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CONTROLLED ENVIRONMENT LIFE SUPPORT SYSTEM: GROWTH STUDIES WITH POTATOES

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R. M. WHEELER

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CONTROLLED ENVIRONMENT LIFE SUPPORT SYSTEM: GROWTH STUDIES WITH POTATOES

T. W. TIBBITTS
R. M. WHEELER
HORTICULTURE DEPARTMENT
UNIVERSITY OF WISCONSIN - MADISON
MADISON, WISCONSIN

PREPARED FOR
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National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

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SUMMARY

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). It offers high yields per unit area and time, with most of this production in the form of highly digestible carbohydrate. Potatoes like wheat and rice are particularly useful in human diets because of their nutritional versatility and ease of processing and preparation.

The specific objectives of the work reported herein have been to 1) develop effective cultural procedures for high production in controlled environments, 2) determine the most effective photoperiod for high productivity, and 3) develop systems for mist culture of potatoes.

'Russet Burbank', 'Norchip', 'Superior', 'Kennebec' and 'Norland' were selected for study in this CELSS project. These cultivars were chosen based on: 1) their popularity for production and consumption in the United States, and 2) their range of short-season to long-season maturities.

Plants for experimental use were obtained from stem cuttings maintained under asceptic conditions on nutrient agar. Stem cuttings were grown into plantlets 8-10 cm in length and transplanted into media or placed into liquid culture systems for experimentation.

Two potting media, peat-lite and calcined clay chips, were compared in a series of experiments at the U.W. Biotron with plants grown only to tuber initiation. Plants grown in peat-lite under 12-h photoperiods produced 10-20% greater shoot and tuber dry weight than plants grown in arcillite. When plants were grown under continuous light, the growth differences were even greater, with shoot and tuber dry weights of arcillite-grown plants being 50% less than plants grown in peat-lite.

Recycling liquid culture systems were constructed using 7.5 liter opaque polyethelene containers to support individual plants. The system included a pump which continuously recycled a portion of liquid from all containers into a common mixing chamber where pH and solution conductivity could be maintained. A series of exploratory studies with different types of container systems were undertaken both in a greenhouse and in a growth chamber under cool-white fluorescent lamps. The best tuberization occurred when a system where sphagnum moss was used to fill a stolon development compartment just above the solution level and just beneath the cover of the container. Very few tubers were initiated if the stolon development compartment was left empty, whereas a large number of small tubers were initiated when the solution completely filled the stolon development area. All tubers that developed below liquid level formed callus on their surfaces.

Considerable problems were experienced with necrosis and corking of an area of the stem just below foam plug collars used to support the plants. We hypothesize that this resulted from nutrient wicking up the stems causing toxic salt concentrations on the exposed stem areas.

A mist-culture system was constructed consisting of a metal framework used to support black polyethylene sheeting draped into a plastic tub at the base. A continuously spinning impellor disc supported just above the solution level of the vat was used to provide the mist. The impellor was driven by a stainless steel shaft connected to a motor mounted atop the cover of the mist chamber. The solution was continuously recirculated between the growing vat and a 20-liter mixing tank at a rate of 2 ℓ per minute. The solution was pumped from the mixing tank to the growing system and returned by gravity to the mixing tank through a drain in the bottom of the growing vat. The pH of the solution was regulated at 6.0 in the mixing tank through use of an automatic pH controller.

Plants have grown rapidly in the mist system showing normal leaf, stem, and root growth development. However, tuber development has been very poor in the system thus far. Small tubers were initiated on some stolons but enlargement did not appear to proceed normally. Some improvement in tuberization has been obtained by filling the stolon development area with sphagnum moss but this has not provided normal tuberization of the plants. Some additional stimulation of tuberization has been obtained in a single preliminary study by removing nitrogen from the solution after 6 weeks of growth.

Several studies have been undertaken to establish the effectiveness and efficiency of different lighting regimes for tuber production in controlled environments.

In one series of studies, plants were grown in separate controlled environment rooms under photoperiods of 12, 16 or 20-h in 20-liter black plastic containers of peat-vermiculite. Irradiance was provided by cool white fluorescent lamps at a PPFD level of 400 μmol m^{-2} s^{-1} for the entire photoperiod of each treatment. Temperatures were maintained constant at 20°C and relative humidity at 70%. At 6 weeks, the plants were encaged in wire fence cylinders, 46 cm in diameter and 122 cm in height, to support the elongating stems. With the exception of 'Kennebec' plants under 16 and 20-h, all the cultivars showed an increase in total biomass with increasing irradiation. 'Kennebec' plants under 16 and 20-h photoperiods were stunted and showed dimunitive, upright leaves and "rusty" flecking of the adaxial surfaces of the leaflets. Tuber yield varied significantly across the irradiance levels depending on cultivar. Tuber yields of 'Norland' plants were the highest of all cultivars and increased with the increasing irradiation, yielding 2.35, 2.44, and 2.88 kg/plant fresh mass per plant from the 12, 16, and 20-h treatments. 'Superior' and 'Norchip' yields were similar

under 12 and 20-h treatments, but dropped under 16-h. The 'Kennebec' plants produced good tuber yields under 12 h, 2.26 kg/plant, but poor yields under 16 and 20-h irradiance where injury was seen.

The highest harvest index for each cultivar and hence the highest edible to inedible production occurred under the shortest photoperiod, 12-h. 'Norland' plants under 12-h had the highest harvest index of all the cultivars with an average of 69% of their final biomass in the form of tubers.

In another series of studies comparisons were made with different cultivars under continuous lighting treatments provided either by maintaining continuous PPFD levels or by extending the day length with dim light. Greater tuber yields were obtained under continuous light at 400 μmol $s^{-1}m^{-2}$ than with 12 h light:12 h dark with 'Norland', 'Norchip' and 'Russet Burbank' cultivars. However, low yields and injury under continuous light were seen with 'Superior' and 'Kennebec' cultivars. Replacing the dark period with dim light suppressed tuberization in all cultivars and no injury was seen. Cutting the light intensity in half but maintaining it continuously also suppressed tuberization, and greatly increased shoot growth along with inducing injury and stunting of 'Superior' and 'Kennebec' cultivars.

Information on canopy development was obtained from the different cultivars during growth under 12-h light period in the photoperiod studies. All cultivars showed an increase in leaf area index (LAI) from about 1.5 to about 4.0 between 2 and 6 weeks of age. In a study using just 'Norchip' plants grown for 13 weeks, the LAI of the stand peaked at 4.6 at 9 weeks and stabilized near this level for the remainder of the experiment. Measurements of above- and below-canopy PAR levels showed an exponential decrease of the irradiance penetration as the canopy density increased. The first two leaf layers accounted for nearly 90% of the incident PAR attenuation. An LAI of

2.7 reduced PAR by 95%, while over 98% of the incident PAR was attenuated when LAI exceeded 4.0.

Calculations of tuber production have been made both from plants in the photoperiod study, where each plant was maintained in a separate caged enclosure, and from plants grown in a solid canopy within a growing room.

In the caged study, plants were grown in 20-liter containers and harvested at 15 weeks from transplanting. In the solid canopy study, plants were grown in 40-liter containers and harvested at 20 weeks from transplanting. The calculations document a tuber production of 20.7 g m^{-2} day^{-1} in the caged study grown for 15 weeks, and 12.3 g m^{-2} day in the solid canopy study grown for 20 weeks. These rates indicate that one person could be maintained by a surface area of 36 m^2 with the caged plants and 61 m^2 with the solid canopy plants. These yields equate to power demand of 11.0 and 18.5 KW m^{-2} of electricity, respectively. The higher yield in the caged study was felt to result from greater amounts of side lighting in that study, thereby exposing more photosynthetic leaf surface on these plants. The calculations assumed a calorie requirement of 2800 kcal per day for one person and a conversion of 3.73 kcal per gram dry mass of potato tuber. Electrical energy calculations for lighting were based on a converson of 304 lamp watts of HPS lighting per m^2 to provide 400 μmol s^{-1} m^{-2} of photosynthetic irradiance.

It is felt that the productivity obtained in this initial study is considerably below the maximum productivity that can be obtained. Combining the effects of higher irradiance levels with other tuber-promoting conditions such as cooler temperatures, increased carbon dioxide levels, and lowered nitrogen concentrations should allow further increases in tuber production and electrical efficiency of this crop.

INTRODUCTION

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; Hoff et al., 1982). It was proposed for intensive study for CELSS along with wheat and beans by a higher plant workshop in July 1982 at the Ames Research Center. Potatoes offer high yields per unit area and time, with most of this production in the form of highly digestible carbohydrate (Tibbitts and Alford, 1982). Like wheat and rice, potatoes are particularly useful in human diets because of their versatility in the diet and ease of processing and preparation.

Most of a tuber is in the form of highly digestible starch thereby providing high-calorie yields (Tibbitts and Alford, 1982). The protein content (ca. 2%) is not as high as that of wheat or soybeans, but the protein that is present is of a highly digestible form (Hoff et al., 1982; Paiva et al., 1983), and could provide a significant amount of protein to the diet.

The very high productive potential of potatoes is one of the more significant favorable aspects of the species. An average of 30,100 kg fresh weight per hectare were produced from potato fields in the USA in 1981 (USDA, 1983). A maximum yield of 90,000 kg ha^{-1} has been reported in Europe (Zaag, 1984). Assuming a dry matter solid level of 19% and a 130 day growing season, the average yield equates to 570 g m^{-2} of dry weight production or 4.3 g dry weight $m^{-2}day^{-1}$. Yields in controlled environments have surpassed these field results, and in one study, 14.4 g dry weight $m^{-2}day^{-1}$ were obtained from 'Kennebec' variety plants grown in the University of Wisconsin Biotron (McCown and Kass, 1977). A Soviet study cited by Gitel'son et al. (1976)

reports even higher yields, but transplants were used for this study and thus the yield calculations do not include all of the total space and time required from start of the plants.

A wealth of field data exist for potato because of its worldwide popularity. For example, Poland and the Soviet Union produced 43 million and 72 million metric tons of potatoes in 1981 (compared to the USA's 15 million tons) and potatoes comprise a major contribution to the diets of the people and domestic stock of these countries (USDA, 1983). Although field data are not directly applicable to the productivity of CELSS systems, they do provide understanding of the interacting factors controlling development and do provide useful guidelines for the CELSS studies.

The specific objectives of the work reported herein have been to 1) develop effective cultural procedures for high production in controlled environments, 2) determine the most effective photoperiod for high productivity, and 3) develop systems for mist culture of potatoes.

Specific interest and concern has been directed toward establishing the proportion of inedible production to edible biomass under different growing environments and the tolerance of different cultivars to long photoperiods.

Photoperiod

A major factor controlling the induction of tuber growth and productivity in potatoes is photoperiod. Tuberization of the potato is generally considered to be under "short day" control (Gregory, 1965; Vince-Prue, 1975; Ewing and Wareing, 1978) and this is particularly true in closely related species such as S. andigena, S. demissum, and S. phureja (Mendoza and Haynes, 1976). In the common potato, some cultivars tuberize readily under all photoperiods, while other cultivars tuberize readily under short photoperiods and slowly under long photoperiods. As with other photoperiod-controlled phenomena (e.g. flowering) the length of the night period appears to be the crucial variable, rather than the length of the day (Vince-Prue, 1975).

Scientists have attempted to assign critical photoperiods (longest photoperiod to which a plant is exposed and yet still be fully induced to tuberize) to the different potato cultivars, but this has not been very precise because irradiation intensity and other factors can vary or shift the critical daylengths (Mendoza and Haynes, 1976; Ewing, 1978).

H. O. Werner (1942) published the results of a comprehensive comparison of growth and tuber response of several potato varieties to simulated photoperiods in Nebraska ("northern conditions") and gulf coastal states ("southern conditions") over their growing seasons. Over the 125-day growing period the 'northern' photoperiod was decreased steadily from 15 h to 11 h while the 'southern' photoperiod was increased steadily from 11 h to 14 h. Continuously changing temperatures were also used, so photoperiod was not the sole influence in this study. Of the seven varieties tested, including early-, mid-, and late-season maturing types, all grew more vigorously under 'northern' conditions. This included: increased shoot fresh weight, greater stolon (rhizome) extension, greater number of tubers, and greater tuber fresh weight. However, 'southern' condition produced higher tuber to shoot weight ratios (Werner, 1942).

In the mid 1950's, G. E. Gregory conducted more carefully controlled studies with the help of Fritz Went at the Cal Tech Phytotron. In these studies, Gregory (1956) demonstrated a clear short day response in the commercial late season variety 'Kennebec', and that the tuberization stimulus from induced plants (plants grown under short photoperiods) was graft-transmissible to noninduced plants (plants grown under long days). Grafting studies have also shown that the stimulus was promotive rather than inhibitory in nature (Kumar and Wareing, 1973). Similar results were published by Chapman (1958) in a comparison of 9, 18, and 24-h photoperiods with 'Triumph' variety. Thus, the inductive stimulus for tuberization in

potato appears to be hormonal. There is evidence for several different hormones participating in the control of tuberization including gibberellin (GA) (Okazawa and Chapman, 1962, Menzel, 1980, Krauss and Marschner, 1982); cytokinin (Smith and Palmer, 1970; Sattelmacher and Marschner, 1978 a,b); and abscissic acid (ABA) (Palmer and Smith, 1969; Krauss, 1978). Recently, ratios of ABA to GA have been proposed as being the controlling factor for tuberization, with a balance toward ABA being promotive and balance toward GA's being inhibitory (Menzel, 1980, Krauss and Marschner, 1982).

As a consequence of affecting tuber response in potato, photoperiod also affects the amount of shoot growth in relation to tuber growth (Steward et al., 1981, Gregory, 1956). When photoperiods were extended by light interruptions during the dark cycle, shoot fresh weight production compared to tuber production was increased (Bonaminio, personal com.). Also, Hammes and Nel (1975) observed nearly twice as much shoot production in plants grown under 15-h photoperiods than in plants grown under 9 hours, despite very little difference in tuber yield. Stem height and weight increased with increasing photoperiod in controlled environment tests conducted by Mendoza and Haynes (1976) at the N.C. State Phytotron.

Steward, Moreno, and Roca (1981) compared several S. tuberosum and S. tuberosum subsp. andigenum hybrids under controlled environments and observed more tuber growth under 10-h photoperiods than under 14-h photoperiods, and in some varieties total tuber plus shoot production was greater in the 10-h photoperiod plants. This implies a possible higher inherent photosynthetic efficiency by potatoes grown under short-day conditions. Because short days favor tuberization, the availability of these sinks for photosynthetic production may explain such net assimilation increases (Moorby, 1970; Sale, 1973). In tests where tubers were removed as they developed, whole-plant net carbon fixation rates were reduced (Burt, 1964; Nosberger and Humphries,

1965). The implications from this for CELSS production of potatoes, in which energy inputs will be costly, are clearly important.

Some evidence contrary to the short-day promotion of tuberization also exists. For example, Bodlaender (1963) reported European field data showing increased yields in June from plants grown with artificially extended daylength when compared to plants with no daylength extension. Bodlaender concluded that short daylengths accelerated tuberization but did not increase final yields. But such results may be difficult to interpret because of conflicting effects from higher irradiance input and overall increases in total plant growth with long daylengths.

Early varieties are generally regarded as being less dependent upon short period for tuberization than late varieties (Bodlaender, 1963); nonetheless, 'Kennebec', a North American late season variety which would be expected to have a short critical photoperiod, performs very well in Alaska under extended summer daylight. 'Kennebec' plants also have been observed to tuberize under continuous irradiation in controlled environments (McCown, per. com.).

Light Intensity

Experiments directed specifically at light intensity response of potatoes have been limited. Bodlaender (1963) reported higher weight per unit of illumination at lower light intensity of 8000 lx, compared to an intensity of 16,000 lx. However, the higher intensity caused earlier tuber initiation and produced higher tuber yields. Ku et al. (1977) reported a saturated photosynthesis response and maximal transpiration in short duration leaf chamber studies with potatoes when light intensities were near 850 umol $s^{-1}m^{-2}$ of photosynthetically active radiation. This correlates roughly to 1/2 the intensity of sunlight when directly overhead. Bonaminio grew 'Katahdin' variety plants for six weeks under 9-h photoperiods of high level light (735 umol $s^{-1}m^{-2}$) and approached yields comparable to those of field

situations. Plants spaced widely in controlled environment tests have produced higher tuber yields per plant than closely spaced plants. This has been attributed primarily to higher peripheral lighting in the more widely spaced pots (Roztropowicz and Rykaczewska, 1982). In field studies, Sale (1973) deliberately shaded plants to varying degrees and observed reductions in both tuber number and yield from plants grown under decreased light intensity.

Temperature

Potatoes are generally considered to be a cool season crop. Estimates of optimal photosynthetic temperatures have ranged from 15 to 25°C with 17°C often prescribed as the optimum temperature for growth and yield (Ewing, 1981). Partitioning of photosynthates within the potato plant also appears to be affected by temperature. High temperatures (e.g. 32 D/18 N) have been shown to suppress tuberization and promote shoot growth, whereas low temperatures (22/18), promote tuberization and inhibit shoot growth (Marinus and Bodlaender, 1975; Menzel, 1980; Benoit et al., 1983). For example, 'Kennebec' plants produced about 12 times as much top biomass at 30/23°C day/night temperatures when compared to 17/10°C temperatures, but tuber yields were much greater under the cooler regime (Gregory, 1965).

High temperatures appear to favor stem elongation at the expense of tuber yield. In greenhouse tests with five varieties, stem elongation, number of leaves, and flower development were all enhanced by 27°C compared to 16° and 22° growing temperatures (Marinus and Bodlaender, 1975). In contrast, the temperature of 27° significantly decreased tuber number and fresh weight, while little yield difference was observed between 16 and 22° environments. Tuber to haulm (shoot) ratios decreased significantly as temperature increased (Marinus and Bodlaender, 1975).

Several extensive studies have been conducted on the temperature tuberization responses of particular potato cultivars in closely controlled environments and four of these are particularly pertinent here: cv. 'Kennebec' (Gregory, 1956); cv. 'Katahdin' (Bonaminio, pers. com.); cv. 'Kennebec' (McCown and Kass, 1977); S. tuberosum x andigenum hybrids (Steward et al., 1981).

'Kennebec' potatoes grown by Gregory (1956, 1965) had a slight increase of tuber yield with decreasing temperature from 30°C to 17°C, but these effects were only evident under an inductive photoperiod (8 h). With temperature decreases under non-inductive photoperiods (16 h), there was little effect on tuber yield, however, there was induction of tuberization on the stolons at 10°C.

'Katahdin' potatoes grown by Bonaminio (pers. com.) had equal tuber production at temperatures of 26°C and 18°C when grown under short days (9 h), but noted a trend of increasing tuber production with decreasing temperature under long days (16 h). He recorded higher tuber to top weight ratios with cooler temperatures under short days, but no consistent response to temperatures under long days.

S. tuberosum x andigenum hybrid potatoes grown by Steward et al. (1981) had higher tuber yields with lower temperatures, however the effects of different temperature on tuberization were not as strong as those of photoperiod. As with the previous studies, temperature exerted a strong effect on shoot to tuber ratio. Plants grown under either 10 or 14-h photoperiods showed more than double the stem production when grown under 24°C versus 12°C (Steward et al., 1981).

'Kennebec' potatoes grown under 12-h photoperiods by McCown and Kass (1977) were moved between cool (20°D and 14°N) and warm (26°D and 20°N) temerature chambers at three stages of plant growth. These phases of growth

roughly coincided with: planting to tuber initiation, tuber initiation to maximum vine growth, and maximum vine growth to scenescence. The largest production was obtained from plants grown under a warm-warm-cool (WWC) regimes. Plants grown under WWW treatments produced less tuber and shoot growth, and had a much lower tuber to top weight ratio. Plants grown under WCC environments also produced less shoot and tuber mass, but had a higher tuber to top ratio than the WWW or WWC plants. Plants grown totally under cool environments (CCC) showed the highest tuber to top ratio, but total tuber production was less than any other treatment.

It appears then that temperature has interacting effects with photoperiod which regulate tuberization (Ewing, 1978), but temperature's most prominent effect is expressed in shoot growth, thereby affecting shoot to tuber ratios.

Recent studies report maximum stem elongation rates for cv. 'Katahdin' occurred near 30°C, while maximum leaf weight occurred near 25°C (Benoit et al., 1983).

Smith (1975) states that temperature is probably the single most important factor in regulating the specific gravity of tubers, with cooler temperatures favoring higher specific gravities.

Nitrogen Nutrition

In general, high nitrogen levels tend to promote large amounts of vine growth and prolong the season of growth in potatoes, while lower levels result in earlier maturation and tubers of higher specific gravity (Smith, 1975; Werner, 1934). Supplying nitrogen as either nitrate or ammonia was effective in suppressing tuber initiation (Krauss and Marschner, 1976).

Recently it has been shown that nitrogen levels may regulate stolon growth and tuberization through control of endogenous ratios of GA's and ABA (Krauss and Marschner, 1982). When nitrogen is adequately supplied, ABA

concentrations stay low giving a high GA:ABA ratio and no tuberization occurs, but if nitrogen is withheld, ABA levels increase and tuberization is favored (Krauss and Marschner, 1982). When nitrogen stress was applied under warm temperatures (30°C), ABA levels increased, but GA levels also increased, thereby preventing any significant change in the overall hormone ratio, and no tubers formed (Krauss and Marschner, 1982).

The availability of nitrogen also affects cytokinin activity in the potato plant (Sattelmachner and Marschner, 1978b). Although the cytokinin activity appears to increase in young tubers and stolons during tuberization, this activity is probably not directly responsible for tuberization per se (Sattelmachner and Marschner, 1978a). However, a decrease in the nitrogen supply also causes a steep increase in cytokinin activity and this might be involved in the mechanisms controlling apparent increases in photosynthetic activity of induced potato plants (Sattelmacher and Marschner, 1978a, Moorby, 1970).

Tuberization in soilless cultures appears particularly sensitive to nitrogen levels, and tuber formation can be difficult to initiate unless nitrogen concentrations are reduced sharply from normal levels (Marschner, per. com.).

Carbon Dioxide

Arthur et al. (1930) conducted controlled climate studies with potato using either ambient (0.03%) or supplemental (0.3%) CO_2 levels. Under cool temperatures, the high CO_2 increased tuber yields. But under warm temperatures, no advantage was obtained from the CO_2-enrichment. These studies were conducted under the light levels present in greenhouses in late winter and early spring near New York City.

Increasing carbon dioxide (CO_2) concentrations have been shown to increase photosynthesis of leaves (Ku et al., 1977), and a report has been

made of increased numbers of tubers when the CO_2 level of the nutrient media was increased (Arteca et al., 1979).

Solution and Mist Culture

We were unable to obtain any reports of the use of solution or mist cultures for the growing of potatoes to full maturity of tubers. These techniques have been used only for short period studies of specific physiological processes in potatoes, such as nutrient uptake and induction of tuberization. Chapman (1958) placed seed pieces atop inverted pots in a vat of aerated nutrient solution which he covered with black tar paper. This kept the seed pieces and emergent stolons above the solution while permitting the roots to trail over the pots and reach the solution level. Tuber enlargement occurred both above and below the solution level (Chapman, 1958). Fong and Ulrich (1969) transplanted sprouted 'White Rose' variety potatoes into 5-gallon pots containing aerated 1/2 strength Hoagland solution. Plant stems were supported by corks placed in holes of a masonite cover. Although the intent of these studies was to observe nutrient effects on shoot growth, the authors reported that tuber growth was abnormal (Fong and Ulrich, 1969). Ulrich et al. (1972) later combined water culture and soil culture techniques to more closely study both shoot and tuber responses. Five-gallon pots filled with alvolite (exploded volcanic ash) were placed atop water holding tanks from which the nutrient solution was pumped to the top of the alvolite and then allowed to drain back into the holding tank below. Salt and pH levels were maintained continuously in the lower water-holding pots. These modifications permitted normal tuber initiation and development (Ulrich et al., 1972).

Arteca et al. (1979) sprouted seed pieces by positioning them in holes bored into a styrofoam sheet after which the sheet was floated on

continuously-aerated water. After two weeks, plants were transferred to individual 3-liter containers of aerated, full-strength Hoagland solution. Solutions were changed weekly and tuber and stolons were allowed to develop in a suspended position above the solution. The tubers and stolons were supported by rubber netting as used in dishwashing sinks (Arteca, per. com.). The harvested tubers were all of small size.

H. Marschner and colleagues (Sattelmacher and Marschner, 1978, Krauss and Marschner, 1982) grew 'Ostara' cultivar plants in 5-liter pots of continuously-aerated nutrient solution. Tubers that developed below the surface of the solution were small and did not enlarge normally (Marschner, per. com.). Tubers apparently developed better in the area above the solution, but no data are provided for comparison of this growth to tuber development in solid media. Pictures of submerged stolons and tubers show an abnormal callus-like surface texture (Sattelmacher and Marschner, 1982) similar to that shown by Fong and Ulrich (1969). We have also observed this surface appearance in our solution culture tests. Tubers and stolons allowed to develop above solution levels have frequently shown calcium deficiency symptoms, while stolons and tubers developing below the surface of the solution showed no calcium deficiency (Marschner, per. com.).

Studies in Holland have demonstrated that stolons require some form of tactile resistance in order for tuber enlargement to proceed normally. Plants growing with roots in solution culture and stolons growing in a dark compartments above the solution did not develop tubers unless the compartment was filled with sand (Borg, per. com.).

GROWING PROCEDURE DEVELOPMENT

Cultivar Selection

'Russet Burbank', 'Norchip', 'Superior', 'Kennebec' and 'Norland' were

selected for study in this CELSS project. These cultivars were chosen based on: 1) their popularity for production and consumption in the United States, and 2) their range of short-season to long-season maturities. The United States average production and other data are shown in Table 1. 'Russet Burbank' is grown and utilized most widely.

The 'Norland' cultivar is a red potato. All others are white. The 'Russet Burbank' and 'Kennebec' cultivars are late maturing and grown for high dry matter content (20-22%) and utilized widely for baking, french fries and potato chips; whereas 'Norchip' and 'Superior' are early-mid maturing and have slightly lower dry matter contents (19-20%). 'Norland' is a very early cultivar with low dry matter (18%) and utilized for boiling or mashing.

Table 1. Potato cultivars selected for investigation.

Cultivar	Certified Seed Acreage grown in U.S.[y]	Maturity
Russet Burbank	70,000	Late
Norchip	17,100	Early-Mid
Kennebec	10,900	Late
Superior	10,500	Early
Norland	6,100 [z]	Early

[y]R. Webb, personal communication.

[z]Includes average of 'Red Norland'.

Propagation

Plants for experimental use were obtained from plantlets maintained under aseptic conditions. Initially .5-1 cm long stolons with buds were excised

from growing plants of each cultivar; these sections were washed with 10% chlorox solution for 4-6 minutes and then rinsed with sterile distilled water and placed on sterile agar media (modified M-S with 6% sucrose) in 8 oz. baby food jars with Magenta (plastic) B-caps. All contaminated cultures were discarded (about 25%). The aseptic cultures were grown to develop shoots 8-10 cm long. Nodal cuttings were then made from these shoots and transferred to 15 cm long and 2 cm wide glass culture tubes with ridged, translucent polypropylene caps containing the media described above. Each cutting included about 0.2 cm of stem above and 0.4 cm of stem below the node. The remaining plantlet parts were discarded.

The cutting was pushed into the agar so that the stem below the node was beneath the agar surface and the nodal bud was at the agar surface.

The cuttings were maintained under 50-80 $umols^{-1}m^{-2}$ PPFD of cool-white fluorescent irradiance for 16 hours each day at 23°C temperature.

Cuttings were grown until they were 8-10 cm in length and then either sectioned for propagation or utilized for experimental studies. When used for experiments the agar was gently separated from the roots in a beaker containing distilled water and plants were transplanted into media or placed into liquid culture systems as discussed in the following sections.

The use of a 6% sucrose in the media was based on a study utilizing four cultivars of potatoes. Best growth was obtained with 6% sucrose. Growth was slowed and internodes elongation was suppressed with 1, 2, 3, 4, and 5% sucrose whereas 8, 10 and 12% sucrose produced no additional growth advantage.

We have found that inclusion of N-dimethyl succinamic acid (Alar) at 200 ppm in the agar media will greatly slow growth and thus has the potential for reducing the frequency that plants must be regenerated from stem cuttings. Plants have remained green and vigorous for three months with no significant

stem or leaf growth. Rapidly developing plantlets can be regenerated from these stunted seedling when the Alar is removed.

Solid Media Systems

Two potting media have been compared in a series of short experiments at the U.W. Biotron with plants grown only to tuber initiation. The one medium was Jiffy Mix peat-lite (Grace Co., Inc.), a mixture of peat and vermiculite (50:50 vol.). The peat-lite has the advantage of light weight, high water holding capacity, and being a commonly used medium in plant research. The second was arcillite, or calcined clay chips. This has been used successfully in past potato research (McCown and Kass, 1977) and has the advantage of being relatively light weight, well drained, and easy to separate from roots, stolons and tubers.

The arcillite was leached with 1% HCl prior to use becuase it is known that there are variable cation complexes held on exchange sites in different lots of arcillite. The leaching involved 12 h of soaking with 1% HCl followed by four flushes with distilled water over a 48-hour period until effluent tested above 5.0 pH. The media was then flushed with two successive flushings of nutrient solution and then used for planting.

Plants grown in peat-lite under 12-h photoperiods produced 10-20% greater shoot and tuber dry weight than plants grown in arcillite. When plants were grown under continuous light, the growth differences were even greater, with shoot and tuber dry weights of plants grown in arcillite being 50% less than plants grown in peat-lite. Thus, we chose to proceed using peat-lite in succeeding studies when a solid growing medium was desired. We suspected that the reduced growth in the arcillite media was due to toxic effects resulting from acid residues trapped within the clay particles. Additional study is

warranted to determine if arcillite could be used effectively for potato growth.

When planting, the media to be utilized for an experiment is placed on a potting bench and distilled water added until the media is as moist as possible without "balling up" when handled. This media is then placed in containers loosely to the top. The containers are then lifted and gently tapped to settle the media to reduce its volume 1/3. They are then refilled to a level 4 cm from the top. The automatic watering system is then attached and the system allowed to operate until 250 ml of liquid for each 1000 ml of media flows from the base of each container.

Plantlets 6-8 cm in length were selected for planting. The plantlets were placed into the media so that 4-6 cm of stem was covered and 2 cm of stem were above the surface. A 150 ml beaker was then inverted over each plant for two days to mitigate transplant shock. Seven days after planting the containers were filled with media to 2 cm from the top.

A nutrient solution (Hammer et al., 1978) was applied to the containers with an automatic watering system with a single 1 mm ID polyethylene tube to each container of less than 4000 ml and multiple tubes or a Chapin watering ring with larger containers. The tubes were secured about 1 cm above the surface and toward the center of the containers with a pot stake which had a hole drilled through it slightly smaller than the tube diameter. The ring was secured with three wooden pot stakes. Elevation of the watering rings was necessary to prevent small plant roots from entering and plugging the tubes. The timer was set so watering occurred every 6 hours with at least 50 ml per watering. As plants enlarged the quantity was increased so that approximately 50% of each addition leached through the media to avoid nutrient buildup in the containers.

The pH of the nutrient solution was adjusted to 5.5 at the start of experiments but as plants enlarged this adjustment was reduced based on the pH of the effluent of the pots. With nutrient solutions using only nitrate as an N-source, it has been found that the effluent pH increases significantly with large plants, reaching levels as great as 7.5-8.0, despite lowering the supply nutrient solution pH to 4.0.

Liquid Systems

Recycling liquid culture systems were developed by utilizing 7.5-liter opaque polyethelene containers 25 cm x 14 cm x 28 cm high. The containers were fitted with rigid PVC fittings to provide overflow into a common container in which pH and nutrient replenishment was provided in a manner described previously (Tibbitts et al., 1978). About 200 ml per minute of nutrient (Hammer et al., 1978) was pumped into each container and pH was adjusted with 0.1 N HCl as needed.

The liquid containers were fitted with gray 2 mm thick PVC sheet covers in which 3.5 cm holes were cut for the plants.

Seedlings 6-8 cm in length were supported by ethanol washed, autoclaved white foam plugs 3.8 cm in diameter (No. T1382, American Scientific Products) through which vertical slits were cut one-half way through. The seedlings were placed in the slit of the plug so that sufficient stem extended on the underside of the plug to keep the stem root junction continuously immersed in liquid. Generally, 3-4 leaf nodes extended below the foam plug. The foam plugs were not allowed to contact the nutrient solution.

The following treatments were studied in the course of the different growth studies conducted in a greenhouse and growth chambers under cool white fluorescent lamps:

a) nutrient level 1 cm below the cover.

b) nutrient level 6 cm below the cover with plastic netting having 3 mm openings suspended 5 cm below the cover.

c) same as (b) treatment and with area between netting and cover filled with moist sphagnum moss.

A minimum of three replicates of each treatment were maintained in each study.

It was necessary to support plants after 2-3 weeks growth with a string tied loosely around the stem and secured above the plants.

Best tuberization was found in the treatment with sphagnum moss in the stolon development area. Very few tubers were initiated in the open stolon development area whereas a large number but small tubers were initiated when the solution covered the stolon development area. All tubers that developed below liquid level formed callus on their surfaces.

Considerable problems were experienced with a necrosis or corking of an area of the stem just below the foam plug. We hypothesize that this resulted from nutrient wicking up the stems causing toxic salt concentrations on the exposed stem areas. There was also evidence of necrosis of the tip of stolons that developed in the open area above the netting when spagnum was not used. It was not determined whether this also resulted from salt accumulation or was a result of calcium deficiency in the developing tip areas.

Mist Systems

The system developed was a modification of an aeroponic system developed by Richard W. Zobel, Peter Del Tredici, and John G. Torrey of the Cabot Foundation at Harvard University.

The system consisted of a framework supporting black polyethylene sheeting and enclosing a plastic tub at the base. A motor drove a plastic impellor disc supported above the liquid in the tub which atomized solution as

it was drawn out from the rim. This created a mist which fed the roots of the potato plant in an aeroponic environment (Figure 1).

The framework of the apparatus measured 28 x 56 x 28" (WxLxH) and was made of 2 x 3" lumber or of 2" galvanized angle iron in different studies.

A plastic container (cement mixing vat) measuring 2'x4'x8" (WxLxH) was placed in the bottom of the box. This acted as the nutrient reservoir and mixing chamber. A 1/2" PVC bulkhead fitting, positioned 2 cm above bottom of tub, acted as a gravity drain to facilitate constant renewal of solution. Black polyethylene plastic was secured to the top of the frame on the inner side of the box and draped into the plastic tub to create sides for the mist box. This also acted as a light curtain. A second layer was attached on the inner side of the frame but on the outside of the tub to prevent any light penetration.

The cover of the box consisted of 1" polystyrene foam hinged to a board located across the center of the box. This gave the effect of two 70 x 70 cm hinged tops on either side of the center support.

One-inch holes were drilled in the top of the polystyrene in the desired locations for the plants. Plants were supported with polyurethane foam plugs. Additional plant support was provided from above using strings attached to the ceiling above each plant. Plant stems were held by twist wires attached to the string. Holes for plants should be at least 6" apart for experiments up to 6 weeks and at least 10" apart for longer experiments as a safe average distance to insure adequate plant growing space and prevent crowding. Plastic mesh baskets with 1/4" openings were added below each plant to hold and support tubers and to aid in the spreading of the roots.

The motor assembly was secured to the center 2x4 support to which the box cover was hinged. The motor was supported vertically with a stainless steel shaft dropping into the mist box. The impellor was attached to the end of the

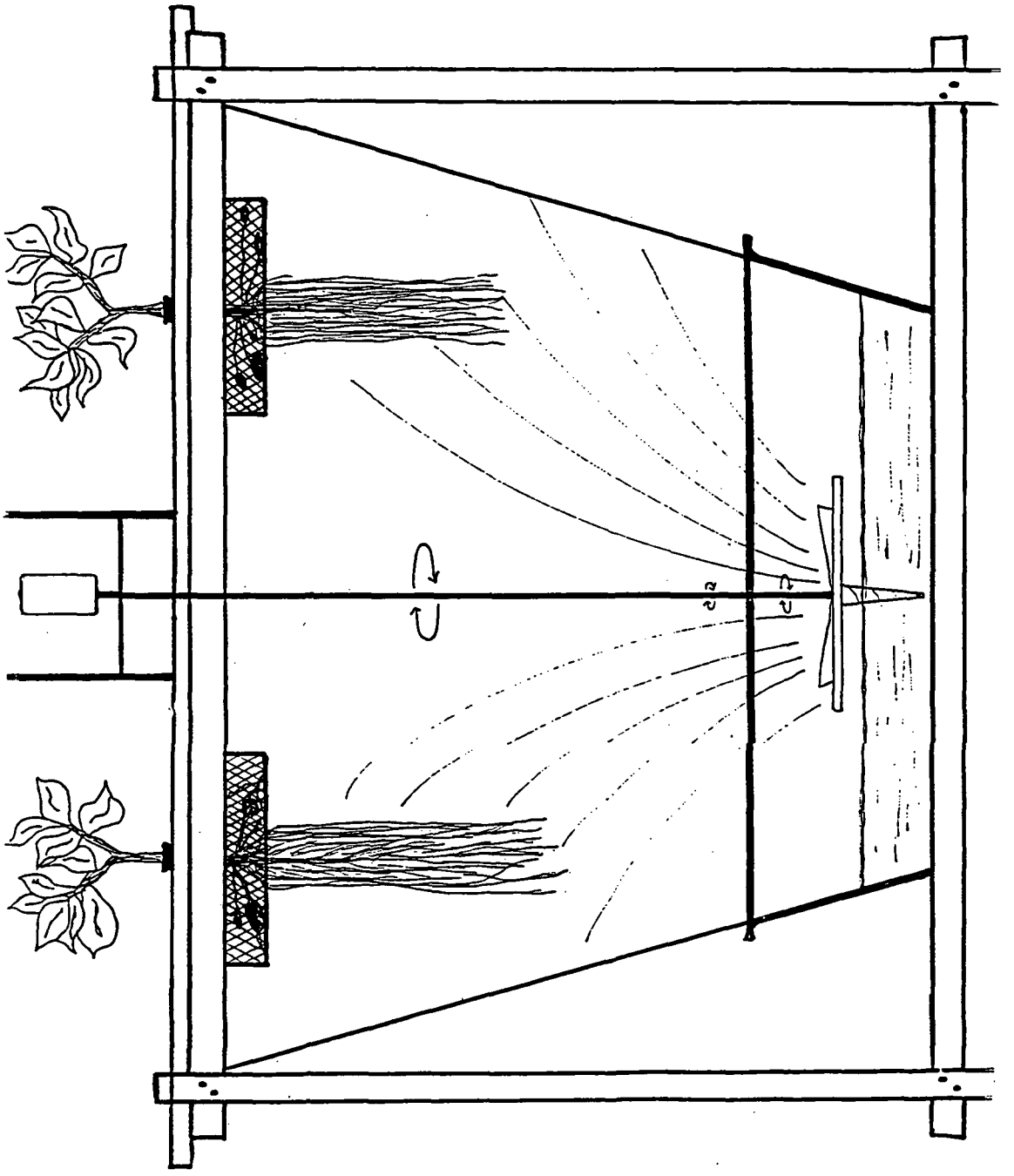

Figure 1. Diagram of system utilized for mist culture of potatoes.

shaft and secured by threading the end of the stainless steel shaft and tightening with a nut. The tip of the impellor was located ≈1" below the surface of the solution in the bottom of the tub. The hole in the impellor bottom was enlarged to 3/16 inch to obtain a greater quantity of mist. The impellor was obtained from Electric Service Station, Hattica, Miss. 39401--Cat. #38994-000 and the electric motor was obtained from Electro Sales Co., 100 Fellsway West, Somerville, Mass. 02145. The motor was a 1/35 horsepower, 3400 RPM solid bearing motor, Model #d208, Type U21.

The solution in the growing vat was continuously recirculated with solution in a 20-liter mixing tank at a rate of 2 ℓ per minute. A pump was utilized to move the solution from the mixing tank to the growing system. Solution returned by gravity to the mixing tank through a drain (1/2"diameter) in the bottom of the misting vat. The pH of the solution was regulated at 6.0 in the mixing tank through use of an automatic pH controller that added 0.1N HCl or 0.1N NaOH as needed. The solution in the mixing tank was replenished with fresh nutrient solution through use of a float assembly that opened a solenoid to permit addition of fresh solution when the solution lowered below a set level. The nutrient solution utilized was the formulation reported by Hammer et al. (1978).

Plants have grown rapidly with normal leaf stem and root growth in the mist chambers. However, there was very poor development of tubers in the system. Small tubers were initiated on some stolons but enlargement did not appear to proceed normally. Two separate cultural modifications have been attempted to improve tuberization. These involved 1) filling the stolon area above the screen with sphagnum moss and 2) reducing the nitrogen concentration of the nutrient solutions after plants had enlarged.

The sphagnum moss was screened to eliminate all fine particles less than 0.5 cm and then soaked to thoroughly moisten the material before filling the stolon area.

The sphagnum moss has provided some improvement in tuberization but it did not provide normal tuberization on the plants.

Nitrogen uptake was regulated by growing the plants in the nutrient containing 7.5 meg/ℓ N_2 for 7 weeks until the plants were 50 cm in diameter and stolons were well developed. The solution in the misting vat and in the mixing chamber was then discarded and immediately replaced with solution containing no nitrogen. Other major element concentrations were essential the same as the starting solution, while the minor elements were exactly the same. Results from a single short study using this procedure indicated some stimulation of tuberization over plants with normal amounts of nitrogen. Thus, an additional study is underway to repeat this investigation and future studies are planned to determine the optimum timing of nitrogen reduction and most desirable concentration shift.

GROWTH STUDIES

Principal effort in the research to date has been to establish the effectiveness and efficiency of different lighting regimes for tuber production in controlled environments. Initially, effort was directed toward establishing the capacity of different cultivars to tuberize under different photoperiods and then to establish the interacting effect of different light intensities under continuous light periods. In the course of these studies detailed data have been taken on canopy formation to establish desirable spacing requirements at different stages of development.

Photoperiod

Sterile grown plants from cvs. 'Norland' (early-season), 'Superior' (early-mid), 'Norchip' (early-mid), and 'Kennebec' (late) transplanted to 20-liter black plastic containers of peat-vermiculite for the study. Experiments were conducted in walk-in growth rooms (2.6 m x 3.6 m) at the

University of Wisconsin Biotron. Plants were grown in separate rooms under 12, 16 or 20-h photoperiods. Irradiance was provided by 60 VHO 210W cool white fluorescent lamps. PPFD levels were maintained at 400 μmol m^{-2} s^{-1} (± 20 μmol s^{-1} m^{-2}) at the top of the canopies by turning off pairs of lamps as plants grew. This provided approximately 17.3, 23.0, and 28.8 mols m-2 day-1 of PPFD for the 12, 16 and 20-h treatments. Temperatures were set at a constant 20 C (± 0.5 C) and relative humidity at 70% (± 5%). At 6 weeks, the plants were encaged in wire fence cylinders, 46 cm (18 inches) in diameter and 122 cm (48 inches) 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 limit shoot growth to the circumference of the enclosure. Harvest was made at 15 weeks from transplanting with data on leaf, stem, and tuber fresh and oven-dry mass obtained.

The total dry mass for the four cultivars and the three irradiance regimes are shown in Table 2. With the exception of 'Kennebec' plants under 20-h, all the cultivars showed an increase in total biomass with increasing irradiation. 'Kennebec' plants under 16 and 20-h photoperiods showed dimunitive, upright leaves and gold "rusty" flecking of the adaxial surfaces of the leaflets. Additional studies indicate that this injury is a physiological response to the longer irradiance periods as reported for tomatoes (Hillman, 1956). Tuber growth was suppressed under the 16-h photoperiod in comparison to the 12 or 20-h treatments.

Table 2. Biomass of 15-week-old potato plants grown under three irradiance periods. Data represent means of three plants ± the standard deviation.

Cultivar		Irradiance Period[z] 12-h	16-h	20-h
		(grams dry mass per plant)		
Norland	Tuber	325 ± 28	361 ± 19	435 ± 78
	Total	472 ± 32	663 ± 10	815 ± 31
Superior	Tuber	257 ± 11	224 ± 19	293 ± 61
	Total	422 ± 34	520 ± 5	677 ± 66
Norchip	Tuber	258 ± 32	194 ± 30	304 ± 59
	Total	455 ± 33	530 ± 19	710 ± 77
Kennebec	Tuber	337 ± 34	32 ± 4[y]	163 ± 93[y]
	Total	533 ± 46	442 ± 93[y]	512 ± 31[y]

[z] PPFD = 400 μmol s^{-1} m^{-2}.

[y] Plants stunted and malformed.

In contrast to total biomass, the tuber yield varied significantly depending on cultivar. Tuber yields of 'Norland' plants increased with the increasing irradiation, yielding 325, 361, and 435 g dry mass per plant from the 12, 16, and 20-h treatments (Table 2). 'Superior' yields showed a small increase when irradiation was increased from 12 to 20-h (257 to 293 g/plant), but dropped under 16-h irradiation to 224 g/plant. 'Norchip' plants showed a similar trend with 258 and 304 g/plant under 12 and 20-hr with a drop to 194 g/plant under 16-h. The 'Kennebec' plants produced good tuber yields under 12-h, 337 g/plant, but small yields under 16 and 20-h irradiance where injury was seen.

Table 3 presents the yield data on an area basis using a spacing of 0.2 m^2 per plant. 'Kennebec' plants produced the highest dry mass yields under 12-h irradiance, while 'Norland' plants showed the highest yields under 16 and 20-h. 'Norland' plants under 20-h irradiance produced over 4 kg total dry mass per square meter with nearly 2.2 kg tuber dry mass.

Table 3. Tuber and total plant biomass yields per unit area of 15-week-old potatoes grown under three irradiance levels ± the standard deviation.[z]

Cultivar		Irradiance Period[z] 12-h	16-h	20-h
			($g\ m^{-2}$)	
Norland	tuber	1625 ± 140	1805 ± 95	2175 ± 390
	total	2360 ± 160	3315 ± 10	4070 ± 330
Superior	tuber	1285 ± 55	1120 ± 95	1465 ± 305
	total	2110 ± 170	2600 ± 25	3385 ± 330
Norchip	tuber	1290 ± 160	970 ± 150	1520 ± 295
	total	2275 ± 165	2650 ± 90	3550 ± 385
Kennebec	tuber	1685 ± 170	160 ± 20[x]	815 ± 465[x]
	total	2665 ± 230	2280 ± 465[x]	2560 ± 155[x]

[z] Spacing of 0.2 m^2 per plant.

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

[x] Plants stunted and malformed.

A comparison of the harvest index values (i.e. tuber dry mass/total plant dry mass) is shown in Table 4. 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 12-h were the highest of

all the cultivars with an average of 69% of their final biomass in the form of tubers. The harvest indices decreased sharply for all cultivars under 16-h of irradiance and remained the same or increased slightly from this level under 20-h.

Table 4. Harvest index (tuber biomass/total biomass) of 15-week-old potatoes grown under three irradiance periods. Data represent means of three plants ± the standard deviation.

Cultivar	Irradiance Period[z] 12-h	16-h	20-h
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[y]	0.32 ± 0.17[y]

[z] PPFD = 400 μmol s^{-1} m^{-2}.

[y] Plants stunted and malformed.

Comparisons of total biomass on an area basis per hour of irradiance showed little change with increasing irradiance in 'Norland', 'Superior', or 'Norchip' plants. In contrast, because of the stunted growth under 16 and 20-h treatments, the "growth efficiency" of the 'Kennebec' plants dropped sharply with lengthened irradiance period (Table 5). Comparing the tuber yields in a similar fashion to calculate tuber mass per area per hour irradiance showed a distinct decrease in efficiency at 16-h and 20-h irradiance periods over 12-h irradiance (Table 6). 'Norchip' had greater tuber production efficiency at 20-h than at 16-h whereas 'Norland' and 'Superior' had similar efficiency at 16 and 20-h.

Table 5. Potato plant biomass per unit area and per hour of daily irradiance at 15-weeks-age ± the standard deviation.

Cultivar	Irradiance Period[z] 12-h	16-h	20-h
	g m^{-2} per hr irradiance[y]		
Norland	197 ± 13	207 ± 1	204 ± 8
Superior	176 ± 5	163 ± 2	169 ± 17
Norchip	190 ± 14	166 ± 6	178 ± 19
Kennebec	222 ± 19	143 ± 29[x]	128 ± 8[x]

[z] PPFD = 400 µmol s^{-1} m^{-2}.

[y] Spacing of 0.2m^2 per plant.

[x] Plants stunted and malformed.

Table 6. Potato tuber production per unit area and per hour of daily irradiance at 15-weeks-age ± the standard deviation.

Cultivar	Irradiance Period[z] 2-h	16-h	20-h
	(g m^{-2} h^{-1} of irradiance)[y]		
Norland	135 ± 12	113 ± 6	109 ± 20
Superior	107 ± 5	70 ± 6	73 ± 15
Norchip	108 ± 13	61 ± 9	76 ± 15
Kennebec	140 ± 14	10 ± 1[x]	28 ± 23[x]

[z] PPFD = 400 µmol s^{-1} m^{-2}.

[y] Spacing of 0.2 m^2 per plant.

[x] Plants stunted and malformed.

Comparisons of the different cultivars indicates that the earliest cultivar, 'Norland', increased tuber yield more than the later maturing cvs. of 'Norchip' and 'Superior' with increasing light duration, while 'Kennebec'

only tuberized well under the 12-h treatment. This trend follows the general observations of others that the length of the light period exerts a stronger influence on tuberization of late cultivars than on earlier cultivars (Driver and Hawkes, 1943; Bodlaender, 1963). In related studies we have grown these same cultivars under 24-h photoperiods with 12-h of 400 μmol s^{-1} m^{-2} and 12-h of 5 μmol s^{-1} m^{-2} and observed no injury. Hence, injury to the 'Kennebec' plants appears to be a symptom of the high irradiance and not the long photoperiod. Also, the susceptibility of different cultivars to high irradiance injury does not appear to follow any early to late maturity trends: for example, 'Superior', an early-mid cultivar, injuries when under continuous 400 μmol m^{-2} s^{-1} irradiance, while 'Russet Burbank', a late cultivar does not.

The success of the early cultivar 'Norland' to produce a large amount of tubers (2.88 kg/plant) under 20-h of irradiance indicates the potential of longer photoperiods to accelerate the growth and edible production of potatoes. Other studies have shown that elevated irradiance levels must be maintained to obtain effective tuber production. But when irradiance durations are compared on the basis of energy efficiency (i.e., edible calories returned per lamp-watt input), the 12-h plants had greater efficiency. Therefore, it appears that the suppressing effects of the long photoperiod on tuberization are not completely negated by the higher total irradiance in the study. It is noteworthy, however, that 'Norchip' showed an increase in efficiency by increasing irradiance levels from 16-h to 20-h. The fact that total dry mass production per unit of irradiance was similar at all irradiance durations (Table 5) indicates that the photosynthetic potential for tuber production is similar at 12, 16, and 20-h photoperiods. Thus combining the effects of higher irradiance levels with other tuber-promoting conditions such as cooler temperatures and lowered nitrogen concentrations may allow further increases in the irradiance efficiency under the long photoperiods.

Continuous Lighting

In these studies five separate light treatments were utilized to determine the effectiveness of different lighting procedures for tuber production. All experiments were conducted in walk-in growth rooms of the University of Wisconsin Biotron under cool white fluorescent lamps with canopy-level PPFD maintained at 200 or 400 μmol s^{-1} m^{-2} (± 10). Dim lighting (5 μmol s^{-1} m^{-2}) for daylength extension was provided with either cool white fluorescent (CWF) or incandescent (INC) lamps.

Experiment treatments included: 1) 24 h at 200 μmol s^{-1} m^{-2}, 2) 24 h at 400 μmol s^{-1} m^{-2}, 3) 12 h at 400 μmol s^{-1} m^{-2} plus 12 h at 5 μmol s^{-1} m^{-2} with dim INC irradiance, 4) 12 h at 400 μmol s^{-1} m^{-2} plus 12 h at 5 μmol s^{-1} m^{-2} with dim CWF irradiance, and 5) 12 h at 400 μmol s^{-1} m^{-2} and 12 h dark. Plants given a 12-h photoperiod and 12-h dark were used as a control comparison, representative of induced potato growth and development.

Cultivars studied included: 'Norland' (NL), 'Superior' (SP), 'Norchip' (NC), 'Russet Burbank' (RB), and 'Kennebec' (KN), early to late maturity, respectively. Uniform sterile culture plantlets were transplanted to 20-l plastic pots of peat-vermiculite (50:50 v/v). Five plants of each of the five cultivars were positioned randomly in each room at a spacing of 50-cm between centers. Plants were harvested at 6 weeks after transplanting, tubers and shoots were separated, and weights taken of fresh and oven dry mass. A 6-week harvest age was chosen to avoid overlap of leaves between plants and complications arising from competition for canopy space. All treatments except 12 + 12 dim INC were repeated in different growth rooms to minimize potential chamber effects.

Distinct cultivar differences were apparent in regard to tolerance to continuous lighting at 200 and 400 μmol s^{-1} m^{-2} PPFD levels after 6 weeks; KN and SP plants in these treatments grew vigorously for the first week but began to show flecking and malformation of the leaves after 10 to 12 days. Other early injury symptoms in SP included a mottled chlorosis and cupping of the young, expanding leaves. As a consequence, the overall growth and development of SP and KN plants under continuous 200 or 400 μmol s^{-1} m^{-2} was severely restricted. NC plants showed leaf flecking and mild leaf chlorosis on the main shoot after 10 days, but emergent axillary branches remained dark green and healthy. Aside from some reddish-purple coloration or streaking on abaxial laminae surfaces, NL and RB plants showed no obvious abnormal responses to constant irradiation at 200 or 400 μmol s^{-1} m^{-2} after 6 weeks growth. All the cultivars sustained healthy shoot growth when given 12 h high irradiance in combination with 12 h dark, 12 h dim INC, or 12 h dim CWF irradiance.

A comparison of tuber production for the different treatments in shown in Figure 2 and Table 7. All cultivars had begun to tuberize at 6 weeks under 12 h at 400 μmol s^{-1} m^{-2} and 12 h dark, with early cvs. NL and SP showing the greatest tuber development, and the late-season cultivar KN the least (Table 7). Replacing the dark period by either dim INC or CWF irradiance suppressed tuberization in all cultivars, with dim INC light causing slightly more suppression. Continuous 200 μmol s^{-1} m^{-2} also suppressed tuberization in relation to plants given 12 h of dark, but not as completely as dim light treatments. Growing plants under a continuous 400 μmol s^{-1} m^{-2} level increased tuber weights of uninjured cultivars dramatically over continuous 200 μmol m^{-2} s^{-1} plants at 6-weeks-age and also surpassed tuber weights of plants given a 12-h dark period. KN and SP plants with stunted shoot growth under continuous 200 or 400 μmol s^{-1} m^{-2} showed little tuber, stolon, or root development.

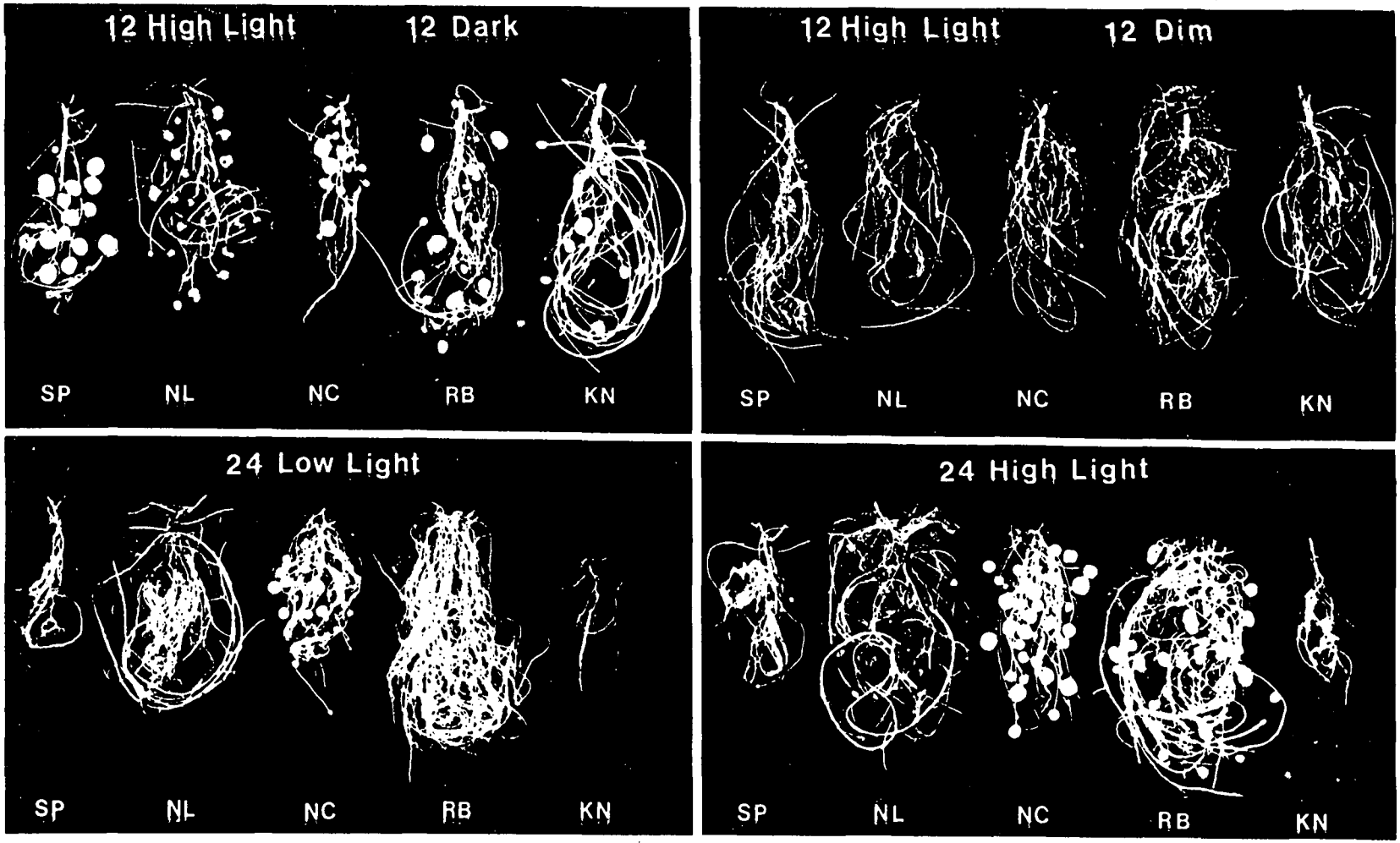

Figure 2. Tuberization of potato in response to upper left - 12 h at 400 µmol $s^{-1}m^{-2}$ PPFD and 12 h dark; upper right - 12 h at 400 µmol $s^{-1}m^{-2}$ and 12 h at 5 µmol $s^{-1}m^{-2}$; lower left - 24 h at 200 µmol $s^{-1}m^{-2}$; lower right - 24 h at 400 µmol $s^{-1}m^{-2}$. Plants were 6 weeks old at harvest. Cultivars included: Superior(SP), Norland (NL), Norchip (NC), Russet Burbank (RB), and Kennebec (KN). All treatments shown were with cool white fluorescent lamps. The treatment utilizing incandescent lamps during the dim light period was similar to the upper right treatment. Norland (NL) tubers are not clearly shown because of their red color.

Table 7. Potato tuber fresh mass of 6-week-old plants grown under different irradiance treatments. Coefficients of variation are indicated in parentheses after each weight.

Cultivar	Irradiance Duration and Level[z] 12 h (400) 12 h dark	12 h (400) 12 h (5 INC)[y]	12 h (400) 12 h (5)	24 h (200)	24 h (400)
			(g)		
Norland (NL)	107 (33)	0 ([x])	0 ([x])	3 ([x])	141 (29)
Superior (SP)	94 (33)	<.5 ([x])	3 ([x])	<.5([x])[w]	1 ([x])[w]
Norchip (NC)	39 (21)	<.5 ([x])	7 ([x])	18 (48)	100 (15)
Russet Burbank (RB)	46 (30)	<.5 ([x])	1 ([x])	3 ([x])	128 (38)
Kennebec (KN)	23 (115)	0 ([x])	0 ([x])	0 ([x])[w]	0 ([x])[w]

[z] Values in parentheses indicate levels in μmol s^{-1} m^{-2} PPFD provided by cool white fluorescent lamps.

[y] Incandescent lamps were used for this 12 h low irradiance treatment.

[x] Coefficient of variability is not applicable for some plants had no tubers.

[w] Plants stunted with malformed leaves.

With the exception of RB plants, at 6-weeks-age, tuber to shoot dry biomass ratios were highest in plants provided a 12-h dark period, with ratios under 24-h at 400 μmol s^{-1} m^{-2} second highest (Table 8). RB plants showed a slightly larger tuber to shoot biomass ratio under continuous 400 μmol s^{-1} m^{-2} than when given a dark period. The other treatments studied had allocated only small amounts of biomass to tubers by the 6 week harvest time (thus this ratio has little meaning for these treatments).

Table 8. Ratio of tuber to shoot biomass of 6-week-old plants grown under different irradiance treatments.

Cultivar	Irradiance Duration and Level[z] 12 h (400) 12 h dark	12 h (400) 12 h (5 INC)[y]	12 h (400) 12 h (5)	24 h (200)	24 h (400)
Norland (NL)	0.32	0.00	0.00	<0.01	0.21
Superior (SP)	0.36	0.00	<0.01	<0.01[x]	<0.01[x]
Norchip (NC)	0.20	0.00	0.02	0.04	0.17
Russet Burbank (RB)	0.16	0.00	<0.01	0.01	0.18
Kennebec (KN)	0.07	0.00	0.00	0.00[x]	0.00[x]

[z] Values in parentheses indicate levels in μmol s^{-1} m^{-2} PPFD provided by cool white fluorescent lamps.

[y] Incandescent lamps were used for this 12 h low irradiance treatment.

[x] Plants stunted with malformed leaves.

Extension of the daylength period by dim INC radiation increased stem elongation in all cultivars over elongation in all other treatments. (Table 9). The stem length of the plants with dim CWF daylength extension, continuous irradiance at 400 μmol s^{-1} m^{-2}, and plants given a dark period was similar and of least length. The stem length of plants grown with continuous irradiance at 200 μmol s^{-1} m^{-2} was intermediate to the dim INC and other treatments. These stem length comparisons were true also for KN and SP plants despite the leaf injuries and malformation. Generally, increased stem length resulted from increased internodal lengths with little difference in node numbers on the main stem apparent between treatments (Table 10). An exception was KN plants injured under continuous 200 or 400 μmol

s^{-1} m^{-2} irradiance which developed more main stem nodes in comparison to other treatments.

Table 9. Main stem length of 6-week-old potato plants grown under different irradiance treatments. Coefficients of variation are indicated in parentheses after each stem length.

Cultivar	Irradiance Duration and Level[z]				
	12 h (400) 12 h dark	12 h (400) 12 h (5 INC)[y]	12 h (400) 12 h (5)	24 h (200)	24 h (400)
	(cm)				
Norland	34 (7)	66 (0)	34 (8)	56 (8)	29 (12)
Superior	28 (11)	52 (7)	29 (10)	32 (33)[x]	22 (16)[x]
Norchip	18 (9)	55 (1)	24 (14)	34 (18)	25 (12)
Russet Burbank	25 (11)	63 (6)	28 (10)	38 (13)	31 (6)
Kennebec	24 (9)	45 (3)	23 (12)	27 (6)[x]	19 (4)[x]

[z] Values in parentheses indicate levels in μmol s^{-1} m^{-2} PPFD provided by cool white fluorescent lamps.

[y] Incandescent lamps were used for this 12 h low irradiance treatment.

[x] Plants stunted with malformed leaves.

Table 10. Number of nodes on main stem of 6-week-old potato plants grown under different irradiance treatments. Coefficients of variation are indicated in parenthesis after each node number.

Cultivar	Irradiance Duration and Level[z] 12 h (400) 12 h dark	12 h (400) 12 h (5 INC)[y]	12 h (400) 12 h (5)	24 h (200)	24 h (400)
Norland (NL)	25 (6)	25 (0)	27 (5)	27 (5)	21 (10)
Superior (SP)	24 (8)	25 (3)	26 (5)	25 (15)[x]	26 (5)[x]
Norchip (NC)	24 (2)	25 (4)	26 (3)	28 (5)	27 (5)
Russet Burbank (RB)	25 (5)	25 (3)	26 (4)	27 (2)	24 (4)
Kennebec (KN)	25 (6)	26 (4)	27 (9)	30 (10)[x]	30 (6)[x]

[z] Values in parentheses indicate levels in μmol s^{-1} m^{-2} PPFD provided by cool white fluorescent lamps.

[y] Incandescent lamps were used for this 12 h low irradiance treatment.

[x] Plants stunted with malformed leaves.

Extending the daylength with dim INC resulted in significantly reduced plant biomass gains at 6-weeks-age when compared to the other treatments given similar total PAR levels (Table 11). Extending the daylength with dim CWF light resulted in similar total plant biomass in comparison to treatments given 12 h dark. Continuous 200 μmol s^{-1} m^{-2} increased total plant biomass by more than 50% in comparison to control plants grown with similar total PAR provided over a 12-h day length or with dim CWF light extension. Maintaining continuous 400 μmol s^{-1} m^{-2} irradiance increased dry mass of these same cultivars by more than 140% of plants grown under 400 μmol s^{-1} m^{-2} level for only 12 h.

Table 11. Total plant dry mass of 6-week-old potato plants grown under different irradiance treatments. Coefficients of variation are indicated in parenthesis after each weight.

Cultivar	Irradiance Duration and Level[z] 12 h (400) 12 h dark	12 h (400) 12 h (5 INC)[y]	12 h (400) 12 h (5)	24 h (200)	24 h (400)
			(g)		
Norland (NL)	53 (15)	33 (8)	44 (7)	80 (8)	125 (7)
Superior (SP)	39 (5)	24 (15)	43 (16)	17 (28)[x]	25 (25)[x]
Norchip (NC)	27 (8)	23 (18)	35 (14)	44 (16)	74 (5)
Russet Burbank (RB)	45 (8)	42 (9)	50 (11)	74 (9)	115 (6)
Kennebec (KN)	39 (10)	22 (8)	41 (15)	12 (18)[x]	10 (29)[x]

[z] Values in parentheses indicate levels in μmol s^{-1} m^{-2} PPFD provided by cool white fluorescent lamps.

[y] Incandescent lamps were used for this 12 h low irradiance treatment.

[x] Plants stunted with malformed leaves.

The injury from continuous irradiation of potato cultivars has not previously been reported although there have been no previous continuous light investigations with the particular cultivars injured in this study. 'Irish Cobbler', a cultivar not included in this study, showed no injury under continuous irradiation in a previous controlled environment studies (Arthur et al., 1930) and potatoes have been grown normally at the Arctic Circle under continuous light (Driver and Hawkes, 1943). In contrast, there have been reports of injury to other species of plants from continuous irradiation. Tomato, coleus, and geranium all have been found to be injured by continuous

irradiation (Arthur et al., 1930). Of these, tomato appeared the most sensitive showing injury within 5-7 days of transfer to continuous-light environments. This appeared as mottled leaf chlorosis and brown necrotic spotting depending on leaf age and growing temperatures (Hillman, 1956). These symptoms closely resemble the injury seen with KN and SP plants under continuous 200 or 400 μmol m^{-2} s^{-1} irradiation in this study. The injury on tomatoes could be prevented if temperatures were varied on a diurnal basis (Hillman, 1956).

It appears that the problems with potatoes grown under continuous light are not photoperiodic in nature as shown by the lack of injury under the dim daylength extension treatments. Rather, the injury to the sensitive potato cultivars appear to be a growth-related phenomenon. The sensitive cultivars required an interval of low-level irradiance or darkness to maintain vigorous shoot growth.

Plants given either dark or low-level irradiance maintained defined circadian leaf movements: during the light period, young expanding leaves maintained a low and nearly prostrate orientation, while during the dark or dim-light periods, the leaves were inclined upward. Also, guttation occurred frequently during the dark or dim light cycles. In contrast, under continuous 200 and 400 μmol s^{-1} m^{-2} treatments leaves were always partially inclined upward and no guttation was noted. A comparison of stomatal conductance revealed that both the injury sensitive and insensitive cultivars given either dark or dim irradiance treatments closed their stomata during these periods, while plants grown under constant irradiance levels maintained open stomata.

The stomatal data would indicate that the photosynthetic systems are operating continuously under the constant 200 and 400 μmol m^{-2} s^{-1} irradiance; hence, the susceptibility to injury may be related to capability

of the different cultivars to maintain continuous photosynthesis and continuous rates of carbohydrate export from the leaves. Certain cultivars may be unable to avoid deleterious accumulation of free radicals or excessive build-up of starch within the chloroplasts (Powles, 1984; Bradley and Janes, 1984). The range of tolerances to continuous irradiance shown by the cultivars examined (NL and RB insensitive, NC transiently sensitive, and SP and KN highly sensitive) indicate that this group of potato cultivars may be a potentially useful contrasting system for photoinhibition studies.

The reduced growth of the plants given dim INC daylength extension when compared to plants given either dim CWF daylength extension or a dark period could have resulted from shifts in carbon allocation from leaves to stems resulting in reduced photosynthetic leaf-surface area. The dim INC plants' stems comprised an average of 34% of the total shoot dry weight for all cultivars, while stems were only 19% of the shoot dry weight of plants given a dark period, and 25% for plants given dim CWF daylength extension. Although plants of the high irradiance tolerant cultivars grown under continuous 200 $\mu mol\ s^{-1}\ m^{-2}$ PAR also allocated a larger percent of the shoot biomass to stems, 31%, they still showed total biomass gains 50% greater than plants given a dark period. The growth stimulation in this continuous light treatment might be explained by the more efficient photosynthetic utilization of light when spread over 24-h instead of 12-h. The growth stimulation in this continuous 200 $\mu mol\ s^{-1}\ m^{-2}$ treatment also may be due to the fact that these plants had larger canopy diameters than plants from other treatments and as a consequence would have intercepted more PAR and had greater photosynthetic carbon fixation than plants of the other treatments.

At the 6-week-harvest, the plants grown under continuous 200 $\mu mol\ s^{-1}\ m^{-2}$ showed higher biomass gains per unit input of irradiant energy than plants with continuous 400 $\mu mol\ s^{-1}\ m^{-2}$. It is apparent that doubling

the total PAR input did not result in a doubling of biomass. Bodlaender (1963) reported a similar trend of higher mass per unit illumination at low irradiance levels in comparing potato growth between irradiance levels varying from 2000 to 16000 lux.

The suppressed tuberization with daylength extensions using dim irradiance levels or with continuous 24-h irradiance at low PAR levels closely follows the findings of others (Garner and Allard, 1923, Pohjakallio, 1951; Gregory, 1956; Chapman, 1958; Steward et al., 1981). However, maintaining continuous 'high' level irradiance (400 μmol s^{-1} m^{-2}) substantially increased tuber growth and resulted in tuber weight gains approximately twice those of plants given a dark period. 'Tuber to top' ratios (Table 8) suggest that the tuber induction of plants under continuous high-level irradiance is nearly as strong as that in the plants given a dark period. Hence, the results of this study indicate that continuous lighting encourages vegetative development at the expense of tuber production unless the daily PAR levels are sufficiently high. Pohjakallio (1951) noted a similar suppression by low-light daylength extensions following high "daytime" light levels, while daylength extensions following relatively low "daytime" light levels were capable of enhancing tuberization. Data from longer-term studies (15 weeks), with the same cultivars, indicate that high irradiance loads can sustain a strong tuberization stimulus, but tuber to top ratios under long day-length environments fail to be as great as those attained under shorter day lengths.

Canopy Development

Information on canopy development was obtained from different cultivars during the growth of plants under 12-h light periods in the photoperiod studies. In these studies, plants were grown under cool-white fluorescent lamps at 400 μmol $s^{-1}m^{-2}$ 20°C and 70% RH.

Data were obtained utilizing a plumbline point quadrat procedure. This involved lowering an elliptical (20 mm x 14 mm) 28-g lead weight on a nylon line (0.2 mm diam) through the growing area at random scattered locations and counting the number of plant contacts between the plant and line (Brown, 1982). A minimum of 75 drops were made across the plant growing area.

Data were gathered as plants enlarged to fill the growing area and into the subsequent weeks of tuber growth and maturation. Information on the number of leaf layers was determined as leaf area index (leaf area per unit ground area) and foliage area index (leaf and stem area per unit ground area).

The effectiveness of leaf layers in intercepting the irradiation over the growing area was determined by monitoring the photosynthetic irradiance at the soil suface as the plants enlarged.

LAI estimates from plumb-line point quadrats are shown over time for individual plants of cultivars 'Norchip', 'Kennebec', 'Norland', and 'Superior' in Fig. 3. Each of the cultivars showed an increase in LAI from about 1.5 to about 4.0 between 2 and 6 weeks of age, with 'Norland' plants showing the most rapid increase in LAI during this time. A large LAI increase occurred between the second and third weeks in all cultivars which coincided with the initial elongation of axillary branches.

The canopy development of a solid stand of 'Norchip' potato plants grown for 13 weeks in a walk-in growth room is shown in Fig. 4. Leaf and foliage area index estimates from plumb-line point quadrats for both individual plants and the entire stand are shown prior to 6 weeks (Fig. 4). After 6 weeks, the gaps between plants had closed i.e., ground cover was 100%, and individual plant estimates of LAI and FAI equalled total stand estimates. Estimates of LAI and FAI peaked at 4.6 and 5.7 at 9-weeks-age respectively, after which a collapse occurred in the center of the stand. This lodging caused a reduction in the number of contacts recorded during the tenth and eleventh weeks. By

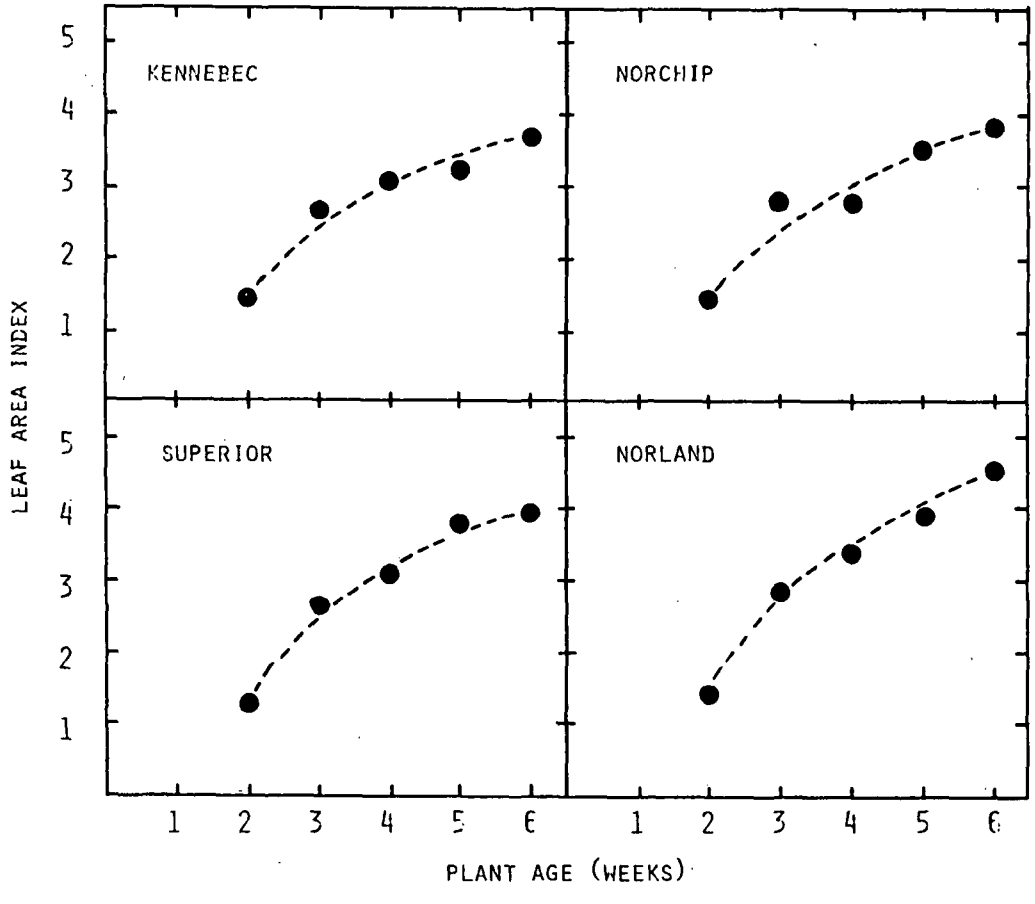

Figure 3. Leaf area index of four cultivars of potato grown as isolated individual plants.

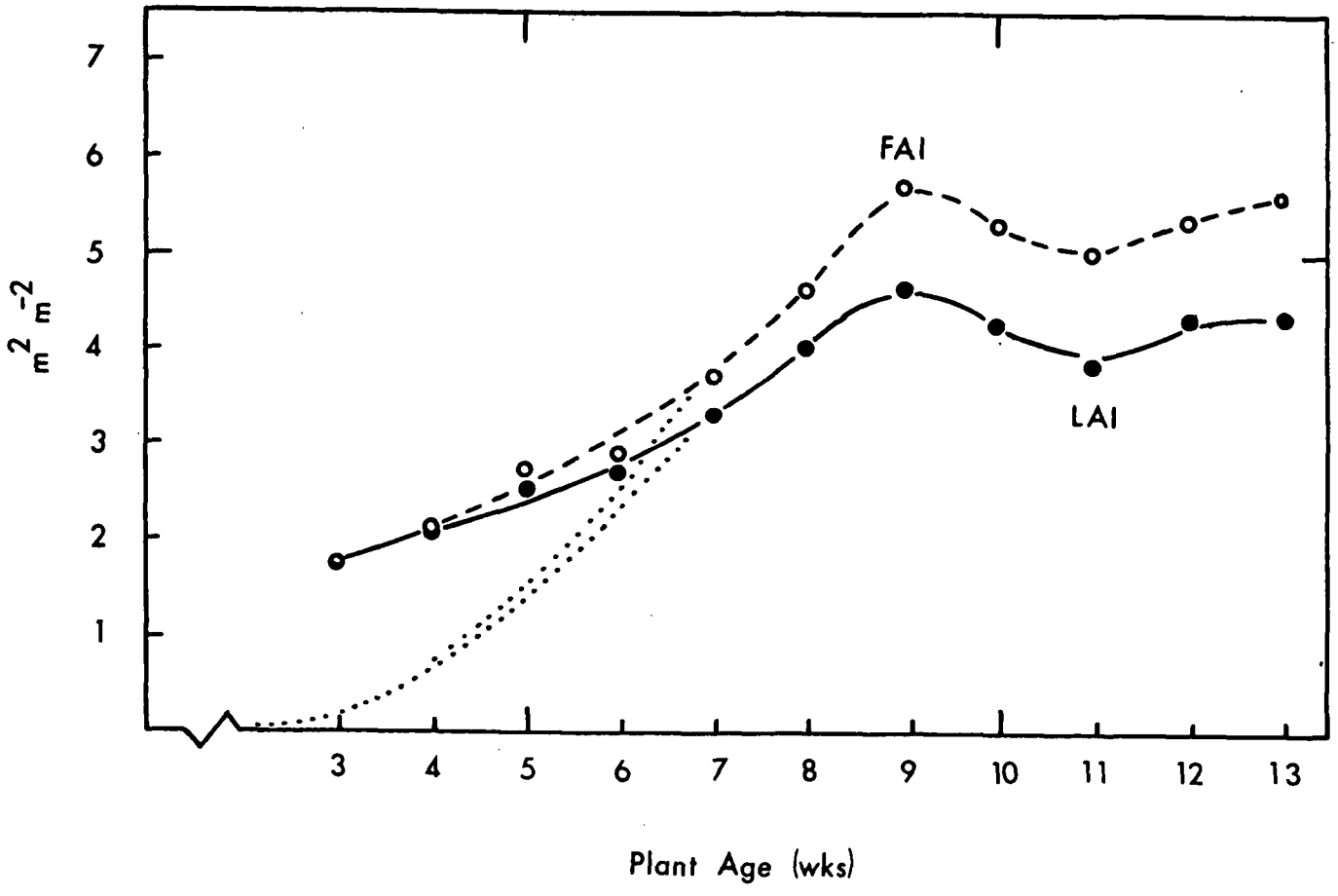

Figure 4. Leaf area index (LAI) and total foliage area index (FAI) for a solid stand of controlled-environment-grown potatoes through time. Prior to 6-weeks-age, both values are shown on an individual plant and solid stand (dotted lines) basis. After 6 weeks, the stand foliage gaps closed and both estimates were equal.

week 12, gaps in the canopy had filled and contact frequency nearly returned to prelodging values.

Measurements of above- and below-canopy PAR Levels showed an exponential decrease of the irradiance penetration as the canopy density increased (Fig. 5). The first two leaf layers accounted for nearly 90% of the incident PAR attenuation. Further increases in canopy thickness showed diminishing effects on total PAR attenuation. An LAI of 2.7 reduced PAR by 95%, while over 98% of the incident PAR was attenuated when LAI exceeded 4.0. The average Beer's Law Coefficient of Extinction, K, determined from point quadrat estimates of LAI equaled 1.05. Using harvested foliage area to calculate LAI yielded an average K value of 1.18.

PRODUCTION CALCULATIONS

Calculations of tuber production have been made both from plants in the photoperiod study, where each plant was maintained in a separate caged enclosure, and from plants grown in a solid canopy within a growing room. When individual plants were caged, each plant was contained within a 46 cm (18 inch) diameter area and were spaced out uniformly within the growing room. When plants were permitted to develop a solid canopy, the containers were spaced so that plants were on 45 cm centers and a mesh fence with 0.6 cm openings was erected around the periphery of the growing area. A 55 cm wide walkway surrounded the fenced area in the growth room. The plants formed a solid canopy between 6 and 7 weeks of growth.

Both studies utilized 'Norland' cultivar grown under 400 μmol s^{-1} m^{-2} irradiance of cool white fluorescent lamps at 20 C and 70% RH. Plants were grown in peat-vermiculite media and watered automatically with nutrient solution as described previously. In the caged study, plants were grown in 19 liter (5 gallon) containers and harvested at 15 weeks from transplanting. In the solid canopy study, plants were grown in 38 liter (10 gallon) containers and harvested at 20 weeks from transplanting.

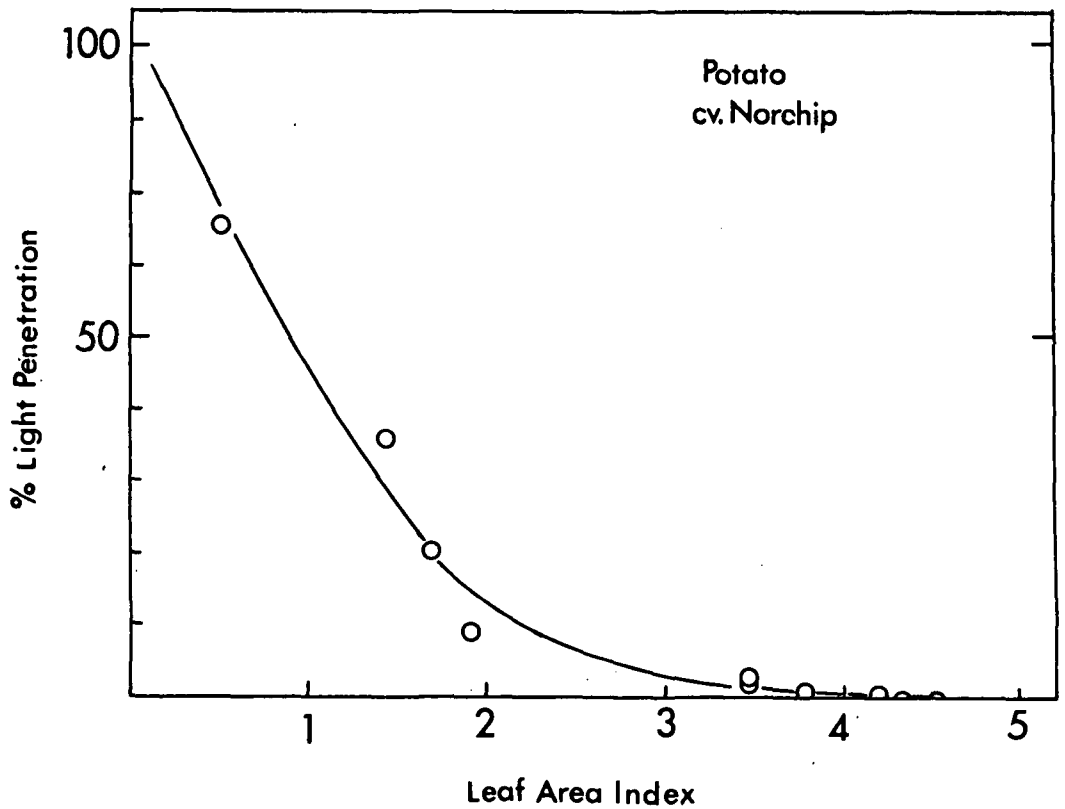

Figure 5. Percent penetration of photosynthetically active radiation through a canopy of potato leaves as a function of leaf area index.

The tuber weight obtained for the calculations included all tubers over 1 cm in diameter. Dry weight was obtained by taking core samples from 3-5 tubers in each sample and drying them at 70 C for 2 days. The yield was determined on the basis of area covered by the canopy of each plant. With caged plants the basis was the upper surface of the plant canopy in an area each fenced cage, 0.2 m^2, whereas in the solid canopy study, the basis was the total area within the fenced area divided by the number of plants, also 0.2 m^2.

The calculations assumed a calorie requirement of 2800 kcal per day for one person and a conversion of 3.73 kcal per gram dry mass of potato tuber. Electrical energy calculations for lighting were based on efficiencies achieved at a commercial plant growth facility (Phytofarm at DeKalab, IL). This system utilizes 304 lamp watts of HPS lamps per m^2 to provide 400 $\mu mol\ s^{-1}\ m^{-2}$ of photosynthetic irradiance (400-700 nm).

The calculations provided in Table 12, document a tuber production of 20.7 $g\ m^{-2}\ day^{-1}$ in the caged study grown for 15 weeks, and 12.3 $g\ m^{-2}$ day in the solid canopy study grown for 20 weeks. These production rates indicate that one person could be maintained by a surface are of 36.3 m^2 with the caged plants and 61.0 m^2 with the solid canopy plants and have utilized 11.0 and 18.5 KW m^{-2} of electricity, respectively. The higher yield in the caged study was felt to result from a greater amount of side lighting in this study, thereby exposing more photosynthetic leaf surface on these plants. In the solid canopy study, tuber yields from the border plants were 60% greater than the yield from the center plants. It appeared that this increase was not only a result of border plants obtainting additional irradiation along the sides but also resulted from the extension of branch stems by the border plants that tended to overgrow the center plants more than branch extension of center plants in the reverse direction.

Table 12. Surface area and electrical requirements to provide food energy requirements for one person.

	Caged plant study[z]	Solid canopy study[y]
Edible food ($g\ m^{-2}\ day^{-1}$)	20.7	12.3
Energy[x] ($kcal\ m^{-2}\ day$)	77.2	45.9
Surface area required for one person (m^2)[w]	36.3	61.0
Electricity required for one person ($kw\ m^{-2}$)[v]	11.0	18.5

[z] Norland cv grown for 15 weeks under 20 hrs irradiance period.

[y] Norland cv grown for 20 weeks under 24 hrs irradiance period.

[x] Based on one gram of potatoes producing 3.73 kcalories.

[w] Based on daily requirement of 2800 kcalories per person.

[v] Based on 304 lamp watts required per m^2 to provide 400 $\mu mol\ s^{-1}\ m^{-2}$ of PPFD.

It is felt that the productivity obtained in this initial study is considerably below the maximum productivity that can be obtained. Several avenues for improvement are available: First, these studies were all conducted at ambient CO_2 levels (330-360 ppm) and CO_2 enrichment of plant growing areas in closed systems could be practiced relatively easily. This would almost certainly raise productivity through enhanced photosynthetic rates. Second, our choice of 15 and 20 weeks as desireable harvest times was arbitrarily based on the typical range of growing periods in the field and this may not necessarily be the most efficient point in time to harvest. It is apparent that small containers encourage rapid tuberization and large containers permit greater total yields. Thus optimization of container size

for specific growing periods should increase production per unit area and unit time. Third, the calculation assumes a single harvest but possibilities will be explored for continuously harvesting tubers as soon as each tuber reaches useful size. This will likely require soilless culture systems that are presently under development. Fourth, higher irradiance levels should speed growth and increase tuber yields. Fifth, temperature studies now in progress, demonstrate that an increasingly larger percentage of the photosynthetic production can be directed to tubers as temperature is decreased. Thus, selection of a temperature that maximizes photosynthate allocation to tubers and also maintains high total productivity, should increase the yield.

Also, any determination of the yield potential of plant systems should not neglect the possibility that a portion of the inedible biomass could be directed through other organisms to retrieve some of the energy content of the inedible stems, leaves and roots. For example, the cellulose and other indigestible components of the foliage might be used to feed lower organisms which could then be processed into food acceptable to humans (Bredt, 1984). The use of higher animals such as goats to consume the foliage might also be considered for recovery of a portion of this energy (Bredt, 1984). The nutritional value of pressed potato vine silage has been found to be an acceptable feed for goats (Parfitt et al., 1982).

Thus studies are continuing to assess the overall productive potential of the potato with an ultimate goal of obtaining sufficient calories to sustain one person from a 10 m^2 growing area and requiring no more than 8 kw of electrical power to irradiate the area.

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APPENDIX A:
CELSS Documents Published as NASA Reports

1. Johnson, Emmett J.: Genetic Engineering Possibilities for CELSS: A Bibliography and Summary of Techniques. NASA CR-166306, March 1982.

2. Hornberger, G.M. and Rastetter, E.B.: Sensitivity Analysis as an Aid in Modelling and Control of (Poorly-Defined) Ecological Systems. NASA CR-166308, March 1982.

3. Tibbitts, T.W. and Alford, D.K.: Controlled Ecological life Support System: Use of Higher Plants. NASA CP-2231, May 1982.

4. Mason, R.M. and Carden, J.L.: Controlled Ecological Life Support System: Research and Development Guidelines. NASA CP-2232, May 1982.

5. Moore, B. and MacElroy, R.D.: Controlled Ecological Life Support System: Biological Problems. NASA CP-2233, May 1982.

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15. Supplementary Notes

Point of Contact: Robert D. MacElroy, NASA Ames Research Center, MS 239-4, Moffett Field, CA 94035, 415-694-5573 or FTS 8-464-5573

16. Abstract

This report details results of experiments conducted to maximize the productivity of potatoes grown under controlled environmental conditions. A variety of parameters are examined which affect potato growth, specifically, photoperiod, light intensity, temperature, nitrogen nutrition, carbon dioxide concentration and culture techniques. These experiments were conducted using five different cultivars, 'Russet Burbank', 'Norchip', 'Superior', 'Kennebec' and 'Norland'. To achieve high productivity, three specific objectives were explored: 1) to develop effective cultural procedures, 2) to determine the most effective photoperiod and 3) to develop a mist culture system. It is felt that the productivity obtained in this study is below the maximum that can be obtained. High irradiance levels coupled with tuber-promoting conditions such as cooler temperatures, increased CO_2 levels and lowered nitrogen concentrations should allow increases in tuber production. Tuberization appears to be accelerated by short daylengths although final yields are not increased. Mist culture techniques have not yet produced fully developed tubers. The use of supporting media and alteration of the nitrogen content of the mist solution are being explored as a way to allow tubers to develop to maturity.

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