Values in parentheses indicate the g m^{-2} day^{-1} for each harvest.

irradiance level of 400 μmol $s^{-1}m^{-2}$ and relative humidity of 70% were maintained in this study. Each plant was contained by a wire cage having a cross sectional area of 0.2 square meters. These caged plants were separated some in the growing room, thus each plant received some side lighting. The production efficiency at different times during this study is shown by the values in parentheses above each bar. The production efficiency increased rapidly to 105 days and then was essentially constant between 105 days and the final harvest at 147 days. The production during this period would provide the daily energy requirements for one person from a 23.6 m^2 area. This is calculated with the following assumptions.

One gram dry weight of potatoes = 3.73 k calories

Daily energy requirement of one person = 2800 k calories

The electrical power to provide lighting required for this production was estimated to be 7.2 KW per m^2 of continuous electricity. This is based on the use of high pressure sodium lamps and reflectors as installed at the Phytofarm, a commercial plant growth facility in DeKalb, Illinois. This installation obtains 400 μmol $s^{-1}m^{-2}$ photosynthetic irradiance with 304 W of high pressure sodium lamps over each m^2. This calculation of irradiance requirement may underestimate the requirement of a production system when plants are grown close together in a closed canopy. However studies suggest that greater irradiation efficiency can be obtained with elevated carbon dioxide levels and by tailoring lighting systems to the particular species being grown in CELSS.

Concurrent studies have been conducted examining the use of soilless culture system for growing potatoes in controlled environments. These have including recirculating solution cultures and continuous misting systems. These systems offer the potential of reducing growing medium requirements and providing more precise control of root-zone nutrient concentrations and pH control. In each case, vigorous shoot growth can be obtained, but induction of tuberization has proved difficult. However, lowering ambient temperatures and reducing solution nitrogen levels has been found to enhance tuber production. Additional studies are in progress directed toward obtaining consistant tuber initiation in liquid systems and comparing tuber production between solid media and liquid culture systems.

In summary it is felt that potatoes do provide a useful plant species for life support systems and should be considered seriously for inclusion in long-term space habitats.

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