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Statistical Analysis of Environmental Variability Within the CELSS Breadboard Project's Biomass Production Chamber

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TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

INTRODUCTION

Systematic analysis of the atmospheric variability of physiologically significant parameters has not been performed for KSC's Breadboard Project Biomass Production Chamber (BPC), and no mechanism exists to readily identify and isolate the factor(s) which limit biomass production within the chamber. However, it is known that significant spatial variability in total biomass production and edible biomass occurs within the BPC (Wheeler, et al., 1990).

A number of engineering characterizations of the BPC have been conducted, including design characteristics and specification (Hilding, et al., 1987), spectral quality and distribution of irradiance system (Fortson, et al., 1992), integrity of atmospheric closure (Knott, et al., 1992; Sager, et al., 1988), atmospheric contaminants (Peterson, unpublished) and microbial populations (Strayer, 1991).

The information obtained from these characterizations has resulted in numerous modifications of components of the BPC as well as in the monitoring and control systems. In general, modifications have been made to improve the control and monitoring capabilities of the BPC, and as a direct result, have improved both the quality of the physiological information derived from BPC crop growouts, and greatly enhanced the Breadboard project's capability to explore the environmental limitations of crop production in a closed system.

A continuously updated database of atmospheric conditions within the BPC is available (R. Fortson, et al., 1992). However, this database, although extensive, is of limited value for making meaningful statistical analysis of the environmental limitations of plant development. Perhaps the most significant limitation of the database is that there is no way to determine if the collected data is representative of the total chamber. Thus, it is impossible to know whether the limited number of collection sites are directly comparable for analytical purposes. For example, the positions of the two thermocouples

which monitor air temperature in each chamber, may or may not be similar with respect to spatial referencing or temperature gradient.

To partially offset the limitations of the monitoring system (MS) database, weekly measures of temperature, PPF, and air velocity are obtained manually (C.L. Mackowiak and L. Siegriest, personal communication) at canopy level for each plant tray. Assuming that gradients within the upper and lower chambers are comparable and that the locations of the measurements are representative of the trays, these manually collected data are invaluable in determining whether the variations between the upper and lower chambers are influencing the validity of experimental results obtained during growouts. The accuracy of these assumptions has not been experimentally tested.

A modification to the BPC was performed in 1991 that permits atmospheric integrity to be maintained between the upper and lower chambers. This modification was performed to permit scientifically valid comparisons of growing conditions to be made. In essence, this modification resulted in two, theoretically identical, large scale chambers for studying the feasibility of incorporating biological life support systems into long-term space habitats. A schematic diagram of the chamber configuration is shown in Figure 1. Since that modification, two crops, lettuce cv. Waldmann's Green (BLT921), and White Potato, cv. Norland (BWP921), have been grown.

This analysis was performed to test the assumption that the chambers were identical in their enviromental control characteristics. A statistical approach was used to characterize the chambers for a number of reasons. The first reason was to determine whether variations between the two chambers (BPC-upper and BPC-lower) were introduced when atmospheric integrity was incorporated. Second, if statistically significant variations occurred, then determine

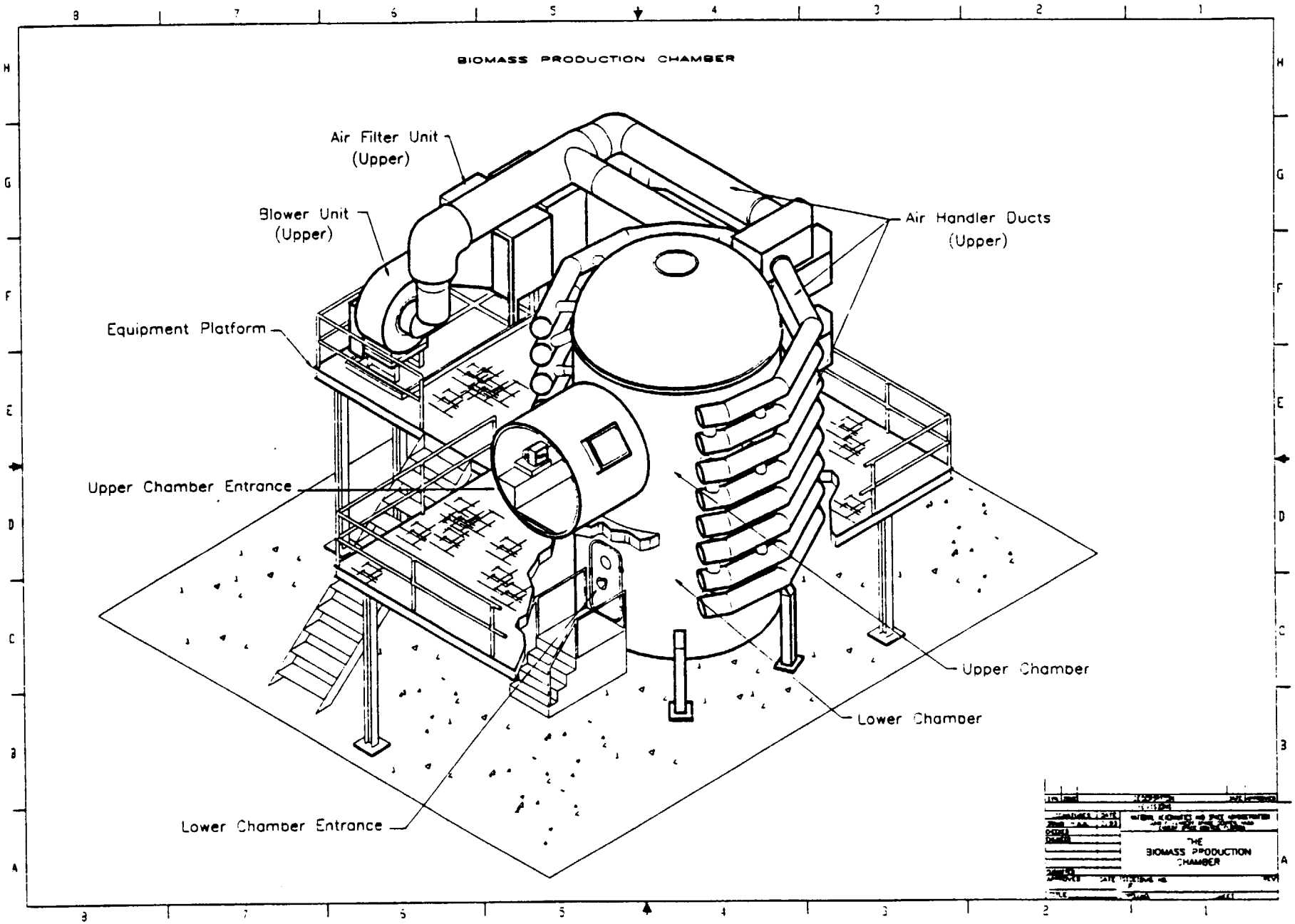

Figure 1: Schematic of the NASA Breadboard Project Biomass Production Chamber

whether these changes are of physiological significance to the plant and within engineering design limitations.

A third reason was to localize and characterize variability *within* each chamber. This characterization was determined necessary in order to identify overall design characteristics which would regulate plant growth and development.

MATERIALS AND METHODS

For purposes of the characterization, environmental parameters for a lettuce crop and a potato crop grown before and after chamber separation were analyzed. The lettuce experiments were BLT911 and BLT921. The white potato experiments were BWP912 and BWP921.

For statistical purposes, the environmental data were analyzed as a completely randomized block design with the main treatments being the two chambers: BPC-upper and BPC-lower. Within the two treatments, data were blocked with the two growing levels: top and bottom. Where appropriate, tray position was used as sample sites. A drawing showing the arrangement of the trays and the relationship between the top and bottom growing levels in the chambers is shown in Figure 2. The number of replicates and samples, which varied according to the parameter monitored, are detailed in the data tables.

Each chamber (upper and lower) has independent monitoring and control systems. Sensors connected to a programmable logic controller (PLC) are used to maintain environmental set points. An independent monitoring system (MS), with a different set of sensors, records actual environmental conditions. Both the PLC and MS sensor data are collected in 5-minute intervals and stored on an HP-9000 minicomputer. Sensors are calibrated on an as-needed basis whenever readings from the PLC and MS differ significantly. The difference rarely exceeds 10% between the PLC and MS signals.

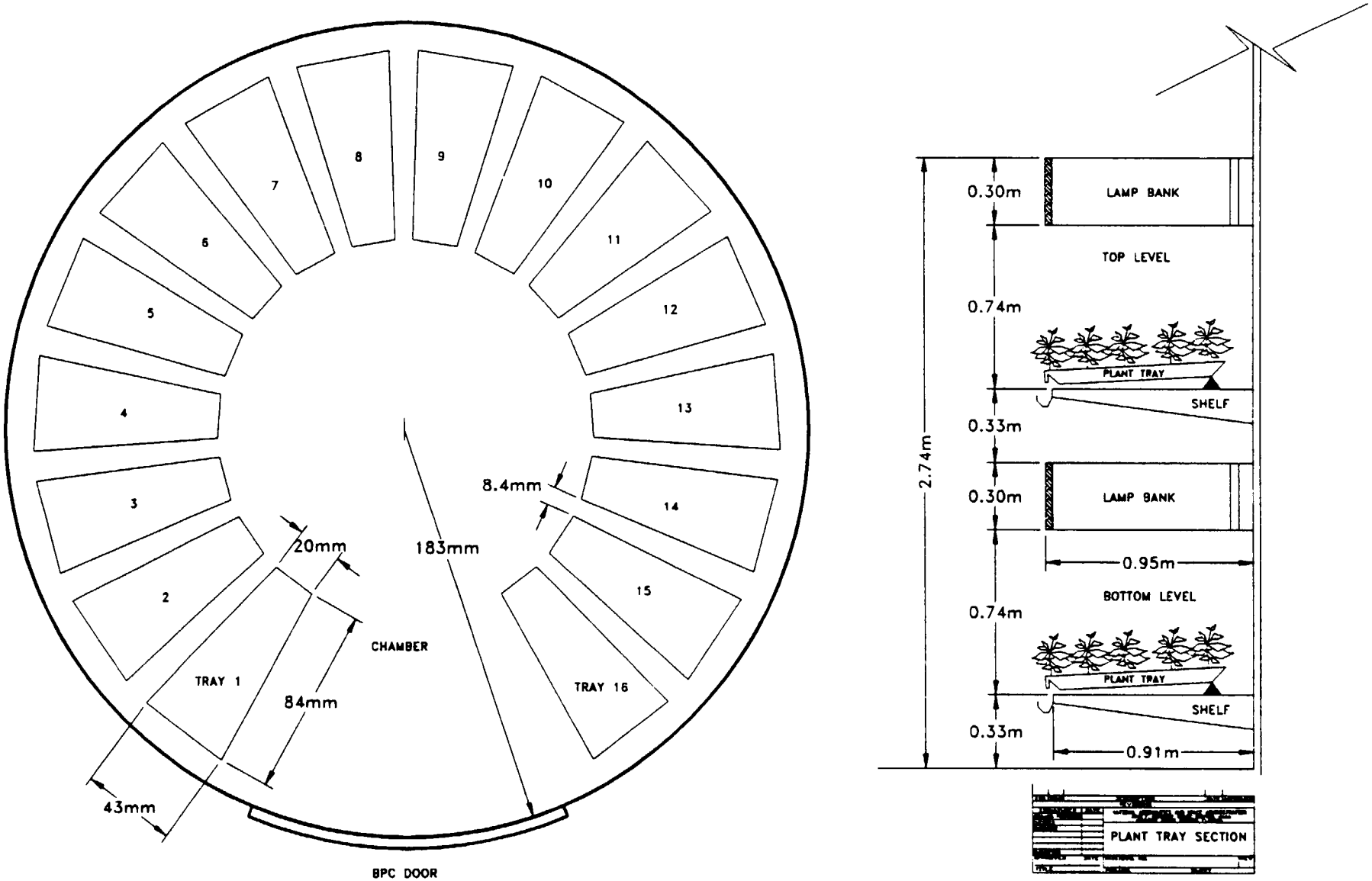

Figure 2: Schematic of tray position and growing levels within a chamber.

significantly. The difference rarely exceeds 10% between the PLC and MS signals.

The environmental control systems which are independent subsystems were utilized for this analysis. The independent variables of the aerial environment were air temperature, photosynthetic photon flux (PPF), air velocity and relative humidity. The independent variables in the root environment were nutrient solution temperature, solution pH, and electrical conductivity. For the experiments chosen, both the upper and lower chambers had the same environmental set points. As a consequence, experimentally programmed changes in a particular set-point are accommodated by the statistical analysis chosen.

The independent variables described were controlled and monitored for the entire chamber or growing level in both the upper and lower chambers. Growth and yield data were obtained at canopy level from individual trays (16 - 0.25m^2 growing trays per growing level). As such, it was of considerable interest to determine the growing environment at tray level. Air velocity, PPF, and temperature of the plant canopy were analyzed with respect to individual tray position.

SHOOT ENVIRONMENT

Air Temperature: Air temperature was obtained with iron/constantine thermocouples, and daily averages of the 5-minute monitoring system data during the light and dark cycle of each day were utilized for the analysis. Assuming a 12h light/12h dark cycle, 144 (12 temps x 12 hours) points were averaged for a single sample. Assuming two samples per day (light/dark) over a 28-day lettuce growout, then 56 values per level were utilized in the analysis.

Relative Humidity: BPC monitoring data were obtained with a Vaisala Model HMI 111A relative humidity sensor (Finland)[1] and analyzed as described for Air Temperature.

Air Velocity: Air velocity was obtained at weekly intervals with a KURZ Model 1440 anemometer (Carmel Valley, CA) at canopy level for each tray throughout the growout, except during periods of long-term closure. For example, in lettuce study BLT911 there was a total of (4 weeks x 16 trays) 64 values per growing level utilized in the analysis.

Photosynthetic Photon Flux: PPF was obtained at the same time as Air Velocity using a calibrated LICOR Quantum sensor (Lincoln, NE).

Canopy Temperature: Canopy temperature was obtained at the same time as Air Velocity and PPF readings using an Everest Model 210 Infrared Thermometer (Tuscin, CA).

ROOT ENVIRONMENT

Solution Temperature: Solution temperatures were obtained with Type J, iron/constantine, thermocouples and daily averages of the 5-minute monitoring system data were used for the analysis as previously described.

pH: pH were acquired with pH electrodes and daily averages of the 5-minute analysis. The PLC data set was used since the variation within the 5-minute data were more consistent than the MS data.

Electrical Conductivity: EC data were acquired with an Omega conductivity electrode, validated and analyzed as described for pH.

STATISTICAL ANALYSIS

Analysis of Variance (ANOVA) was performed to determine the sources of experimental error in the data set, and mean

[1] Mention of a trade name does not constitute an endorsement by either The Bionetics Corporation or by NASA.

separation was performed using Duncan's multiple-range test on all main effect means. In the case of two comparisons (upper vs. lower chamber; top vs. bottom level), this test is equivalent to the KRUL-T-TEST (SAS, Inc., Cary, NC).

RESULTS

The results of the statistical analysis for chamber, growing level, and tray position are presented in Tables 1-12.

Small but statistically significant differences between the upper and lower chamber were observed in PPF, ATEMP and RH prior to chamber modification. Air temperature was consistently higher in the upper chamber by ~0.4°C. (Tables 1 and 7). This overall variation was within 2% of the targeted setpoint for each experiment.

There were also chamber differences in PPF at canopy level which varied from experiment to experiment. These variations reflect the spatial development of the plant to a greater extent than the other parameters, however, since PPF is directly proportional to distance from the light source, and any variation in plant development would be correlated to this parameter.

Chamber variations in RH were also observed prior to closure, with the lower chamber being highest during BLT911 and the upper during BWP912. Sealing the chamber had little or no effect on the chamber variation. Depending on the growout, there were either no significant differences between the upper and lower chambers (BLT921) or the variation was the same as before sealing (BWP921). Closure also had no effect on relative humidity gradients between the chambers. In all cases tested, statistically significant differences in RH occurred. However, the direction of the gradient appears to be related to type of crop, with the lower chamber having a higher RH than the upper chamber when lettuce was grown (Tables 1 and 4) and the upper chamber having a higher RH when potato was grown (Tables 7

and 9). No significant differences in air velocity at plant height were observed between chambers.

Subsequent to sealing the atmospheric exchange between the upper and lower chambers, statistical differences in root zone parameters (S.Temp, pH and EC) were no longer observed. This is likely related more to improvements in control rather than a direct effect of the closure.

Tables 13 through 19 show the comparison of inter and intra-chamber variability for lettuce and white potato before and after sealing the floor. The major results are summarized below.

SHOOT ENVIRONMENT

Significantly different levels in PPF between the upper and lower chambers were observed prior to chamber modifications (Table 13). These differences were eliminated when the floor was sealed. There were no statistical differences between the growing level, except for BWP912. Although not always statistically significant, it should be noted that the bottom growing level tended have a higher PPF than the top level. This is likely due to a relay which was not providing full power to a bank of lights on the top growing level of the lower chamber.

The top growing level is consistently warmer than the bottom growing level (Table 14). Sealing the floor increased the steepness of the gradient 0.2 to 0.3°C for both lettuce and potato. The steepness of the gradient appears to be influenced by the temperature set point. With potato, having a statistically significant difference of 1.7°C between the top and bottom growing level. This contrasts with the 0.4°C gradient between the upper and lower chambers, which was not affected by sealing the floor.

Modifying the chamber had statistically, and potentially physiologically, significant effects on relative humidity gradients between and within each chamber (Table 15). Before the chamber was modified, a 2 to 7% gradient existed between the

upper and lower chambers. The direction of the gradient was crop dependent, suggesting an interaction with temperature set point. After sealing, the gradient ranged from 9 to 12%, with the direction again dependent on the crop being grown.

In contrast to the crop dependent inter-chamber variation, the intra-chamber variation was more predictable, the top of a chamber had a lower RH than the bottom of a chamber. Prior to modifying the chamber, the difference between the levels was less than five percent. After sealing, the difference was as high as 14 percent. There are no significant differences in air velocity between either the chambers or growing levels (Table 16).

The greatest variation within the chamber during an experiment was correlated to tray position within a growing level. Air velocity showed the greatest spatial variability with three fold differences being commonplace. Trays 8-12 had the highest air velocity. There was an inverse relation between air velocity and canopy temperature in all experiments (Figure 3). There was also a positional effect on PPF at canopy level with the end trays (positions 1, 2, 15 and 16) having significantly lower PPF levels than the rest of the trays.

ROOT ENVIRONMENT

There were no statistically significant differences in either solution temperature (Table 17), or solution pH (Table 18). There were statistically different values in EC control between both the upper and lower chamber and the top and bottom growing levels. These differences are within 2% of PLC set point, and fall within the range of electrode sensitivity and are not of physiological significance.

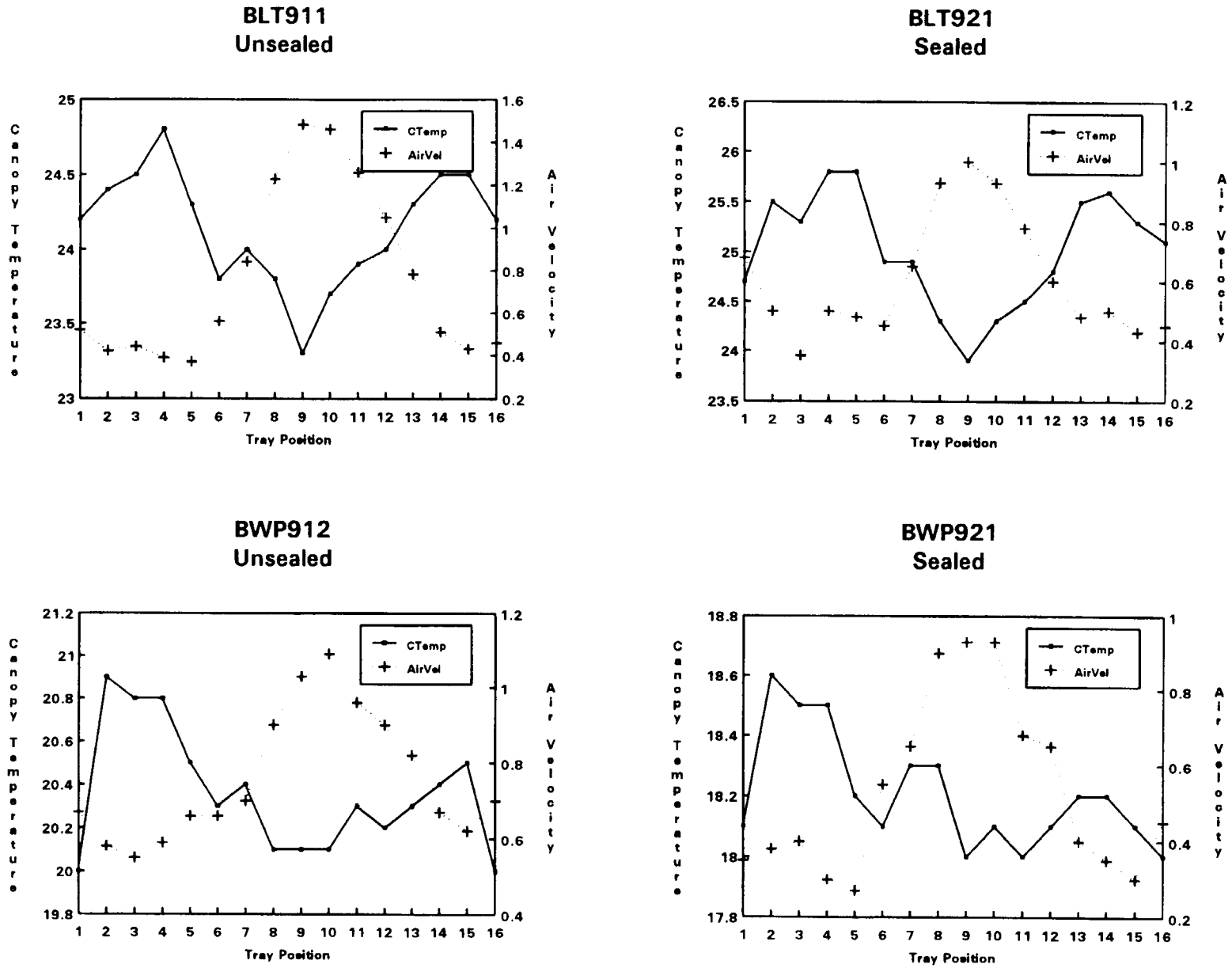

Figure 3: Relationship between tray position with a growing level and canopy temperature (+) and air velocity ( ) for 4 crops grown in the KSC Biomass Production Chamber.

DISCUSSION

Based on the analyses of available environmental data recorded from lettuce and potato crops grown prior to and subsequent to chamber modification, it appears that there was no detrimental effect on the control of environmental components between the upper and lower chambers associated with the modification. In fact, the modification reduced the overall environment variation to less than 5% from set point for all parameters measured. This suggests that experiments performed prior to the modification can be compared directly to subsequent experiments with regard to biomass production, gas exchange and partitioning. Further, these results indicate that comparisons between the upper and lower chambers can, and should, be made since there is no obvious difference between the chambers. In fact, even when statistically significant differences exist between the upper and lower chambers, the physiological significance of the differences is questionable since they rarely exceeded 0.5°C in temperature and 10% in RH. These differences, while real, fall within the range of resolution for the sensors, and are within a range where the impact on growth and development is negligible.

However, this relative uniformity of the environmental conditions does not exist within the chamber. There are significant gradients that appear inherent with the design of the BPC. The temperature gradient between the top and bottom growing levels is twice that of the difference between the upper and lower chambers, and positional variation within a single level can be three times that of the gradient between the upper and lower chamber. A similar situation exists with respect to relative humidity.

However, the greatest detectable variation at this time is in air velocity. The differences between chamber and growing levels are not physiologically significant (<5%), but the positional differences can be as high as 300% within a growing level. In fact, a distance of less than one meter reveals a

100% difference in the air velocity. This indicates that if treatments are imposed at the tray level (e.g., modifying nutrient solution components), then the treatment must be blocked across the trays. Further, the gradient in air velocity was inversely proportional to a gradient in canopy temperature. Since canopy temperature is affected by rate of evapo-transpiration, the gradients observed may reflect differences in water utilization by the plants. This hypothesis needs further testing before a definitive statement can be made.

The ability to obtain statistically valid data from individual tray treatments is severely limited at this time. Strategies for subsampling will require either careful pairing of the sites, or a large number of randomly selected samples collected across the gradient.

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Table 1: Characterization of environmental conditions affecting plant growth within the CELSS Breadboard Project Biomass Production Chamber prior to sealing: Chamber characteristics during BLT911.

	SHOOT ENVIRONMENT[z]			ROOT ENVIRONMENT[y]		
CHAMBER[x]	PFF (umol m^{-2} s^{-1})	ATEMP (°C)	RH (%)	AVEL (m s^{-1})	STEMP (°C)	pH	EC (uS cm^{-1})
Upper	282 a[w]	22.6 a	71 b	0.74 a	25.8 a	5.8 a	1210 b
Lower	294 b	22.3 b	74 a	0.79 a	25.6 b	5.7 a	1222 a
df	109	224	224	109	216	208	208

[z] PPF and AVEL measurements determined at plant canopy of each tray at weekly intervals. ATEMP and RH taken from daily 5-minute averages from BPC monitoring system.

[y] STEMP, pH, and EC readings from daily averages of 5-minute sampling from PLC control system.

[x] Upper chamber = Growing levels 1 and 2; Lower chamber = Growing levels 3 and 4.

[w] Duncan mean separation between columns at P >0.05.

Table 2: Characterization of environmental conditions affecting plant growth within the CELSS Breadboard Project Biomass Production Chamber prior to sealing: Growing Level characteristics during BLT911.

	SHOOT ENVIRONMENT[z]				ROOT ENVIRONMENT[y]		
LEVEL[x]	PFF (umol m^{-2} s^{-1})	ATEMP (°C)	RH (%)	AVEL (m s^{-1})	STEMP (°C)	pH	EC (uS cm^{-1})
Top	285 a[w]	22.7 a	70 b	0.73 b	25.9 a	5.7 a	1226 a
Bottom	291 a	22.2 b	74 a	0.80 a	25.8 a	5.7 a	1207 b
df	109	224	224	109	212	212	216

[z] PPF and AVEL measurements determined at plant canopy of each tray at weekly intervals. ATEMP and RH taken from daily 5-minute averages from BPC monitoring system.

[y] STEMP, pH, and EC readings from daily averages of 5-minute sampling from PLC control system.

[x] Top level = Growing levels 1 and 3; Bottom level = Growing levels 2 and 4.

[w] Duncan mean separation between columns at P >0.05.

Table 3

Characterization of environmental conditions affecting plant growth within the CELSS Breadboard Project Biomass Production Chamber prior to sealing: Growing position characteristics during BLT911.

SHOOT ENVIRONMENT[z]

POSITION	PFF (umol m^{-2} s^{-1})	CTEMP (°C)	AVEL (m S^{-1})
1	236 e[y]	24.2 bcd	0.52 e
2	286 c	24.4 b	0.42 e
3	303 abc	24.5 ab	0.44 e
4	305 abc	24.8 a	0.39 e
5	301 abc	24.3 bc	0.37 e
6	294 bc	20.8 bcd	0.56 e
7	316 a	24.0 cde	0.84 d
8	298 abc	23.8 ef	1.23 b
9	296 abc	23.3 g	1.48 a
10	297 abc	23.7 f	1.46 a
11	298 abc	23.9 def	1.26 b
12	312 ab	24.0 cdef	1.05 c
13	311 ab	24.3 bc	0.78 d
14	292 bc	24.5 ab	0.51 e
15	257 d	24.5 ab	0.43 e
16	202 f	24.2 bcd	0.46 e
df	109	109	109

[z]PPF, CTEMP and AVEL measurements determined at plant canopy of each tray at weekly intervals.

[y]Duncan mean separation between columns at P>0.05.

Table 4: Characterization of environmental conditions affecting plant growth within the CELSS Breadboard Project Biomass Production Chamber prior to sealing: Chamber characteristics during BWP912.

	SHOOT ENVIRONMENT[z]			ROOT ENVIRONMENT[y]		
CHAMBER[x]	PFF (umol m^{-2} s^{-1})	ATEMP (°C)	RH (%)	AVEL (m s^{-1})	STEMP (°C)	pH	EC (uS cm^{-1})
Upper	915 a[w]	17.4 a	82 b	0.77 a	17.9 a	5.6 a	1195 b
Lower	817 b	17.0 b	75 a	0.75 a	17.9 a	5.6 a	1205 a
df	391	704	702	391	704	704	704

[z] PPF and AVEL measurements determined at plant canopy of each tray at weekly intervals. ATEMP and RH taken from daily 5-minute averages from BPC monitoring system.

[y] STEMP, pH, and EC readings from daily averages of 5-minute sampling from PLC control system.

[x] Upper chamber = Growing levels 1 and 2; Lower chamber = Growing levels 3 and 4.

[w] Duncan mean separation between columns at P >0.05.

Table 5: Characterization of environmental conditions affecting plant growth within the CELSS Breadboard Project Biomass Production Chamber prior to sealing: Growing Level characteristics during BWP912.

	SHOOT ENVIRONMENT[z]			ROOT ENVIRONMENT[y]		
LEVEL[x]	PFF (umol m^{-2} s^{-1})	ATEMP (°C)	RH (%)	AVEL (m s^{-1})	STEMP (°C)	pH	EC (uS cm^{-1})
Top	846 a[w]	17.8 a	78 a	0.74 a	17.9 a	5.6 a	1195 a
Bottom	887 b	16.5 b	79 a	0.77 a	17.9 a	5.6 a	1204 a
df	391	704	702	391	704	704	704

[z] PPF and AVEL measurements determined at plant canopy of each tray at weekly intervals. ATEMP and RH taken from daily 5-minute averages from BPC monitoring system.

[y] STEMP, pH, and EC readings from daily averages of 5-minute sampling from PLC control system.

[x] Top level = Growing levels 1 and 3; Bottom levels = Growing levels 2 and 4.

[w] Duncan mean separation between columns at P >0.05.

Table 6

Characterization of environmental conditions affecting plant growth within the CELSS Breadboard Project Biomass Production Chamber prior to sealing: Growing position characteristics during BWP912.

SHOOT ENVIRONMENT[z]

POSITION	PFF ($\mu mol\ m^{-2}\ s^{-1}$)	CTEMP (°C)	AVEL ($m\ s^{-1}$)
1	848 b	20.0 e	0.67 efg
2	933 a	20.9 a	0.58 fg
3	863 b	20.8 a	0.55 g
4	902 ab	20.8 a	0.59 efg
5	857 b	20.5 b	0.66 efg
6	839 b	20.3 bcde	0.66 efg
7	856 b	20.4 bc	0.70 e
8	865 b	20.1 bcde	0.90 cd
9	931 a	20.1 cde	1.03 ab
10	890 ab	20.1 cde	1.09 a
11	879 ab	20.3 bcde	0.96 bc
12	859 b	20.2 bcde	0.90 cd
13	889 ab	20.3 bcd	0.82 d
14	875 ab	20.4 bc	0.67 ef
15	839 b	20.5 b	0.62 efg
16	731 c	20.0 de	0.70 e
df	391	391	391

[z]PPF, CTEMP and AVEL measurements determined at plant canopy of each tray at weekly intervals.

[y]Duncan mean separation between columns at $P > 0.05$.

Table 7: Characterization of environmental conditions affecting plant growth within the CELSS Breadboard Project Biomass Production Chamber prior to sealing: Chamber characteristics during BLT921.

	SHOOT ENVIRONMENT[z]				ROOT ENVIRONMENT[y]		
CHAMBER[x]	PFF (umol m^{-2} s^{-1})	ATEMP (°C)	RH (%)	AVEL (m s^{-1})	STEMP (°C)	pH	EC (uS cm^{-1})
Upper	319 a[w]	22.3 a	75 b	0.60 a	25.9 a	5.8 a	1213 b
Lower	309 b	22.2 a	85 a	0.61 a	25.7 a	5.8 a	1262 a
df	128	216	216	32	112	208	204

[z] PPF and AVEL measurements determined at plant canopy of each tray at weekly intervals. ATEMP and RH taken from daily 5-minute averages from BPC monitoring system.

[y] STEMP, pH, and EC readings from daily averages of 5-minute sampling from PLC control system.

[x] Upper chamber = Growing levels 1 and 2; Lower chamber = Growing levels 3 and 4.

[w] Duncan mean separation between columns at P >0.05.

Table 8: Characterization of environmental conditions affecting plant growth within the CELSS Breadboard Project Biomass Production Chamber prior to sealing: Growing Level characteristics during BLT921.

	SHOOT ENVIRONMENT[z]				ROOT ENVIRONMENT[y]		
LEVEL[x]	PFF (umol m^{-2} s^{-1})	ATEMP (°C)	RH (%)	AVEL (m s^{-1})	STEMP (°C)	pH	EC (uS cm^{-1})
Top	308 a[w]	22.6 a	76 b	0.60 a	25.9 a	5.8 a	1232 b
Bottom	320 a	21.8 b	83 a	0.61 a	25.8 a	5.9 a	1244 a
df	128	216	216	32	112	208	208

[z] PPF and AVEL measurements determined at plant canopy of each tray at weekly intervals. ATEMP and RH taken from daily 5-minute averages from BPC monitoring system.

[y] STEMP, pH, and EC readings from daily averages of 5-minute sampling from PLC control system.

[x] Top level = Growing levels 1 and 3; Bottom level = Growing levels 2 and 4.

[w] Duncan mean separation between columns at P >0.05.

Table 9

Characterization of environmental conditions affecting plant growth within the CELSS Breadboard Project Biomass Production Chamber prior to sealing: Growing position characteristics during BLT921.

SHOOT ENVIRONMENT[z]

POSITION	PFF ($\mu mol\ m^{-2}\ s^{-1}$)	CTEMP (°C)	AVEL ($m\ s^{-1}$)
1	245 d	24.7 cde	0.68 bcd
2	312 abc	25.5 abc	0.50 cde
3	330 abc	25.3 abcd	0.35 e
4	341 ab	25.8 a	0.50 cde
5	332 abc	25.8 a	0.48 de
6	331 abc	24.9 bcde	0.45 de
7	355 a	24.9 bcde	0.65 bcd
8	341 ab	24.3 ef	0.93 ab
9	318 abc	23.9 f	1.00 a
10	323 abc	24.3 ef	0.93 ab
11	308 bc	24.5 def	0.78 abc
12	335 ab	24.8 bcde	0.60 cde
13	332 abc	25.5 abc	0.48 de
14	320 abc	25.6 ab	0.50 cde
15	291 c	25.3 abcd	0.43 de
16	219 d	25.1 abcde	0.45 de
df	128	32	32

[z]PPF, CTEMP and AVEL measurements determined at plant canopy of each tray at weekly intervals.

[y]Duncan mean separation between columns at $P > 0.05$.

Table 10: Characterization of environmental conditions affecting plant growth within the CELSS Breadboard Project Biomass Production Chamber prior to sealing: Chamber characteristics during BWP921.

	SHOOT ENVIRONMENT[z]				ROOT ENVIRONMENT[y]		
CHAMBER[x]	PFF (umol m^{-2} s^{-1})	ATEMP (°C)	RH (%)	AVEL (m s-1)	STEMP (°C)	pH	EC (uS cm^{-1})
Upper	868 a[w]	16.8 a	72 a	0.69 a	17.4 a	5.5 a	1205 a
Lower	852 a	17.2 b	60 b	0.36 b	17.5 a	5.4 a	1204 a
df	551	828	828	64	824	820	768

[z] PPF and AVEL measurements determined at plant canopy of each tray at weekly intervals. ATEMP and RH taken from daily 5-minute averages from BPC monitoring system.

[y] STEMP, pH, and EC readings from daily averages of 5-minute sampling from PLC control system.

[x] Upper chamber = Growing levels 1 and 2; Lower chamber = Growing levels 3 and 4.

[w] Duncan mean separation between columns at P >0.05.

Table 11: Characterization of environmental conditions affecting plant growth within the CELSS Breadboard Project Biomass Production Chamber prior to sealing: Growing Level characteristics during BWP921.

	SHOOT ENVIRONMENT[z]			ROOT ENVIRONMENT[y]		
LEVEL[x]	PFF (umol m^{-2} s^{-1})	ATEMP (°C)	RH (%)	AVEL (m s^{-1})	STEMP (°C)	pH	EC (uS cm^{-1})
Top	837 a[w]	17.8 a	59 b	0.54 a	17.4 a	5.5 a	1208 a
Bottom	877 a	16.1 b	73 a	0.51 b	17.5 a	5.5 a	1200 a
df	551	826	828	120	824	824	807

[z] PPF and AVEL measurements determined at plant canopy of each tray at weekly intervals. ATEMP and RH taken from daily 5-minute averages from BPC monitoring system.

[y] STEMP, pH, and EC readings from daily averages of 5-minute sampling from PLC control system.

[x] Top level = Growing levels 1 and 3; Bottom level = Growing levels 2 and 4.

[w] Duncan mean separation between columns at P >0.05.

Table 12

Characterization of environmental conditions affecting plant growth within the CELSS Breadboard Project Biomass Production Chamber prior to sealing: Growing position characteristics during BWP921.

SHOOT ENVIRONMENT[z]

POSITION	PFF ($\mu mol\ m^{-2}\ s^{-1}$)	CTEMP (°C)	AVEL ($m\ s^{-1}$)
1	821 b	18.1 a	0.350 k
2	925 a	18.6 a	0.375 i
3	846 ab	18.5 a	0.400 h
4	919 a	18.5 a	0.300 l
5	840 ab	18.2 a	0.275 n
6	851 ab	18.1 a	0.550 f
7	880 ab	18.3 a	0.650 e
8	898 ab	18.3 a	0.900 c
9	851 ab	18.0 a	0.925 b
10	862 ab	18.1 a	0.925 a
11	839 ab	18.0 a	0.675 d
12	866 ab	18.1 a	0.650 e
13	858 ab	18.2 a	0.400 h
14	901 ab	18.2 a	0.350 j
15	850 ab	18.1 a	0.300 m
16	717 c	18.0 a	0.450 g
df	551	635	64

[z]PPF, CTEMP and AVEL measurements determined at plant canopy of each tray at weekly intervals.

[y]Duncan mean separation between columns at $P > 0.05$.

[w]One date only.

Table 13: Inter-chamber and intra-chamber differences in shoot growing environment: PPF (umol m^{-2} s^{-1})[z].

	Lettuce		White Potato	
	BLT911 (unsealed)	BLT921 (sealed)	BWP912 (unsealed)	BWP921 (sealed)
		Chamber[y]		
Upper	282 a[x]	319 a	915 a	868 a
Lower	294 b	309 a	817 b	852 a
df	109	128	512	551
		Growing Level		
Top	285 a	308 a	846 a	837 a
Bottom	291 a	320 a	886 b	877 a
df	109	128	512	551

[z] Weekly measures at canopy level with a Licor Quantum Sensor were used for the analysis.

[y] Upper chamber = Growing levels 1 and 2; Lower chamber = Growing levels 3 and 4; Top levels = Growing levels 1 and 3; Bottom levels = Growing levels 2 and 4.

[x] Duncan mean separation between columns at P>0.05.

Table 14: Inter-chamber and intra-chamber differences in shoot growing environment: Air Temperature[z].

	Lettuce		White Potato	
	BLT911 (unsealed)	BLT921 (sealed)	BWP912 (unsealed)	BWP921 (sealed)
		Chamber[y]		
Upper	22.6 a[x]	22.3 a	17.3 a	16.8 a
Lower	22.2 b	22.2 a	16.9 b	17.2 b
df	224	216	704	828
		Growing Level		
Top	22.7 a	22.6 a	17.8 a	17.8 a
Bottom	22.1 b	21.8 b	16.5 b	16.1 b
df	224	216	704	826

[z] Daily averages of 5-minute PLC control system data were used for the analysis.

[y] Upper chamber = Growing levels 1 and 2; Lower chamber = Growing levels 3 and 4; Top levels = Growing levels 1 and 3; Bottom levels = Growing levels 2 and 4.

[x] Duncan mean separation between columns at $P > 0.05$.

Table 15: Inter-chamber and intra-chamber differences in shoot growing environment: Relative Humidity (%)[z].

	Lettuce		White Potato	
	BLT911 (unsealed)	BLT921 (sealed)	BWP912 (unsealed)	BWP921 (sealed)
		Chamber[y]		
Upper	71.0 b[x]	75.3 b	81.8 b	72.0 a
Lower	73.9 a	84.5 a	74.7 a	60.5 b
df	224	216	702	828
		Growing Level		
Top	70.0 b	76.4 b	78.1 a	59.9 b
Bottom	74.0 a	83.4 a	78.5 a	73.1 a
df	224	216	702	828

[z] Daily averages of 5-minute PLC control system data was used for the analysis.

[y] Upper chamber = Growing levels 1 and 2; Lower chamber = Growing levels 3 and 4; Top levels = Growing levels 1 and 3; Bottom levels = Growing levels 2 and 4.

[x] Duncan mean separation between columns at $P > 0.05$.

Table 16: Inter-chamber and intra-chamber differences in shoot growing environment: Air Velocity (m s^{-1})[z].

	Lettuce		White Potato	
	BLT911 (unsealed)	BLT921 (sealed)	BWP912 (unsealed)	BWP921 (sealed)
		Chamber[y]		
Upper	0.74 a[x]	0.60 a	0.76 a	0.69 a
Lower	0.78 a	0.61 a	0.74 a	0.36 b
df	109	109	391	64
		Growing Level		
Top	0.72 a	0.60 a	0.74 a	0.54 a
Bottom	0.80 a	0.61 a	0.77 a	0.51 b
df	109	109	391	120

[z] Weekly determinations made at canopy level with a KURZ Model 4140 anonometer were used for the analysis.

[y] Upper chamber = Growing levels 1 and 2; Lower chamber = Growing levels 3 and 4; Top levels = Growing levels 1 and 3; Bottom levels = Growing levels 2 and 4.

[x] Duncan mean separation between columns at $P > 0.05$.

Table 17: Inter-chamber and intra-chamber differences in root growing environment: Solution Temperature (C)[z].

	Lettuce		White Potato	
	BLT911 (unsealed)	BLT921 (sealed)	BWP912 (unsealed)	BWP921 (sealed)
		Chamber[y]		
Upper	25.8 a[x]	25.9 a	17.9 a	17.4 a
Lower	25.6 a	25.7 a	17.9 a	17.5 a
df	216	112	704	824
		Growing Level		
Top	25.9 a	25.9 a	17.9 a	17.4 a
Bottom	25.8 a	25.8 a	17.9 a	17.5 a
df	212	112	704	824

[z] Daily averages of 5-minute PLC control system data were used for the analysis.

[y] Upper chamber = Growing levels 1 and 2; Lower chamber = Growing levels 3 and 4; Top levels = Growing levels 1 and 3; Bottom levels = Growing levels 2 and 4.

[x] Duncan mean separation between columns at $P > 0.05$.

Table 18: Inter-chamber and intra-chamber differences in root growing environment: pH[z].

	Lettuce		White Potato	
	BLT911 (unsealed)	BLT921 (sealed)	BWP912 (unsealed)	BWP921 (sealed)
		Chamber[y]		
Upper	5.7 a[x]	5.8 a	5.6 a	5.5 a
Lower	5.6 a	5.7 a	5.5 a	5.4 a
df	212	160	644	820
		Growing Level		
Top	5.7 a	5.7 a	5.5 a	5.4 a
Bottom	5.7 a	5.8 a	5.6 a	5.5 a
df	212	160	644	820

[z] Daily averages of 5-minute PLC control system data were used for the analysis.

[y] Upper chamber = Growing levels 1 and 2; Lower chamber = Growing levels 3 and 4; Top levels = Growing levels 1 and 3; Bottom levels = Growing levels 2 and 4.

[x] Duncan mean separation between columns at $P > 0.05$.

Table 19: Inter-chamber and intra-chamber differences in root growing environment: Electrical Conductivity (uS cm^{-1})[z].

	Lettuce		White Potato	
	BLT911 (unsealed)	BLT921 (sealed)	BWP912 (unsealed)	BWP921 (sealed)
		Chamber[y]		
Upper	1209 b[x]	1213 b	1194 a	1208 a
Lower	1222 a	1262 a	1205 a	1206 a
df	216	204	704	768
		Growing Level		
Top	1225 a	1232 b	1195 a	1208 a
Bottom	1207 b	1244 a	1204 a	1206 a
df	216	208	704	768

[z] Daily averages of 5-minute PLC control system data were used for the analysis.

[y] Upper chamber = Growing levels 1 and 2; Lower chamber = Growing levels 3 and 4; Top levels = Growing levels 1 and 3; Bottom levels = Growing levels 2 and 4.

[x] Duncan mean separation between columns at $P > 0.05$.

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13. ABSTRACT *(Maximum 200 words)*
Variability in the aerial and root environments of NASA's Breadboard Project's Biomass Production Chamber (BPC) was determined. Data from two lettuce and two potato growouts were utilized. One growout of each crop was conducted prior to separating the upper and lower chambers; the other was subsequent to separation. There were little or no differences in pH, EC, or solution temperature between the upper and lower chamber or within a chamber. Variation in the aerial environment within a chamber was two to three times greater than variation between chambers for air temperature, relative humidity and PPF. High variability in air velocity, relative to tray position, was observed. Separating the BPC had no effect on PPF, air velocity, solution temperature, pH or EC. Separation reduced the gradient in air temperature and relative humidity between the upper and lower chambers, but increased the variability within a chamber. Variation between upper and lower chambers was within 5% of environmental set-points and of little or no physiological significance. In contrast, the variability within a chamber limits the capability of the BPC to generate statistically reliable data from individual tray treatments at this time.

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