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UTILIZATION OF POTATOES FOR LIFE SUPPORT SYSTEMS IN SPACE. I. CULTIVAR-PHOTOPERIOD INTERACTIONS[1]

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Abstract

The productive potential of potatoes (*Solanum tuberosum* L. cvs. Norland, Superior, Norchip, and Kennebec) was assessed for life support systems being proposed for space stations and/or lunar colonies. Plants were grown in walk-in growth rooms for 15 weeks at 20 C under 12-, 16- and 20-h photoperiods of 400 μmol $m^{-2}s^{-1}$ photosynthetic photon flux (PPF). Norland yielded the greatest tuber fresh weight, producing 2.3, 2.4, and 2.9 kg/plant under 12-, 16-, and 20-h photoperiods, respectively. The respective yields for the other cultivars under 12-, 16-, and 20-h were: Superior, 1.9, 1.5, and 1.8 kg/plant; Norchip, 1.8, 1.4, and 2.0 kg/plant; and Kennebec, 2.3, 0.2, and 0.8 kg/plant. Shoot and total plant biomass increased with lengthening photoperiods except for Kennebec, which showed increased shoot growth but no change in total growth with the longer photoperiods. Kennebec shoot growth under the 20-h photoperiod, and to some extent under 16-h, was noticeably stunted with shortened internodes. In addition, leaves of these plants showed mild chlorosis with rusty "flecking" of the surfaces. The harvest index (ratio of tuber yield/total biomass) was highest for all cultivars under the 12-h photoperiod, with a maximum of 0.69 for Norland. Similarly, the tuber yield per input of irradiant energy also was highest under 12-h for all cultivars. The tuber yield expressed on an area basis for the highest yielding treatment (Norland under 20-h) equaled 2.2 kg dry matter m^{-2}. Over 15 weeks this equates to a productivity of 20.7 g tuber dry matter m^{-2} day^{-1}. Assuming 3.73 kcal per g tuber dry matter and a daily human dietary requirement of 2800 kcal, then 36 m^2 of potatoes could supply the daily energy requirement for one human. Potential for increasing productivity is discussed.

Resumen

Se determinó el potencial productivo de las papas (*Solanum tuberosum* L., cultivares Norland, Superior, Norchip, y Kennebec) en los sistemas propuestos para mantener la vida en las estaciones espaciales y/o lunares. Se

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cultivaron plantas, en cámaras de crecimiento que permitían el ingreso, durante 15 semanas, a 20°C, y bajo 12, 16, y 20 horas de fotoperíodo con un flujo de fotones fotosintéticos de 400 mol por metro cuadrado y por segundo. El cultivar Norland rindió el mayor peso fresco de tubérculos, produciendo 2,3; 2,4; y 2,9 kg/planta bajo 12, 16, y 20 horas de fotoperíodo respectivamente. Los rendimientos correspondientes a los otros cultivares, bajo 12, 16, y 20 horas fueron: Superior, 1,9; 1,5; y 1,8 kg/planta; Norchip, 1,8; 1,4; y 2,0 kg/planta; y Kennebec, 2,3; 0,2; y 0,8 kg/planta.

Los brotes y la biomasa total de la planta aumentaron con la longitud de los fotoperíodos excepto para Kennebec, cultivar que mostró con los fotoperíodos más largos un aumento en el crecimiento de los brotes, pero sin cambios en el crecimiento total. El crecimiento de los brotes en Kennebec, bajo el fotoperíodo de 20 horas, y hasta cierto punto con el de 16 horas, fue detenido notablemente da~~ndo~~ lugar a entrenudos más cortos. Además, las hojas de estas plantas mostraron una leve clorosis y un moteado rojizo sobre sus superficies. El índice de cosecha (relación entre el rendimiento en tubérculos y la biomasa total), bajo el fotoperíodo de 12 horas, fue más alto para todos los cultivares con un máximo de 0,69 para Norland. Similarmente, el rendimiento en tubérculos por cantidad de energía radiante recibida fue también el más alto para todos los cultivares, bajo un fotoperíodo de 12 horas.

El rendimiento en tubérculos, para el tratamiento con el mayor rendimiento (Norland bajo 20 horas), expresado en base a superficie, alcanzó 2,2 kg de materia seca por metro cuadrado. En 15 semanas esto equivale a una productividad de 20,7 g de materia seca de tubérculo por metro cuadrado por día. Dado que por gramo de materia seca de tubérculo se tienen 3,73 kcal, y que en la dieta humana se requieren 2 800 kcal por día, se tendría que 36 m^2 de papas podrían abastecer los requerimientos diarios de energía para una persona. Se discute el potencial para incrementar la productividad.

Introduction

As a part of the overall planning for orbiting space stations and moon colonies scheduled for construction in the 1990s, the National Aeronautics and Space Administration (NASA), is exploring the use of higher plants for recycling oxygen, carbon, water, and inorganic substances in closed systems (12, 13, 20). Among the higher plants selected for investigation were wheat, soybeans, potatoes, and lettuce (10, 20, 22). Factors considered in the selection of the potential crop species included overall productive potential, caloric and protein content, edible to inedible biomass ratio, ease of food preparation and processing, palatibility, cultural considerations, growth habit, and ease of propagation (10, 20). Potatoes were included because of their high yield potentials—up to 1.8 kg m^2 of tuber dry matter (23), the high ratio of edible to inedible biomass, ease of propagation, and ease of preparation for consumption (10, 20). In addition, the tubers provide a well-balanced food, high in digestible starch and with substantial amounts of protein (10, 18).

Several long-term studies have been conducted in controlled environments to examine specific environmental effects on shoot and tuber growth (2, 3, 6, 14, 15, 19, 21); however, it is difficult to translate the per plant yields from such studies into production data per unit area and time. Nonetheless, the results indicate that the potential productivity of potato under controlled environments is quite high, approximately 14 g tuber dry mass m^{-2} day^{-1} (14, 20).

Previous studies with potatoes have emphasized that photoperiod is one of the significant factors regulating tuberization, where short days are promotive of tuber growth and long days are suppressive (1, 3, 4, 5, 6, 8, 15). Unfortunately, the use of shortened photoperiods to encourage tuberization in controlled environments restricts the input of daily PAR (photosynthetically active radiation) and hence the rate of overall plant growth. It would be advantageous in a closed life support system to maintain longer light periods thereby decreasing the time to achieve a given level of total plant growth.

To initially explore the possibility of growing potatoes in bioregenerative life support systems (12), we examined the growth and yield of four cultivars under three irradiance regimes. The cultivars ranged from early- to late-season types to determine whether cultivar differences exist with regard to photoperiodic response, as suggested in the literature (2, 4).

Materials and Methods

Solanum tuberosum L. plants, cvs. Norland (early season), Superior (early-mid), Norchip (early-mid), and Kennebec (mid-late), were started from meristem cuttings grown in sterile agar culture (11). After 25 days in tissue culture, uniform plantlets were transplanted to 20-liter black plastic containers of peat-vermiculite (50:50 v:v). Plantlets were covered with glass beakers for 48 h to mitigate transplant shock. All pots were watered four times daily with a complete nutrient solution (7).

Experiments were conducted in walk-in growth rooms (2.6 X 3.6 m) at the University of Wisconsin Biotron. Three plants of each cultivar were grown in separate rooms under 12-, 16-, and 20-h photoperiods. Irradiance was provided by 60 VHO 210-W cool white fluorescent lamps. PPF levels were maintained at 400 μmol $m^{-2}s^{-1}$ ($\pm$20 μmol $m^{-2}s^{-1}$) at the top of the canopies by turning off pairs of lamps as plants grew. This level provided approximately 17.3, 23.0, and 28.8 mols m^{-2} day^{-1} for the 12-, 16- and 20-h treatments. Temperatures were set at a constant 20 C (±0.5 C) so that similar 24-h temperatures could be obtained with the different light and dark periods being studied. The relative humidity was maintained at 70%

(±5%). At 6 weeks, plants were encaged in wire fence cylinders, 46 cm in diameter and 122 cm in height. As plants grew, branches that extended through the 6.3 x 5.1 cm rectangular holes of the fencing were gently pushed back into the cylinder to restrict shoot growth to the circumference of the enclosure. Plants were harvested at 15-weeks-age, and leaf, stem, and tuber fresh and oven-dry weights were recorded. Yields per unit area were calculated on the basis of assigning a 0.2 m^2 cross-sectional area to the wire cylinders containing each plant. Yields per mole PAR were determined by dividing the yield by the total moles of irradiance throughout the 15-week experiment.

Results

With the exception of Kennebec, no large differences in tuber fresh weight per plant were noted among photoperiod treatments (Table 1). Norland plant yields increased slightly with increasing photoperiod, while Norchip and Superior yields were similar under 12- and 20-h treatments and slightly depressed under 16-h. Kennebec plants produced high tuber yields under 12-h (2.26 kg per plant) but low yields under 16- and 20-h treatments (Table 1). By 8 to 10-weeks-age, Kennebec plants under 20-h irradiance exhibited noticeably compact shoot growth, with shortened internodes and diminutive, upright leaves with mild "rusty" flecking on the surfaces of the leaflets. These conditions also began to appear under 16-h by the 12th week. This injury appears to be a physiological disorder similar to that reported for tomatoes when grown under long light periods (9).

TABLE 1. — *Tuber yield of 15-week old potatoes grown under different photoperiods. Data represent means of three plants (±s.d.).*

Cultivar	Photoperiod (h)[1] 12	16	20
		(kg fresh weight/plant)	
Norland	2.35±0.21	2.44±0.13	2.88±0.52
Superior	1.87±0.08	1.49±0.12	1.84±0.38
Norchip	1.78±0.22	1.37±0.21	1.98±0.38
Kennebec	2.26±0.22	0.24±0.05	0.80±0.21

[1] PPF=400 $\mu mol\ m^{-2}s^{-1}$.

Tuber, shoot, and total plant dry matter production per unit area for the four cultivars is shown in Table 2. Tuber dry matter production followed trends similar to those for fresh weight yields in Table 1. The dry matter composition of the tubers ranged from 13 to 16% with no consistent trends among irradiance treatments or cultivars. In contrast to tuber yields, all cultivars had increased shoot dry weight with increasing levels of irradiance, i.e., longer photoperiods. Total dry weights also increased with in-

TABLE 2. — *Tuber, shoot, and total[1] plant dry weight per unit area[2] of 15-week old potatoes grown under different photoperiods. Data present means of three plants (±s.d.).*

Cultivar		Photoperiod (h)[3] 12	16	20
			(kg dry weight m^{-2})	
Norland	tuber	1.62±0.14	1.80±0.10	2.18±0.39
	shoot	0.71±0.02	1.48±0.05	1.82±0.23
	total	2.36±0.16	3.31±0.05	4.07±0.16
Superior	tuber	1.29±0.05	1.12±0.09	1.46±0.31
	shoot	0.81±0.13	1.43±0.10	1.87±0.02
	total	2.11±0.17	2.60±0.03	3.39±0.33
Norchip	tuber	1.29±0.16	0.97±0.15	1.52±0.30
	shoot	0.97±0.04	1.63±0.21	1.99±0.08
	total	2.28±0.16	2.65±0.09	3.55±0.39
Kennebec	tuber	1.69±0.17	0.16±0.02	0.56±0.15
	shoot	0.95±0.13	2.06±0.60	1.91±0.04
	total	2.67±0.23	2.21±0.47	2.54±0.21

[1] Includes weight of stolons and roots.

[2] Values calculated assuming 0.2 m^2 area available for each plant.

[3] PPF=400 μmol m^{-2}s^{-1}.

creasing irradiance for all cultivars except Kennebec, which showed no total weight gain with increasing irradiance. The highest yielding treatment, Norland under a 20-h photoperiod, produced 4.0 kg total dry weight per square meter with nearly 2.2 kg tuber dry weight.

A comparison of the harvest index values (i.e., tuber dry weight/total plant dry weight) is shown in Table 3. For each cultivar, the highest harvest index and hence the highest edible to inedible production occurred under the shortest photoperiod, 12-h. Norland plants under the 12-h photoperiod had the greatest harvest index of all the cultivars with an average of 69% of their final biomass in the form of tubers (Table 3). The harvest indices decreased for all cultivars under 16- and 20-h treatments.

TABLE 3. — *Harvest index (tuber dry weight/total dry weight) of 15-week old potatoes grown under different photoperiods. Data represent means of three plants (±s.d.).*

Cultivar	Photoperiod (h)[1] 12	16	20
Norland	0.69±0.02	0.54±0.02	0.53±0.07
Superior	0.61±0.03	0.43±0.04	0.43±0.05
Norchip	0.57±0.03	0.37±0.06	0.43±0.04
Kennebec	0.63±0.04	0.07±0.02	0.22±0.04

[1] PPF=400 μmol m^{-2}s^{-1}/$_{7}$.

The total biomass produced per mole PAR showed little change with increasing irradiance in Norland, Superior, and Norchip plants (Table 4). In contrast, because of the reduced tuber growth under 16- and 20-h treatments, the "growth efficiency" of the Kennebec plants dropped sharply with increasing irradiance period. The tuber production per mole PAR decreased for all cultivars under 16- and 20-h treatments when compared to 12-h (Table 4).

TABLE 4. — *Tuber and total plant dry weight per mole irradiance.*

Cultivar		Photoperiod (h)[1] 12	 16	 20
			(g m^{-2} mol^{-1} PAR)	
Norland	tuber	0.90	0.75	0.72
	total	1.30	1.37	1.35
Superior	tuber	0.71	0.46	0.48
	total	1.16	1.07	1.12
Norchip	tuber	0.71	0.40	0.50
	total	1.25	1.09	1.17
Kennebec	tuber	0.93	0.07	0.18
	total	1.47	0.91	0.84

[1] PPF=400 μmol $m^{-2}s^{-1}$.

Discussion

The decrease in tuberization of Kennebec, Norchip and Superior cultivars with 16 h irradiance compared to 12 h irradiance is consistent with previous research documenting suppression of tuberization by long photoperiods (4, 6, 19). However, the lack of further decrease and even slight increase in tuberization with 20 h irradiance compared to the 16-h treatment indicates the potential of high total irradiance to override the long photoperiod suppression of tuberization (2).

Using harvest index (Table 3) as a gauge of tuber induction, it is apparent that tuberization of the early cultivar Norland was suppressed the least by extending the photoperiod beyond 12 h, while Kennebec, the latest cultivar, appeared to be suppressed the most. Superior and Norchip, early to mid-season cultivars, were intermediate in their response. This trend follows the general observation that the length of the light period exerts a stronger influence on tuberization of late cultivars (2, 4). However, the stunted and malformed growth of the Kennebec plants under the longer irradiance treatments undoubtedly contributed to the low harvest index and this complicates a determination of true photoperiod effects. Recently completed studies (unpublished) with Russet Burbank, another late cultivar, have shown vigorous growth and rapid tuberization under long photoperiods at constant irradiance levels. Thus the general assumption that there is greater photoperiod sensitivity in late cultivars must be questioned and additional study is needed.

By dividing tuber yields per square meter (Table 2) by the 105-day growing period (15 weeks), one can obtain daily productivity values. For the highest yielding treatment, cv. Norland grown under the 20-h photoperiod, the productivity equals 20.7 g tuber dry weight m^{-2} day^{-1}. Assuming that potato tubers contain 3.73 kcal g^{-1} dry weight (20), this productivity equates to 77 kcal m^{-2} day^{-1} of food over the entire growing period. If an average adult requires approximately 2800 kcal day^{-1}, then one human's daily dietary caloric needs could be provided by 36 m^2 of potatoes. It should be noted that this area requirement may be underestimated due to the supplemental effects of low-level peripheral lighting of the encaged plants (17). But this in turn may be compensated by the fact that a ground cover of 0.2 m^2 was assessed for the entire life cycle of the crop, yet individual plants did not attain this cross-sectional area until the 5th or 6th week. Hence closer spacing when plants were young could have reduced the calculated area.

Although it is likely that initial life support systems will be only partially self-sustaining, clearly the area requirement must be diminished to have effective cropping of potatoes in space (12). Several avenues for potential improvement are available: First, subjecting the plant to cooler temperatures, particularly during the dark, would likely enhance tuberization and/or reduce the proportion of inedible yield (2, 6, 14, 19). However, this may be incompatible with integrated cropping systems where other species exhibit higher production temperature optima than potatoes. Second, these studies were all conducted at ambient CO_2 levels (330-360 ppm) and CO_2 enrichment of closed systems could be practiced relatively easily. This would almost certainly raise productivity through enhanced photosynthetic gains. Third, our choice of 15 weeks as a harvest date was based on an average time for harvest of early cultivars in the field. However this may not have been the best time to harvest for obtaining the highest productivity (grams per square meter per day). A series of tests underway to investigate the effect of harvest date indicates that the highest productivity can be achieved with harvests made between 18 and 21 weeks. Also, the calculation assumes a one-harvest cropping cycle, but possibilities might be explored for continuous harvest schemes, particularly if soilless culture systems can be developed for potatoes. Fourth, higher instantaneous irradiance levels would likely speed growth and reduce time to maturity of the potatoes (2).

Finally, in a sophisticated life support system, a portion of the inedible biomass potentially could be converted through other organisms to retrieve some of the energy content of the vines and leaves thereby increasing space efficiency. For example, the cellulose and other undigestible compounds of the foliage might be used to feed lower organisms which could then be processed into food acceptable to humans (12). Also being considered is the use of higher animals, such as goats, to consume the foliage to recover a portion of this energy. The nutritional value of pressed potato vine silage was evaluated by Parfitt, *et al.* (16). and found it to be acceptable feed for ruminants.

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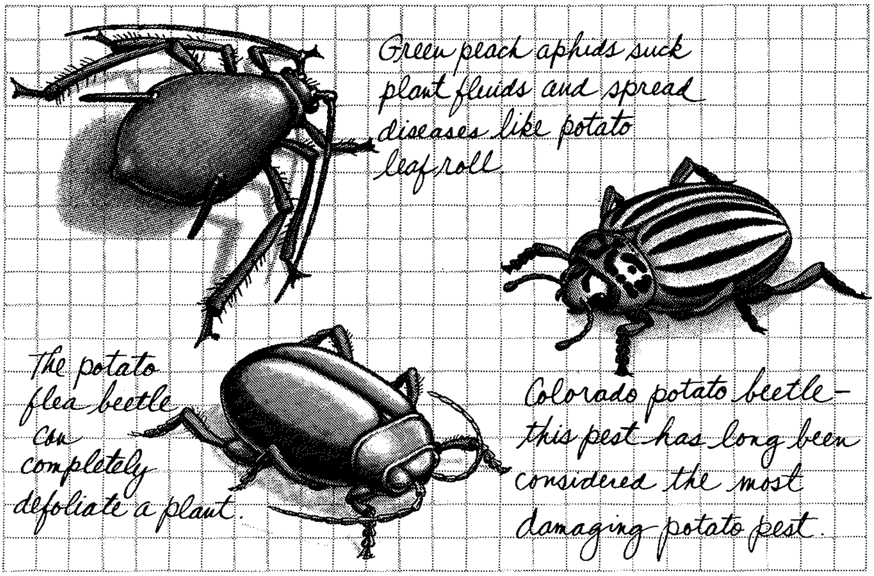
Potato Pest Update



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