A Data Base of Nutrient Use, Water Use, CO_2 Exchange, and Ethylene Production by Soybeans in a Controlled Environment

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ABSTRACT

A data set is given describing daily nutrient and water uptake, carbon dioxide (CO_2) exchange, ethylene production, and carbon and nutrient partitioning at harvest for an entire canopy and root system of a soybean crop [*Glycine max* (L.) Merr. cv. McCall]. The data were obtained from a 20 m^2 stand of plants grown from seed to maturity (97 days) in a closed, controlled environment using a recirculating hydroponic system. Stand CO_2 exchange rates were determined from nocturnal increases in CO_2 (respiration) and morning drawdowns (net photosynthesis) to a set point of 1000 µmol mol^{-1} each day (i.e., a closed system approach). Atmospheric samples were analyzed throughout growth for ethylene using gas chromatography with photoionization detection (GC/PID). Water use was monitored by condensate production from the humidity control system, as well as water uptake from the nutrient solution reservoirs each day. Nutrient uptake data were determined from daily additions of stock solution and acid to maintain an EC of 0.12 S m^{-1} and pH of 5.8. Dry mass yields of seeds, pods (without seeds), leaves, stems, and roots are provided, as well as elemental and proximate nutritional compositions of the tissues. A methods section is included to qualify any assumptions that might be required for the use of the data in plant growth models, along with a daily event calendar documenting set point adjustments and the occasional equipment or sensor failure.

INTRODUCTION

Few data sets are available that simultaneously track daily nutrient, water, and carbon fluxes for whole plant stands throughout the full period of their growth and development (Gerbaud et al., 1988; Wheeler et al., 1993; Andriolo et al., 1996). More typically, studies focus on only one or a few parameters. In addition, such studies are comonly conducted in the field where environmental conditions can vary and/or available resources are difficult to quantify. In an earlier paper, we presented a data base on the nutrient uptake, water use, carbon dioxide (CO_2) fluxes, and biomass yields for a 20 m^2 of wheat grown hydroponically in a closed, controlled environment (Wheeler et al., 1993a). The intent of that paper was to provide a comprehensive

data set of physiological and environmental parameters throughout growth and development of an entire wheat stand, which could then provide a basis for developing and/or validating growth models (Sadler et al., 1991; Willits et al., 1992). (By stand, we refer to all shoot structures, roots, and the associated root-zone microflora). Such models will be important for predicting crop performance in controlled environments that might be used for human life support in long-duration travel and colonization of space (Schwartzkopf, 1992), as well as applications toward general analyses of canopy-level physiological events.

In this report, we present a similar, comprehensive data base for soybean plants grown from seed to maturity. Plants were grown using recirculating hydroponic (NFT) culture in a large, atmospherically closed chamber thereby allowing daily measurements of stand nutrient and water uptake, CO_2 exchange, ethylene evolution, and biomass yields. Because stand ethylene data are difficult to collect, in retrospect, we felt that ethylene measurements from the previously reported wheat study (Wheeler et al., 1993a) should also be included as a point of reference.

MATERIALS AND METHODS

Growth Chamber Description

The Biomass Production Chamber located in Kennedy Space Center, FL is a cylindrical steel vessel that was formerly used for hypobaric testing during NASA's Mercury and Gemini Programs (Prince and Knott, 1989). The chamber is 3.7 m in diameter, 7.5 m high, and is divided into upper and lower halves with two plant growing levels in each half (Fig. 1). Each of the four plant growth levels supports 16 trapezoidal-shaped plastic (ABS) trays having a rooting area of 0.25 m^2 each (Fig. 2). However, when the space between trays and the tendency of shoots to lean over the edges of the trays are considered, the effective canopy area of the chamber at full coverage was approximately 20 m^2 (0.31 m^2 per tray); hence all gas exchange and uptake rates are expressed on a unit area basis assuming 20 m^2 of total growing area. The entire atmospheric volume for both the upper and lower halves of the chamber including air ducting was 113 m^3.

Lighting for plant growth was provide by 96, 400-W high-intensity discharge (HID) lamps (3 lamps per 2 trays) separated from the plants by Pyrex glass barriers. High-pressure sodium (HPS) lamps (Philips Ceramalux, Philips Lighting Corp., Bloomfield, NJ or GE Lucalox, General

Electric, Cleveland, OH) were used in the upper half of the chamber (levels 1 and 2) and metal halide (MH) lamps (Venture Pro-Arc, Venture Lighting, Cleveland, OH) were used in the lower half (levels 3 and 4). An ancillary objective of this study was to compare growth and yield of soybean under HPS with that under MH lamps, which have more blue light than HPS lamps but are less efficient for total photosynthetically active radiation (Wheeler et al., 1991).

Air circulation was provided by two 30-kW blowers (one for each half of the chamber) connected to the chamber by steel ducting. Motors were mounted external to the air ducts to minimize any possible gaseous contaminants from electrical and lubricated components. The air handling systems provided three to four air exchanges (400 m^3) per minute with air velocities ranging from 0.2 to 1.5 m s^{-1} at canopy level. Heat rejection and humidity control were provided by chilled-water coils located after each blower. Following each cold coil was a hot-water coil for air temperature control and a high-efficiency particulate air (HEPA) filter (0.3 μm). For the first 5 days, supplemental humidification was provided by atomized streams of deionized water sprayed directly into the air ducts (water uptake was not calculated for this period).

Nutrient Solution Delivery System

Plants were grown using a nutrient film technique (Cooper, 1979) where solution was maintained from 0.5 to 1.0 cm deep and supplied at a rate of 1.0 to 1.5 L min^{-1} to each tray (Fig. 2). Each of the four growing levels was supplied by a separate external reservoir with the head space atmospherically connected to the main chamber. Nutrient solution volume for each level was approximately 225 L, with 185 L in the reservoir and approximately 40 L in the trays and plumbing. A modified ½ Hoagland solution with nitrate (NO_3) as the only N source was used (Hoagland and Arnon, 1950; Table 1). Solution pH in all systems was automatically maintained near 5.8 using 0.39 M nitric acid. Solution electrical conductivity (EC) was automatically maintained at a minimum of 0.12 S m^{-1} with additions of a complete refill (stock) solution (Table 1). Solution volume in each reservoir was adjusted to 225 L with deionized make-up water added manually each day (typically from 08:00 to 09:00). Nutrient solution from each level was sampled weekly and elemental concentrations were determined using inductively-coupled plasma (ICP) spectrometry. At harvest, the composition of the nutrient solution was similar to that of the starting solution.

Atmospheric Monitoring and Control

Carbon dioxide (CO_2) concentrations for the chamber were monitored and controlled using infrared gas analyzers (Anarad AR-200, Santa Barbara, CA) with all gas sample streams being returned to the chamber. All analyzers were automatically calibrated daily against four standard gases (0, 500, 1000, and 2000 $\mu mol\ mol^{-1}$ CO_2). Chamber air temperature was controlled using sensors (General Eastern model 455) mounted in the air ducts. Redundant temperature and humidity sensors (Vaisala model HMP 111, Helsinki, Finland) for monitoring purposes were positioned at the plant canopy level on each growing level.

Plant Cultural Procedures

Seeds of soybean (*Glycine max* (L.) Merr.) cv. McCall were imbibed in deionized water and placed on to tray inserts where they were supported by juxtaposing strips of white-on-black polyethylene plastic mounted between plastic "T" supports (Prince and Knott, 1989). Seeds were sown at a rate of approximately 10 per tray (32 seeds m^{-2}). For the first four DAP, trays were covered with white, translucent acrylic covers to shade seedlings and maintain high humidity. At 16 days after planting (DAP), seedlings were thinned to four per tray, giving a final spacing of 12.8 plants m^{-2} . As plants grew, shoots were supported by vinyl-coated wire fencing positioned horizontally about 30 cm above tray surfaces.

Environmental Conditions

The chamber was kept dark for the first two days. For the remainder of the study, lamps were cycled to provide 10 h light (07:00 to 17:00) and 14 h dark (17:00 to 07:00) each day. For days 3 and 4, incident photosynthetic photon flux (PPF) was only 15% of normal incident because of the shading by the germination covers. Temperature was controlled at a constant 26 °C in the light and 20 °C in the dark. Relative humidity was maintained near 85 % for first 5 days to promote seedling establishment, after which the humidity set point was lowered to 70 % for the remainder of growth. This provided a water vapor pressure deficit (VPD) of 1.0 kPa in the light (26 °C) and 0.7 kPa in the dark (20 °C).

Photosynthetic photon flux (PPF) readings were taken weekly with a quantum sensor (LiCor 185) at the top of the plant canopy at the center of each of the 64 trays. For the entire study, PPF at the plant canopy level averaged 870 μmol m^{-2} s^{-1} (HPS lamps) for the upper chamber (levels 1 and 2) and 420 μmol m^{-2} s^{-1} (MH lamps) for the lower chamber (levels 3 and 4).

Carbon dioxide concentrations were controlled at a minimum of 1000 μmol mol^{-1} during the light cycle by automatic CO_2 additions. No attempts were made to suppress CO_2 increases during the dark cycles, which often exceeded 2500 μmol mol^{-1} by the end of the 14-h dark period. Likewise, no attempt was made to prevent oxygen (O_2) build-up during light cycles. However, O_2 concentrations seldom exceeded 22% because the chamber was commonly entered daily for maintenance activities (normal ambient O_2 level is about 20.9%) . Thus periods of total atmospheric closure were relatively short, allowing for regular equilibration of the chamber O_2 levels with the outside atmosphere.

Gas Exchange Measurement

Because no attempt was made to suppress CO_2 buildup from respiration during dark cycles, CO_2 concentration showed a repeating pattern of dark-period increase followed by light period ("morning") drawdown to the 1000 μmol mol^{-1} set point (Wheeler, 1992). When the chamber was sealed (leakage rate of 10% vol. day^{-1} or 0.42% vol. h^{-1}), the rates of canopy photosynthesis and respiration could be calculated from the increase of CO_2 during the dark and subsequent drawdown in the light, i.e., a closed gas exchange system (Wheeler, 1992). At a leakage rate of 10% vol. day^{-1}, loss of CO_2 from the chamber around the set-point of 1000 μmol mol^{-1} amounted to only 0.2 μmol m^{-2} s^{-1} and hence was ignored for gas exchange calculations.

Evapotranspiration rates were measured daily from condensed water collected from the heat exchange systems (cold coils) and also from the daily additions (make-up water, nutrient refill solution, and acid) to each of the four nutrient systems.

Ethylene analysis of the chamber atmosphere was conducted on a daily basis (when possible) using gas chromatography with a photoionization detector (GC/PID) positioned immediately outside the chamber entrance door. A 1-ml valve sampled the air automatically at specified intervals through a 3.2 mm diameter by 0.76 m long Teflon tube connected to the chamber.

Because the upper and lower portions of the chamber were not sealed from each other during this study, all gas concentrations and gas exchange rates were calculated for the chamber as a single unit and based on a stand area of 20 m^2. Unfortunately, this does not allow discrimination between the two light treatments in terms of net daily photosynthesis (high PPF in the upper half of the chamber and low PPF in the lower); consequently, correlations of gas exchange with biomass or nutrient and water uptake can only be made for the chamber as a whole. Previous tests in the same chamber with wheat (Wheeler et al., 1993b) and soybean (unpublished) have shown that both biomass yields and stand photosynthetic rates increase linearly with PPF (max. 800 $\mu mol\ m^{-2}\ s^{-1}$ tested). On the basis of these observations, we feel that correlations of gas exchange averaged for the whole chamber with other parameters averaged for the whole chamber should be valid.

Harvest and Tissue Analysis

All plants were harvested at 97 DAP and separated into leaves, stems, pods, and roots. Residual nutrient solution was drained from root mats, after which all plant materials were placed in paper bags for drying. All pods and roots, and some leaves and stems were immediately placed in a forced-air oven at 70 °C for drying. The remainder of leaves and stems were kept in a dark, cold room (4-5 °C) for several days until additional oven space was available. During harvest, sub-samples of leaves, stems, pods (without seeds), seeds, and roots were taken from each level and dried for elemental analysis using ICP spectroscopy (Alexander and McAnulty, 1981). Following oven drying, seeds were manually threshed from pods and dry weights were determined. Additional samples of dried roots, leaves, stems, pods (without seeds) and seeds were ground in Wiley mill and sent to a commercial laboratory for proximate analysis (Nutrition International, Dayton, NJ). Proximate analysis followed standard AOAC (1990) procedures and included moisture by vacuum oven, ash by muffle furnace, protein by total Kjeldahl N (6.25 conversion factor for protein), fiber by digestion and gravimetric technique, fat by acid hydrolysis and ether extraction, and carbohydrate by difference.

RESULTS AND DISCUSSION

Event Calendar

A log of daily events is presented in Table 2. Days on which control or mechanical system failures occurred are noted, and in most cases, anomalies or discontinuities in the data sets can be related to these events. Flowering was first apparent near DAP 28, with small pods appearing 3 to 4 days later. Flowering continued throughout much of the rest of growth period, but gradually decreased as the plants matured (ca. > 70 days). (Note, McCall is an indeterminate cultivar, group 00). Canopy cover was nearly complete in the upper chamber with high HPS lighting at 30 DAP (visual estimate), while canopy cover in the lower chamber with MH lighting was not complete until about 45 DAP. On several occasions, stems that had grown into shaded areas between the lamp banks were pruned and removed from the chamber (Table 2). Abscised leaves that accumulated on the tray surfaces were also removed on several occasions to maintain good light reflectance from the tray surfaces (Table 2).

Gas Exchange

Daily measurements of stand CO_2 exchange rates during the light (net photosynthetic rate) and dark period (dark period respiration rate), and daily measurements of stand condensate production (evapotranspiration) are presented in Table 3. Net photosynthesis rates increased with canopy cover and peaked near 35 μmol m^{-2} s^{-1} at about 40 DAP, when plants reached their maximum height; following this, rates remained relatively constant until about 60 DAP, after which rates decreased. Dark period respiration peaked near 5 μmol m^{-2} s^{-1} at about 40 DAP and maintained this level until about 70 DAP, after which rates gradually decreased. Similar patterns of CO_2 uptake have been reported for field-grown soybeans (Acock et al., 1985; Jones et al, 1985), with peak rates under CO_2 enrichment and high (1400 μmol m^{-2} s^{-1}) solar radiation being about twice that observed in this study at ~700 μmol m^{-2} s^{-1} (ca. 36 and 42 DAP; Table 9) (Acock et al., 1985). Condensate production (evapotranspiration) increased rapidly with canopy cover and peaked near 7 L m^{-2} d^{-1} (7 mm d^{-1}) at about 35 DAP and then declined steadily beginning about 50 DAP. Because only daily measurements were taken for water, light and dark-period components of evapotranspiration cannot be differentiated. Similar patterns of daily water

use have been reported for field-grown soybean, with rates peaking between 5 and 6 L m^{-2} d^{-1} under well-watered, CO_2-enriched conditions (Jones et al., 1985).

Nutrient Refill, Water Use, and Acid Addition

Daily volumes of all fluids from the nutrient refill solution, deionized water, and dilute acid added to each level are shown in Tables 4A through 4D. Total moles of acid are also shown in Tables 4A through 4D. Nutrient refill additions increased steadily from about 10 to 45 DAP for all levels, with relatively large additions occurring for levels 1 and 2 between 45 and 50 DAP. This appeared to correlate to a rapid flush of shoot growth. Acid additions increased steadily from about 15 to 30 DAP and then remained relatively constant until about 50 DAP, followed by a gradual decline with time. Total refill and acid additions for levels 1 and 2 (high HPS light) were approximate twice that of levels 3 and 4 (lower MH light). With exception of the first 10 days of growth, solution pH tended to rise requiring acid for pH control (data not shown). This suggests a preferential uptake of anions over cations from the nitrate-based nutrient solution throughout most of the growth cycle (Willumsen, 1980; Marschner, 1992).

Nutrient Uptake

The rate of K addition over time, as determined from the amount of refill solution added to each level, is shown in Table 4. For all nutrients except N, the refill solution was the only source and nutrient uptake rates can be calculated from the daily amount of K added to the solutions (Tables 1 and 4). In the case of N, the nitric acid used for pH control also supplied N and had to be combined with the refill stock to calculate total N added (Table 4). Nitric acid accounted for about 31 % of the N added to levels 1 and 2 (HPS high light) and about 34 % of the N added to levels 3 and 4 (MH low light). The high nutrient and acid use during early vegetative growth were consistent with results from other studies with hydroponically-grown soybean (Vessey et al., 1991; Gruzak and Pezeshgi, 1994). In comparison, nutrient and acid use by a 20 m^2 wheat stand grown in the same chamber also showed a rapid rise during early growth, but declined more rapidly with the onset of heading (Wheeler et al., 1993a). Nitric acid accounted for 53% of the N added in a similar wheat study (Wheeler et al., 1993a).

Nutrient Partitioning and Recovery

Concentrations of elements in the different plant parts at harvest are shown in Tables 5A through 5D, and their relative distribution (partitioning) among different plant parts is shown in Tables 6A through 6D. Proximate compositions of different plant parts are shown in Tables 7A and 7B. Except for inadvertent spillage and leakage, the four independent nutrient delivery systems were essentially closed systems; hence, uptake by the plants should account for most of the nutrient removal from the solutions. However, discrepancies occurred and recovery of several elements was well below 100% (Tables 4 and 5). Some large differences in the recovery of micronutrients were not surprising, since the amounts of micronutrients present in plant tissues are relatively small compared to the sensitivity of the analysis and to the possible levels of contamination. Among the macronutrients, recovery of P was only 41%, while recovery of K was 82%, Ca 81% and Mg 79%. These recovery numbers indicate a relatively large variance; however, similar trends are apparent in the literature: For example in the studies of tomato and lettuce, Willumsen (1980, 1984) reported recoveries ranging from 65% to 116% for macronutrients. Possible sources of nutrient loss from the system include precipitation, both from the refill stocks and working nutrient solutions (especially P, Ca, and Fe), and nutrient uptake by bacterial biofilm communities (note, algae growth was negligible). In the case of nitrogen, there is also the potential for loss of N_2O and N_2 to the atmosphere through bacterial denitrification (Stutte, 1996).

Biomass Yield

Harvest data expressed on a unit area basis for each of the four levels are shown in Table 8. Total dry biomass from levels 1 and 2 (high HPS light) was 13.85 kg, or 1.38 kg m^{-2} (10 m^2 total area). Total biomass for levels 3 and 4 (lower MH light) was 6.65 kg, or 0.66 kg m^{-2} (Table 8). Seed yield was 4.86 kg, or about 0.49 kg m^{-2}, and 2.82 kg for levels 3 and 4, or 0.28 kg m^{-2}(Table 8). Harvest index (seed dry mass/total dry mass) averaged 35% under high HPS light in levels 1 and 2 and about 42 % under the lower MH light of levels 3 and 4.

PPF Measurements

Weekly PPF measurements taken from the top of the canopy are presented in Table 9. As plants grew closer to the lamp barriers, PPF levels at the top of the canopy increased. Variations in PPF levels over time were likely a result of the inherent variability from single-point readings taken under the HID lamps used in the study. Canopy level PPF for the entire study averaged 870 μmol m^{-2} s^{-1} for levels 1 and 2 (HPS lamps) and 420 μmol m^{-2} s^{-1} for levels 3 and 4 (MH lamps), with a whole-chamber average of 644 μmol m^{-2} s^{-1} (Table 9). Weekly PPF averages for the entire chamber are also shown, which would be the pertinent PPF data to relate to whole chamber gas exchange rates over time (Table 3).

Ethylene Production

Chamber ethylene concentrations throughout growth of the soybean and a previously reported crop of wheat grown in the same chamber (Wheeler et al., 1993a) are presented in Table 10. Ethylene concentrations during soybean growth increased rapidly between 30 and 50 DAP followed by a gradual decline and then a second, smaller increase after 90 DAP. The discontinuities during the period of relatively high ethylene concentrations may coincide with stem pruning and leaf litter removal events, while the rise just prior to harvest may be related to stand senescence (Table 2). Ethylene concentrations during wheat growth (Wheeler et al., 1993a) showed a rapid increase between approximately 20 and 30 DAP followed by a gradual decline at about 40 DAP and no increase during senescence (head emergence occurred near 40 DAP in that study). Because of atmospheric leakage from the chamber, ethylene concentration data from these studies only present "fingerprints" of relative production by the crops throughout crop growth and development (Wheeler et al., 1996); thus, increases in ethylene indicate periods when stand production exceeded leakage, and decreases indicate periods when leakage exceeded stand production.

CONSIDERATIONS FOR DATA USE

It is our hope that these data provide comprehensive information about the environmental and physiological parameters useful in development and validation of soybean growth models. Related data sets on biomass yield and nutrient content have been published, but do not include

gas exchange data on CO_2 , H_2O , and ethylene (Sadler et al., 1991). The measured parameters in this soybean data set correspond closely to those of the wheat data set published previously (Wheeler et al., 1993a), which should allow comparisons between species. As with many experiments, this study has limitations regarding the sensitivity and accuracy of the measurements, in addition to a certain amount of heterogeneity characteristic of biological systems. Such variations become especially apparent in data monitored simultaneously over long time periods, e.g., mass balance data for nutrients, water, and carbon. Potential sources of this variation include "daily" measurements not recorded at precisely the same time each day, sensor and instrumentation drift, and variability between manual readings taken by different individuals. As noted earlier, PPF differences clearly account for much of the difference in biomass and nutrient uptake between levels 1 and 2, and levels 3 and 4.

Gas exchange data represent the average of the entire chamber and should only be related the average PPF for the entire chamber. Likewise, correlations between gas exchange and other parameters, e.g., biomass production, nutrient uptake, acid use or water use, also should be based only on a whole chamber averages. In contrast, biomass production, nutrient uptake, acid use, and water use data (as determined from additions to the nutrient solution) for each growing level can be related directly to the average PPF for that level (Table 9). The built-in difference in PPF between the upper (high PPF) and lower (low PPF) halves of the chamber should permit comparison of lighting effects on any parameters tracked by level (e.g., nutrient uptake, water use, and acid use). Although most of the lighting effects are likely attributable to PPF, it is important to note that spectral quality also varied between levels 1 and 2 (HPS lamps), and levels 3 and 4 (MH lamps), which also may have affected growth (Wheeler et al., 1991).

The data presented offer simultaneous measurements of several parameters taken throughout growth and development for a whole stand of soybeans and include nutrient use, gas exchange, and relative rates of ethylene production. With appropriate considerations of the limitations of this study, we feel that the data can provide information suitable for model development and/or validation of soybean growth in controlled environments. Upon request, we can provide the data on diskette for use in simulation models or other applications.

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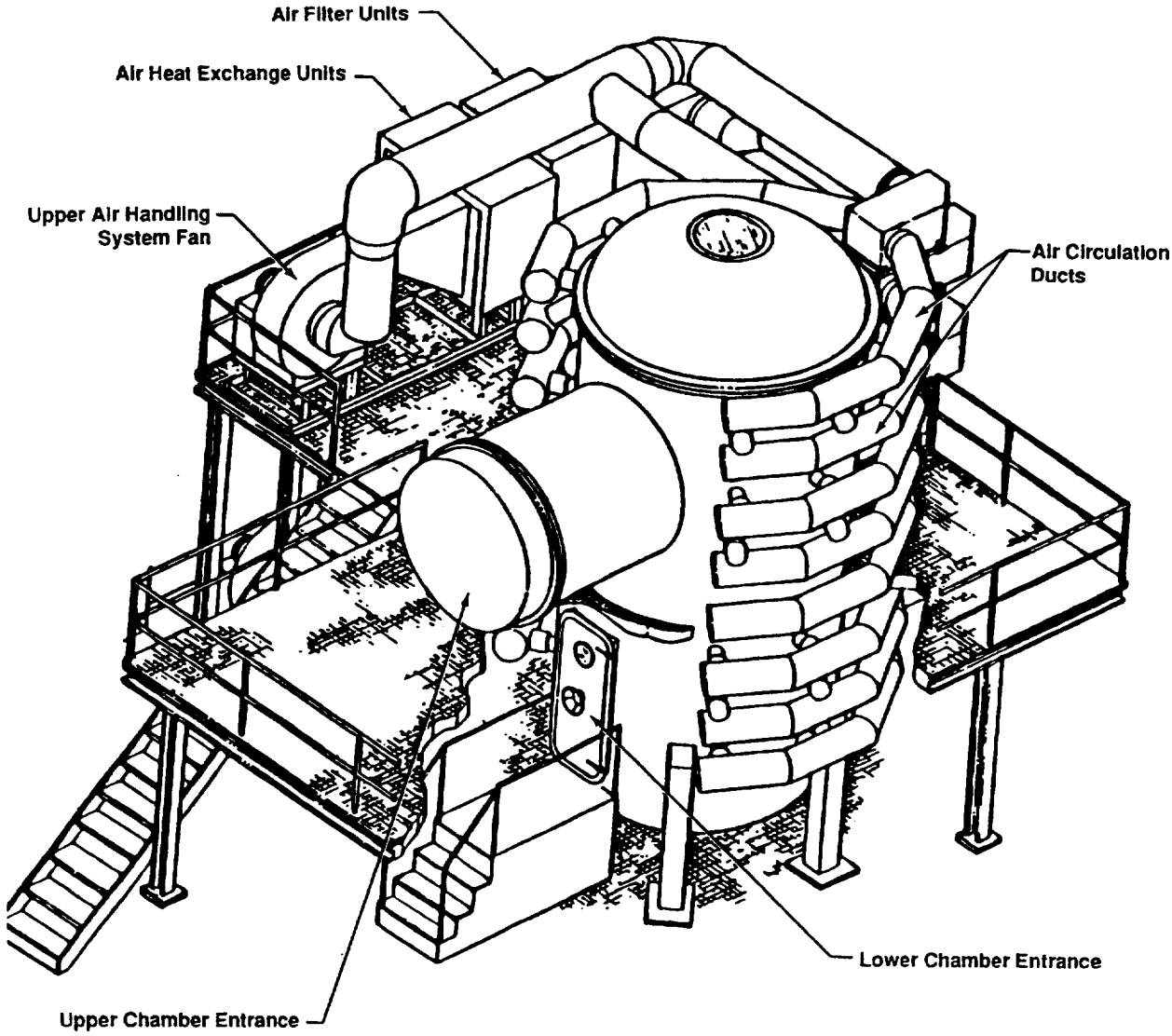

FIGURE 1. Diagram of the NASA's Biomass Production Chamber (BPC) located at Kennedy Space Center, FL. The chamber provides a closed atmospheric volume of 113 m^3 and a plant growing area of 20 m^2 .

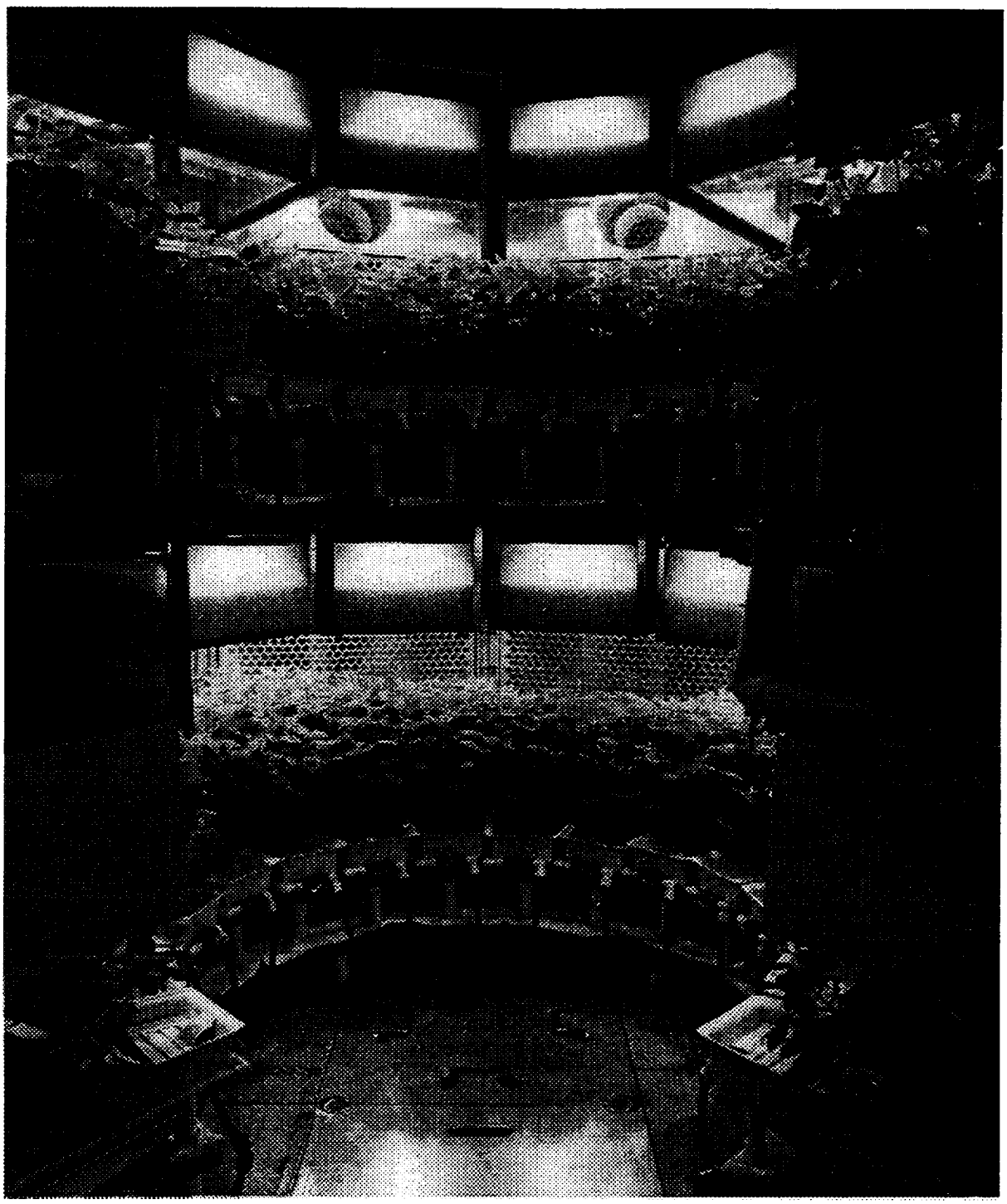

FIGURE 2. Soybean plants (cv. McCall) growing in the upper half of NASA's Biomass Production Chamber. Plants were grown in plastic culture trays using nutrient film technique. Trays were supported on four vertically-stacked shelves (two shown in the photo) with 16 trays per shelf, providing a total of 20 m^2 of growing area. Lighting was provided by high-pressure sodium lamps in the upper half of the chamber and by metal halide lamps in the lower half of the chamber.

TABLE 1 Event log for soybean (cv. McCall) study *

Plant Age (DAP)	Comments
1-9	Seedling establishment
16	Trays thinned to 4 plants / tray
24	Ran out of CO_2 for about 6 hr
28	Ground cover for levels 1 and 2 about 90%; levels 3 and 4 about 50%
29	Stems extending between HPS lamp bank (levels 1 and 2) pruned
32	Seed pods present on all levels; door not sealed over night
38	Lost pH control in levels 2, 3 and 4
39	Calibration error on CO_2 analyzer
41	Door not sealed over night; leaf litter collected from trays and removed
42	Stems between lamp banks pruned; leaf litter removed
43	140 ml of 1M KH_2PO_4 added to each level; leaf litter removed
44	Roots samples collected for microbial analysis
45	Upper condensate tank left open; pH control for level 2 deactivated
46	pH control for level 2 deactivated
52	No EC control in level 2; refill stock solution not added
54	Nutrient solution temperature control inactive all levels
56	Malfunction of CO_2 gas analyzer -- no gas exchange data
57	Some pods aborting
58	CO_2 supply ran out for ~5 hr; 400 ml of 1M $Ca(NO_3)_2$ added to each level
69	Decrease in amount of leaf abscission and pod abortion
81	Loss of temperature control for nutrient solutions; temp. to 30 C
87	Loss of temperature control for nutrient solutions
88	Loss of temperature control for nutrient solutions
90	Loss of humidity control
97	All plants harvested

* Conditions included the following: 10-h light / 14-h dark photoperiod; 26 C light / 20 C dark; 70% to 75% RH; 1000 mmol mol^{-1} CO_2 during the light; HPS lamps for levels 1 and 2; MH lamps for levels 3 and 4.

TABLE 2 Nutrient solution concentrations.

	Macronutrients					
	N	P	K	Ca	Mg	S
	(mmol L^{-1})					
Starter Solution	7.50	0.5	3.00	2.50	1.00	1.00
Refill Solution	75.0	7.50	68.0	7.50	8.10	8.10
Nutrient/K ratio of Refill Solution	1.11	0.11	1.00	0.11	0.12	0.12

	Micronutrients					
	Fe	B	Mn	Zn	Cu	Mo
	(µmol L^{-1})					
Starter Solution	60.00	4.75	3.70	0.64	0.52	0.01
Refill Solution	199.0	4.30	34.00	8.80	9.50	0.09
Nutrient / K ratio of Refill Solution	2.93	0.06	0.50	0.13	0.14	0.001

* Nutrient uptake can be calculated either from the amount of refill used or the ratio of K to the other nutrients in the refill solution and the K uptake (Table 4).

TABLE 3 Daily net photosynthesis, dark period respiration, and condensate volume (evapotranspiration) for a 20 m^2 soybean (cv. McCall) stand.

Plant Age	Net Photosynthesis	Dark Period Respiration	Condensate Volume
(DAP)	(μmol m^{-2} s^{-1})	(μmol m^{-2} s^{-1})	(L m^{-2} d^{-1})
10	n/a	n/a	4.0
11	n/a	n/a	2.4
12	n/a	n/a	3.1
13	n/a	n/a	2.3
14	n/a	n/a	2.2
15	5.0	n/a	1.9
16	5.6	0.7	2.1
17	6.3	0.7	1.7
18	6.7	0.9	1.9
19	6.6	1.0	2.0
20	9.2	1.2	2.2
21	11.6	1.6	1.7
22	14.6	2.2	2.6
23	17.5	2.6	2.8
24	19.3	2.6	2.9
25	14.9	2.3	3.0
26	22.2	2.8	3.1
27	24.8	3.2	3.5
28	25.0	3.6	3.0
29	25.7	2.5	3.5
30	28.5	4.2	3.9
31	26.7	4.2	5.6
32	27.5	4.3	6.6
33	28.3	4.1	6.4
34	29.4	4.5	7.0
35	28.2	4.4	6.9
36	29.9	4.7	6.5
37	n/a	n/a	6.1
38	33.7	4.9	7.4
39	23.7	3.7	7.1
40	29.8	4.2	7.1
41	31.4	4.9	6.8
42	n/a	n/a	6.4
43	32.8	4.9	8.0
44	30.5	4.4	7.7
45	32.5	4.7	5.5
46	31.9	4.9	6.0
47	31.5	4.6	5.7
48	35.2	5.3	6.9
49	33.8	4.8	6.2
50	31.5	4.8	5.6
51	n/a	n/a	8.6
52	29.7	5.4	4.2
53	29.9	5.1	5.7
54	29.0	4.7	5.7

TABLE 3 Daily net photosynthesis, dark period respiration, and condensate volume (evapotranspiration) for a 20 m^2 soybean (cv. McCall) stand.

Plant Age	Net Photosynthesis	Dark Period Respiration	Condensate Volume
(DAP)	(μmol m^{-2} s^{-1})	(μmol m^{-2} s^{-1})	(L m^{-2} d^{-1})
55	28.0	4.5	4.9
56	30.4	4.4	4.4
57	34.0	4.8	4.9
58	32.8	4.8	6.7
59	33.4	4.3	4.5
60	30.8	4.2	5.5
61	31.3	4.2	4.3
62	31.7	4.8	5.1
63	29.6	4.8	4.9
64	28.8	4.3	5.3
65	28.2	4.5	5.0
66	28.3	4.6	5.5
67	26.6	4.4	4.8
68	26.3	4.2	2.3
69	25.5	4.5	4.9
70	24.3	4.5	4.1
71	25.7	4.5	4.9
72	25.8	4.7	4.1
73	25.1	4.5	4.3
74	23.4	4.4	5.5
75	23.4	4.2	2.8
76	23.0	4.3	4.3
77	21.5	4.0	3.7
78	19.8	3.9	4.3
79	19.8	3.9	4.1
80	20.1	n/a	3.3
81	15.6	3.0	5.7
82	15.3	3.2	2.6
83	13.2	3.0	3.9
84	13.7	3.0	3.7
85	13.5	2.8	3.7
86	12.7	2.7	3.5
87	13.5	3.1	3.9
88	12.1	n/a	3.6
89	10.9	2.6	3.3
90	10.3	2.5	3.5
91	9.6	2.6	2.6
92	6.9	1.8	3.2
93	6.4	1.6	2.9
94	7.0	1.4	2.4
95	5.6	1.2	2.5
96	5.6	1.1	2.3
97	5.8	1.3	1.5

n/a = data not available.

TABLE 4A Level 1 additions of nutrient refill (concentrate), make-up water, and acid (2.5% HNO_3) for pH control. Molar values of acid, total N (including acid), and K are also listed.

Plant Age	Nutrient Refill Added	Make-Up Water Added	Acid Added	Acid Added	Total N Added	Total K Added
(DAP)	(L m^{-2} d^{-1})	(L m^{-2} d^{-1})	(mL m^{-2} d^{-1})	(mmol m^{-2} d^{-1})	(mmol m^{-2} d^{-1})	(mmol m^{-2} d^{-1})
10	0.04	1.29	0	0	3	3
11	0.02	0.92	0	0	2	1
12	0.04	0.92	0	0	3	3
13	0.14	1.29	0	0	11	9
14	0.06	1.29	39	8	12	4
15	0.00	1.48	0	0	0	0
16	0.02	1.66	0	0	2	1
17	0.00	1.48	79	16	16	0
18	0.00	1.85	79	16	16	0
19	0.00	2.22	39	8	8	0
20	0.00	2.59	79	16	16	0
21	0.18	2.96	118	24	37	12
22	1.62	1.66	118	24	145	109
23	0.26	3.14	157	31	51	18
24	0.52	2.77	118	24	63	35
25	0.38	3.14	157	31	60	26
26	0.54	2.59	118	24	64	36
27	0.42	3.88	157	31	63	28
28	0.66	2.59	157	31	81	45
29	0.46	3.51	157	31	66	31
30	0.60	3.70	236	47	92	41
31	0.54	7.95	79	16	56	36
32	0.70	9.99	118	24	76	47
33	0.66	9.43	118	24	73	45
34	0.74	10.36	118	24	79	50
35	0.40	9.62	79	16	46	27
36	0.80	8.69	118	24	84	54
37	0.80	8.32	79	16	76	54
38	0.60	8.68	118	24	69	41
39	0.08	8.88	79	16	22	5
40	0.60	8.32	118	24	69	41
41	0.54	8.52	79	16	56	36
42	0.84	7.94	118	24	87	57
43 *	0.90	8.68	118	24	91	61
44	0.44	10.00	118	24	57	30
45	1.38	5.72	79	16	119	93
46	1.28	7.94	79	16	112	86
47	0.56	6.66	157	31	73	38
48	1.82	7.03	79	16	152	123
49	1.12	8.32	197	39	123	76
50	1.58	5.36	39	8	126	107
51	1.42	10.16	118	24	130	96
52	0.78	4.81	0	0	59	53
53	0.42	6.84	39	8	39	28
54	0.42	7.03	79	16	47	28
55	0.36	6.29	79	16	43	24
56	0.36	4.25	39	8	35	24

TABLE 4A Level 1 additions of nutrient refill (concentrate), make-up water, and acid (2.5% HNO_3) for pH control. Molar values of acid, total N (including acid), and K are also listed.

Plant Age	Nutrient Refill Added	Make-Up Water Added	Acid Added	Acid Added	Total N Added	Total K Added
(DAP)	(L m^{-2} d^{-1})	(L m^{-2} d^{-1})	(mL m^{-2} d^{-1})	(mmol m^{-2} d^{-1})	(mmol m^{-2} d^{-1})	(mmol m^{-2} d^{-1})
57	0.24	5.18	79	16	34	16
58 **	0.32	7.58	39	8	32	22
59	0.00	5.73	39	8	8	0
60	0.00	7.21	39	8	8	0
61	0.04	5.92	0	0	3	3
62	0.02	4.81	118	24	25	1
63	0.20	5.18	79	16	31	14
64	0.38	5.55	39	8	36	26
65	0.22	5.18	118	24	40	15
66	0.34	5.55	39	8	33	23
67	0.24	5.18	79	16	34	16
68	0.36	4.07	39	8	35	24
69	0.26	5.55	79	16	35	18
70	0.30	4.62	39	8	30	20
71	0.32	4.99	79	16	40	22
72	0.28	4.62	39	8	29	19
73	0.22	4.81	79	16	32	15
74	0.30	6.07	118	24	46	20
75	0.44	2.40	0	0	33	30
76	0.24	10.36	79	16	34	16
77	0.86	3.70	0	0	65	58
78	0.40	4.44	79	16	46	27
79	0.60	4.62	0	0	45	41
80	0.18	3.88	39	8	21	12
81	0.12	6.10	39	8	17	8
82	0.48	2.22	39	8	44	32
83	0.16	4.25	39	8	20	11
84	0.30	3.70	0	0	23	20
85	0.28	3.70	79	16	37	19
86	0.10	3.51	0	0	8	7
87	0.30	4.07	79	16	38	20
88	0.26	3.70	0	0	20	18
89	0.02	3.33	39	8	9	1
90	0.24	3.51	79	16	34	16
91	0.04	3.14	0	0	3	3
92	0.18	2.77	39	8	21	12
93	0.12	1.85	39	8	17	8
94	0.18	2.03	0	0	14	12
95	0.02	3.70	39	8	9	1
96	0.20	0.74	0	0	15	14
97	0.00	1.85	39	8	8	0
SUM ***	35.86	434.02	6131	1226	3916	2421

* 140 mL of 1M KH_2PO_4 added ; ** 400 mL of 1M $Ca(NO_3)_2$ added; *** sums in L, mL, or mmol per m^2.

TABLE 4B Level 2 additions of nutrient refill (concentrate), make-up water, and acid (2.5% HNO_3) for pH control. Molar values of acid, total N (including acid), and K are also listed.

Plant Age	Nutrient Refill Added	Make-Up Water Added	Acid Added	Acid Added	Total N Added	Total K Added
(DAP)	($L\ m^{-2}\ d^{-1}$)	($L\ m^{-2}\ d^{-1}$)	($mL\ m^{-2}\ d^{-1}$)	($mmol\ m^{-2}\ d^{-1}$)	($mmol\ m^{-2}\ d^{-1}$)	($mmol\ m^{-2}\ d^{-1}$)
10	0.04	1.11	0	0	3	3
11	0.06	0.74	0	0	5	4
12	0.00	0.92	0	0	0	0
13	0.10	1.29	0	0	8	7
14	0.08	0.74	0	0	6	5
15	0.00	1.29	39	8	8	0
16	0.20	1.29	0	0	15	14
17	0.14	1.11	118	24	34	9
18	0.14	1.66	39	8	18	9
19	0.28	1.48	0	0	21	19
20	0.28	2.03	80	16	37	19
21	0.36	1.85	79	16	43	24
22	0.30	2.40	79	16	38	20
23	0.40	2.59	118	24	54	27
24	0.76	2.22	79	16	73	51
25	0.44	2.78	157	31	64	30
26	0.38	2.22	79	16	44	26
27	0.58	3.33	236	47	91	39
28	0.58	2.22	79	16	59	39
29	0.44	2.96	155	31	64	30
30	0.54	3.14	432	86	127	36
31	0.48	6.10	157	31	67	32
32	0.68	10.36	118	24	75	46
33	0.92	3.88	118	24	93	62
34	0.42	8.69	118	24	55	28
35	0.62	8.14	39	8	54	42
36	0.86	7.40	118	24	88	58
37	0.80	6.66	79	16	76	54
38	0.52	7.94	39	8	47	35
39	0.22	8.14	157	31	48	15
40	0.54	7.40	79	16	56	36
41	0.56	7.20	39	8	50	38
42	0.84	6.84	118	24	87	57
43 *	0.90	7.40	79	16	83	61
44	0.38	8.32	39	8	36	26
45	1.46	4.98	0	0	110	99
46	1.70	6.30	0	0	128	115
47	0.14	5.92	39	8	18	9
48	1.84	5.92	39	8	146	124
49	1.84	5.92	118	24	162	124
50	1.84	4.62	79	16	154	124
51	1.60	7.94	197	39	159	108
52	0.00	4.62	39	8	12	4
53	1.00	5.36	79	16	91	68
54	0.42	5.92	79	16	47	28
55	0.36	5.55	79	16	43	24

TABLE 4B Level 2 additions of nutrient refill (concentrate), make-up water, and acid (2.5% HNO_3) for pH control. Molar values of acid, total N (including acid), and K are also listed.

Plant Age	Nutrient Refill Added	Make-Up Water Added	Acid Added	Acid Added	Total N Added	Total K Added
(DAP)	(L m^{-2} d^{-1})	(L m^{-2} d^{-1})	(mL m^{-2} d^{-1})	(mmol m^{-2} d^{-1})	(mmol m^{-2} d^{-1})	(mmol m^{-2} d^{-1})
56	0.38	4.07	40	16	44	26
57	0.22	4.25	40	8	24	15
58 **	0.22	6.66	40	8	24	15
59	0.00	5.36	40	8	8	0
60	0.00	6.47	39	8	8	0
61	0.04	5.55	39	8	11	3
62	0.00	4.25	79	16	16	0
63	0.06	4.62	79	16	20	4
64	0.26	5.36	39	8	27	18
65	0.26	4.99	118	24	43	18
66	0.30	5.18	39	8	30	20
67	0.24	4.99	79	16	34	16
68	0.34	3.88	118	24	49	23
69	0.30	5.55	39	8	30	20
70	0.30	4.25	39	8	30	20
71	0.32	4.62	79	16	40	22
72	0.30	4.44	0	0	23	20
73	0.24	4.62	79	16	34	16
74	0.34	5.73	79	16	41	23
75	0.42	2.59	39	8	39	28
76	0.30	4.44	39	8	30	20
77	0.28	5.36	157	31	52	19
78	0.44	3.88	39	8	41	30
79	0.28	4.07	39	8	29	19
80	0.34	3.51	39	8	33	23
81	0.22	5.55	79	16	32	15
82	0.40	2.41	0	0	30	27
83	0.18	3.70	79	16	29	12
84	0.24	3.51	0	0	18	16
85	0.30	3.70	79	16	38	20
86	0.12	3.33	0	0	9	8
87	0.28	3.88	79	16	37	19
88	0.22	3.70	39	8	24	15
89	0.08	3.14	0	0	6	5
90	0.22	3.51	39	8	24	15
91	0.16	2.96	0	0	12	11
92	0.16	2.96	0	0	12	11
93	0.08	2.77	39	8	14	5
94	0.12	2.22	39	8	17	8
95	0.10	2.40	39	8	15	7
96	0.12	2.03	0	0	9	8
97	0.08	1.85	0	0	6	5
SUM ***	36.30	379.20	5781	1174	3890	2454

* 140 mL of 1M KH_2PO_4 added ; ** 400 mL of 1M $Ca(NO_3)_2$ added; *** sums in L, mL, or mmol per m^2.

TABLE 4C Level 3 additions of nutrient refill (concentrate), make-up water, and acid (2.5% HNO_3) for pH control. Molar values of acid, total N (including acid), and K are also listed.

Plant Age	Nutrient Refill Added	Make-Up Water Added	Acid Added	Acid Added	Total N Added	Total K Added
(DAP)	(L m^{-2} d^{-1})	(L m^{-2} d^{-1})	(mL m^{-2} d^{-1})	(mmol m^{-2} d^{-1})	(mmol m^{-2} d^{-1})	(mmol m^{-2} d^{-1})
10	0.06	1.66	0	0	5	4
11	0.02	1.11	0	0	2	1
12	0.00	1.85	0	0	0	0
13	0.02	2.03	0	0	2	1
14	0.08	1.66	0	0	6	5
15	0.04	1.85	39	8	11	3
16	0.06	1.85	0	0	5	4
17	0.04	1.85	39	8	11	3
18	0.06	2.22	0	0	5	4
19	0.10	2.22	0	0	8	7
20	0.16	2.22	39	8	20	11
21	0.12	2.22	0	0	9	8
22	0.10	2.40	39	8	15	7
23	0.10	2.96	79	16	23	7
24	0.28	2.77	0	0	21	19
25	0.14	3.51	79	16	26	9
26	0.42	3.15	0	0	32	28
27	0.06	3.33	39	8	12	4
28	0.24	2.77	79	16	34	16
29	0.22	3.88	79	16	32	15
30	0.28	4.07	0	0	21	19
31	0.22	4.07	79	16	32	15
32	0.32	3.51	79	16	40	22
33	0.24	3.70	79	16	34	16
34	0.28	5.18	39	8	29	19
35	0.32	4.25	39	8	32	22
36	0.38	4.25	79	16	44	26
37	0.28	4.98	0	0	21	19
38	0.26	5.56	39	8	27	18
39	0.08	8.88	157	31	37	5
40	0.06	4.08	0	0	5	4
41	0.20	4.98	79	16	31	14
42	0.28	4.62	39	8	29	19
43 *	0.52	4.82	39	8	47	35
44	0.04	5.56	0	0	3	3
45	0.56	3.70	79	16	58	38
46	0.40	4.98	39	8	38	27
47	0.62	3.70	79	16	62	42
48	0.64	4.44	39	8	56	43
49	0.20	4.62	39	8	23	14
50	0.84	2.60	79	16	79	57
51	0.40	7.20	0	0	30	27
52	0.24	2.96	39	8	26	16
53	0.24	4.44	0	0	18	16
54	0.16	4.44	39	8	20	11
55	0.10	4.25	39	8	15	7

TABLE 4C Level 3 additions of nutrient refill (concentrate), make-up water, and acid (2.5% HNO_3) for pH control. Molar values of acid, total N (including acid), and K are also listed.

Plant Age	Nutrient Refill Added	Make-Up Water Added	Acid Added	Acid Added	Total N Added	Total K Added
(DAP)	(L m^{-2} d^{-1})	(L m^{-2} d^{-1})	(mL m^{-2} d^{-1})	(mmol m^{-2} d^{-1})	(mmol m^{-2} d^{-1})	(mmol m^{-2} d^{-1})
56	0.16	3.70	0	0	12	11
57	0.20	4.63	0	0	15	14
58	0.18	4.99	79	16	29	12
59	0.28	2.96	0	0	21	19
60	0.08	4.44	39	8	14	5
61	0.24	4.25	39	8	26	16
62	0.22	3.14	39	8	24	15
63	0.06	5.18	39	8	12	4
64	0.26	3.33	0	0	20	18
65	0.14	4.62	39	8	18	9
66	0.14	4.99	0	0	11	9
67	0.18	4.25	39	8	21	12
68	0.28	2.96	0	0	21	19
69	0.14	4.25	39	8	18	9
70	0.20	3.33	39	8	23	14
71	0.14	4.25	39	8	18	9
72	0.20	4.25	0	0	15	14
73	0.08	3.51	79	16	22	5
74	0.14	4.44	39	8	18	9
75	0.22	2.77	0	0	17	15
76	0.06	4.44	0	0	5	4
77	0.28	2.96	39	8	29	19
78	0.14	3.70	39	8	18	9
79	0.16	3.55	0	0	12	11
80	0.14	2.59	39	8	18	9
81	0.18	4.44	39	8	21	12
82	0.12	1.85	0	0	9	8
83	0.10	2.96	39	8	15	7
84	0.10	2.77	0	0	8	7
85	0.18	2.77	39	8	21	12
86	0.02	1.85	39	8	9	1
87	0.18	2.96	79	16	29	12
88	0.12	2.96	0	0	9	8
89	0.02	2.22	118	24	25	1
90	0.10	2.77	0	0	8	7
91	0.10	2.22	0	0	8	7
92	0.06	2.22	0	0	5	4
93	0.22	2.41	39	8	24	15
94	0.00	1.66	0	0	0	0
95	0.08	2.22	39	8	14	5
96	0.04	1.85	0	0	3	3
97	0.00	1.66	0	0	0	0
SUM **	16.42	306.57	2830	566	1797	1108

* 140 mL of 1M KH_2PO_4 added; ** sums in L, mL, or mmol per m^2.

TABLE 4D Level 1 additions of nutrient refill (concentrate), make-up water, and acid (2.5% HNO_3) for pH control. Molar values of acid, total N (including acid), and K are also listed.

Plant Age	Nutrient Refill Added	Make-Up Water Added	Acid Added	Acid Added	Total N Added	Total K Added
(DAP)	(L m^{-2} d^{-1})	(L m^{-2} d^{-1})	(mL m^{-2} d^{-1})	(mmol m^{-2} d^{-1})	(mmol m^{-2} d^{-1})	(mmol m^{-2} d^{-1})
10	0.00	1.48	0	0	0	0
11	0.02	1.11	0	0	2	1
12	0.02	0.74	0	0	2	1
13	0.16	1.48	0	0	12	11
14	0.04	1.85	0	0	3	3
15	0.00	2.22	0	0	0	0
16	0.08	2.59	0	0	6	5
17	0.04	1.85	0	0	3	3
18	0.12	2.59	79	16	25	8
19	0.14	1.48	0	0	11	9
20	0.04	2.96	0	0	3	3
21	0.16	2.41	0	0	12	11
22	0.08	2.96	0	0	6	5
23	0.04	2.22	118	24	27	3
24	0.08	3.70	0	0	6	5
25	0.00	2.59	39	8	8	0
26	0.08	2.96	0	0	6	5
27	0.16	3.70	118	24	36	11
28	0.30	2.22	79	16	38	20
29	0.12	3.70	0	0	9	8
30	0.20	2.96	0	0	15	14
31	0.28	3.70	118	24	45	19
32	0.20	3.70	157	31	46	14
33	0.30	3.70	39	8	30	20
34	0.16	5.18	79	16	28	11
35	0.16	4.07	79	16	28	11
36	0.40	2.22	79	16	46	27
37	0.22	3.70	79	16	32	15
38	0.12	4.44	0	0	9	8
39	0.02	4.44	157	31	33	1
40	0.06	3.70	39	8	12	4
41	0.08	6.66	0	0	6	5
42	0.50	4.44	79	16	53	34
43 *	0.22	5.18	39	8	24	15
44	0.12	4.44	39	8	17	8
45	0.26	4.44	157	31	51	18
46	0.30	4.30	39	8	30	20
47	0.34	4.44	118	24	49	23
48	0.40	4.44	79	16	46	27
49	0.22	2.96	0	0	17	15
50	0.08	6.66	79	16	22	5
51	0.70	4.44	118	24	76	47
52	0.36	3.70	39	8	35	24
53	0.34	3.70	39	8	33	23
54	0.04	5.18	39	8	11	3
55	0.22	4.44	0	0	17	15

TABLE 4D Level 1 additions of nutrient refill (concentrate), make-up water, and acid (2.5% HNO_3) for pH control. Molar values of acid, total N (including acid), and K are also listed.

Plant Age	Nutrient Refill Added	Make-Up Water Added	Acid Added	Acid Added	Total N Added	Total K Added
(DAP)	(L m^{-2} d^{-1})	(L m^{-2} d^{-1})	(mL m^{-2} d^{-1})	(mmol m^{-2} d^{-1})	(mmol m^{-2} d^{-1})	(mmol m^{-2} d^{-1})
56	0.16	3.70	79	16	28	11
57	0.42	1.48	0	0	32	28
58	0.04	5.18	0	0	3	3
59	0.08	3.70	39	8	14	5
60	0.04	4.44	39	8	11	3
61	0.18	4.44	0	0	14	12
62	0.18	5.18	39	8	21	12
63	0.18	4.44	79	16	29	12
64	0.08	5.18	0	0	6	5
65	0.14	5.55	39	8	18	9
66	0.14	5.92	39	8	18	9
67	0.20	4.07	0	0	15	14
68	0.16	2.22	79	16	28	11
69	0.06	5.92	0	0	5	4
70	0.28	2.59	39	8	29	19
71	0.10	5.18	39	8	15	7
72	0.16	3.70	0	0	12	11
73	0.12	3.70	39	8	17	8
74	0.14	4.81	39	8	18	9
75	0.30	1.48	0	0	23	20
76	0.08	2.96	79	16	22	5
77	0.18	3.70	0	0	14	12
78	0.14	4.44	79	16	26	9
79	0.20	4.44	0	0	15	14
80	0.22	2.22	0	0	17	15
81	0.04	4.81	79	16	19	3
82	0.24	1.48	0	0	18	16
83	0.12	3.70	79	16	25	8
84	0.14	1.85	0	0	11	9
85	0.10	3.89	39	8	15	7
86	0.20	2.96	0	0	15	14
87	0.08	4.44	39	8	14	5
88	0.34	2.96	0	0	26	23
89	0.26	2.96	79	16	35	18
90	0.24	2.96	0	0	18	16
91	0.22	2.22	0	0	17	15
92	0.26	2.22	39	8	27	18
93	0.12	2.96	0	0	9	8
94	0.30	2.22	39	8	30	20
95	0.28	2.22	0	0	21	19
96	0.30	2.22	0	0	23	20
97	0.24	0.18	0	0	18	16
SUM **	15.44	304.93	3262	652	1810	1042

* 140 mL of 1M KH_2PO_4 added; ** sums in L, mL, or mmol per m^2.

TABLE 5A Concentration of macronutrients in soybean (cv. McCall) tissues at harvest from levels 1 and 2 (HPS lamps).

Plant Tissue	Element					
	N	P	Na	K	Ca	Mg
			(ppm)			
Seed	57120	3517	19	20000	3583	2763
Pods	11744	2507	36	125000	7043	3970
Leaves	20224	2060	32	47100	31100	5807
Stems	14912	2370	83	51700	3550	1893
Roots	35072	6273	703	71067	6390	6687

TABLE 5B Concentration of micronutrients in soybean (cv. McCall) tissues at harvest from levels 1 and 2 (HPS lamps).

Plant Tissue	Element					
	Fe	B	Mn	Zn	Cu	Mo
			(ppm)			
Seed	99.5	12.67	18.73	21.13	12.33	0.64
Pods	58.7	27.50	14.90	20.83	4.11	0.52
Leaves	145.0	99.93	74.00	26.33	5.81	0.47
Stems	45.8	11.01	5.20	4.98	4.96	0.36
Roots	842.0	20.93	99.23	35.57	52.53	0.93

TABLE 5C Concentration of macronutrients in soybean (cv. McCall) tissues at harvest from levels 3 and 4 (MH lamps).

Plant Tissue	Element					
	N	P	Na	K	Ca	Mg
			(ppm)			
Seed	58816	3873	17	25500	3277	2960
Pods	10352	2257	33	114000	7380	3777
Leaves	20832	2020	30	48533	31100	5180
Stems	13344	2517	113	52767	5400	2493
Roots	39824	8593	1130	79000	4054	8387

TABLE 5D Concentration of micronutrients in soybean (cv. McCall) tissues at harvest from levels 3 and 4 (MH lamps).

Plant Tissue	Element					
	Fe	B	Mn	Zn	Cu	Mo
			(ppm)			
Seed	97.4	25.63	22.27	35.20	13.50	0.55
Pods	49.6	45.40	13.70	18.33	3.25	0.42
Leaves	125.3	148.33	56.83	21.04	6.41	0.24
Stems	58.1	15.30	9.03	10.93	8.71	0.37
Roots	1069.7	27.07	85.30	46.87	65.63	0.95

TABLE 6A Partitioning of macronutrients in soybean (cv. McCall) tissue at harvest from levels 1 and 2 (HPS lamps). Values indicate (%) of nutrient partitioned to each tissue.

Plant Tissue	Element					
	N	P	Na	K	Ca	Mg
Seed	63.5	43.1	10.5	14.0	10.8	26.0
Pods	5.1	11.9	7.7	33.8	8.2	14.5
Leaves	17.4	19.5	13.7	25.4	72.5	42.3
Stems	10.0	17.5	27.7	21.7	6.5	10.7
Roots	4.1	8.0	40.4	5.2	2.0	6.5

TABLE 6B Partitioning of micronutrients in soybean (cv. McCall) tissue at harvest from levels 1 and 2 (HPS lamps). Values indicate (%) of nutrient partitioned to each tissue.

Plant Tissue	Element					
	Fe	B	Mn	Zn	Cu	Mo
Seed	28.5	11.6	19.7	37.6	45.9	42.2
Pods	6.5	9.1	6.1	14.3	5.9	13.3
Leaves	32.1	70.6	60.1	36.2	16.7	23.9
Stems	7.9	6.1	3.3	5.3	11.1	14.3
Roots	25.1	2.0	10.8	6.6	20.3	6.4

TABLE 6C Partitioning of macronutrients in soybean (cv. McCall) tissue at harvest from levels 3 and 4 (MH lamps). Values indicate (%) of nutrient partitioned to each tissue.

Plant Tissue	Element					
	N	P	Na	K	Ca	Mg
Seed	71.9	52.3	9.1	21.7	13.3	34.1
Pods	4.5	10.9	6.3	34.7	10.8	15.6
Leaves	13.4	14.3	8.5	21.7	66.6	31.4
Stems	5.8	12	21.3	15.8	7.8	10.1
Roots	4.4	10.5	54.8	6.1	1.5	8.8

TABLE 6D Partitioning of micronutrients in soybean (cv. McCall) tissue at harvest from levels 3 and 4 (MH lamps). Values indicate (%) of nutrient partitioned to each tissue.

Plant Tissue	Element					
	Fe	B	Mn	Zn	Cu	Mo
Seed	32.6	20.1	32.8	57.8	49.9	52.7
Pods	6.0	12.1	7.2	10.8	4.3	14.4
Leaves	22.1	61.1	44.0	18.2	12.5	12.1
Stems	6.9	4.2	4.7	6.3	11.4	12.5
Roots	32.5	1.9	11.4	7.0	22.0	8.3

TABLE 7A Proximate composition of soybean (cv. McCall) tissue at harvest for levels 1 and 2 (HPS lamps). Values expressed as percent of total dry mass.

Plant Tissue	Protein*	Fat	Carbo-hydrate	Ash	Crude Fiber	Energy** (kcal/100g)
Seed	35.7	22.3	34.5	7.5	13.3	429
Pods	7.3	2.0	69.1	21.5	31.0	200
Leaves	12.6	2.9	62.6	21.9	17.4	257
Stems	9.3	8.0	77.1	11.6	52.2	155
Roots	21.9	2.3	62.7	13.0	37.9	208

TABLE 7B Proximate composition of soybean (cv. McCall) tissue at harvest for levels 3 and 4 (MH lamps). Values expressed as percent of total dry mass.

Plant Tissue	Protein*	Fat	Carbo-hydrate	Ash	Crude Fiber	Energy** (kcal/100g)
Seed	36.8	21.6	34.0	7.6	16.6	412
Pods	6.5	1.4	70.6	21.6	30.4	199
Leaves	13.0	2.7	62.7	21.6	16.4	261
Stems	8.3	1.3	78.8	11.4	48.7	166
Roots	24.9	2.0	57.1	16.0	31.6	219

* Calculated from Kjeldahl nitrogen analysis assuming protein content = N X 6.25.

** Assuming 4 kcal / g for carbohydrate and protein, and 9 kcal / g for fat.

TABLE 8 Final yields of soybean (cv. McCall) plants, expressed as dry mass per unit area*, and percent biomass partitioned to each tissue.

Plant Part	Level 1		Level 2		Level 3		Level 4	
	($g\ m^{-2}$)	(%)	($g\ m^{-2}$)	(%)	($g\ m^{-2}$)	(%)	($g\ m^{-2}$)	(%)
Seeds	488.0	35.0	483.4	35.1	280.8	44.2	282.8	40.7
Pods	191.8	13.7	187.4	13.6	106.6	16.8	103.8	14.9
Leaves	362.9	26.0	387.6	28.3	127.9	20.2	176.5	25.4
Stems	303.7	21.8	264.8	19.2	97.3	15.3	101.7	14.6
Roots	48.7	3.5	52.5	3.8	22.3	3.5	30.8	4.4
Total	1395.1	100.0	1375.7	100.0	634.9	100.0	695.6	100.0

* Each level supported 16 trays (4 plants / tray) and 5 m^2 total growing area.

** Lighting provided by HPS lamps for levels 1 and 2, and MH lamps for levels 3 and 4 (see Table 9)

TABLE 9 Photosynthetic photon flux ($\mu mol\ m^{-2}\ s^{-1}$) averages and standard deviations for different growing levels over time*. Levels 1 and 2 used high-pressure sodium (HPS) lamps and levels 3 and 4 used metal halide (MH) lamps.

DAP	Level 1		Level 2		Level 3		Level 4		Chamber
	Avg	SD	Avg	SD	Avg	SD	Avg	SD	Avg
7	595	77	602	57	287	38	290	25	444
14	648	67	638	74	309	38	310	24	476
21	694	84	699	77	332	41	324	28	512
28	866	54	874	84	352	51	359	46	613
35	925	203	912	203	445	67	432	58	679
42	1015	170	1000	121	506	60	499	88	755
49	874	170	845	206	399	110	401	61	630
56	876	117	848	130	420	44	376	53	630
63	943	127	937	156	465	62	482	70	707
70	964	189	951	152	477	58	508	59	725
77	919	138	946	135	442	77	464	72	693
84	1009	145	1001	140	486	59	511	69	752
91	1058	117	979	129	479	60	527	52	761
Avg	876		864		415		422		644

TABLE 10 Ethylene concentrations (ppb) in growth chamber atmosphere during growth of soybean and wheat (Wheeler et al., 1993a).

Plant Age (DAP)	Soybean (ppb)	Wheat (ppb)	Plant Age (DAP)	Soybean (ppb)	Wheat (ppb)
0		2	49	36	41
1			50	47	
2	4		51	52	26
3	6		52	48	
4	6		53	59	
5	8		54	58	
6	9		55	59	
7	10		56	52	
8	7		57	36	
9	7		58	35	
10	8		59		
11	11		60		
12	10		61	36	
13	8		62	36	
14	10	20	63	29	
15	8		64	24	
16	11	20	65	24	
17	10		66	24	
18	9		67	22	
19	9		68	28	2
20	7		69	17	2
21		47	70	18	
22	6		71	17	2
23	7	23	72	20	
24	7	46	73	19	
25	9		74	23	
26	10		75	17	2
27	7	113	76	18	
28	10	122	77	18	
29	7	40	78	15	
30	7		79	14	
31	8	70	80	14	
32	16		81	12	
33	16		82	16	
34	17	98	83	16	
35	28		84	15	
36	27	97	85	13	2
37	28	87	86		
38	36	96	87		
39	45		88		
40	46		89		
41	43	44	90	23	
42	24		91	21	
43	22	19	92	16	
44	26	14	93	20	
45	28		94	17	
46	44		95	31	
47	43		96	34	
48	40	64	97	38	

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16. Abstract

A data set is given describing daily nutrient and water uptake, carbon dioxide (CO_2) exchange, ethylene production, and carbon and nutrient partitioning from a 20 m^2 stand of soybeans [*Glycine max* (L.) Merr. cv. McCall] for use in bioregenerative life support systems. Stand CO_2 exchange rates were determined from nocturnal increases in CO_2 (respiration) and morning drawdowns (net photosynthesis) to a set point of 1000 µmol mol^{-1} each day (i.e., a closed system approach). Atmospheric samples were analyzed throughout growth for ethylene using gas chromatography with photoionization detection (GC/PID). Water use was monitored by condensate production from the humidity control system, as well as water uptake from the nutrient solution reservoirs each day. Nutrient uptake data were determined from daily additions of stock solution and acid to maintain an EC of 0.12 S m^{-1} and pH of 5.8. Dry mass yields of seeds, pods (without seeds), leaves, stems, and roots are provided, as well as elemental and proximate nutritional compositions of the tissues. A methods section is included to qualify any assumptions that might be required for the use of the data in plant growth models, along with a daily event calendar documenting set point adjustments and the occasional equipment or sensor failure.

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