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MELiSSA

Memorandum of Understanding

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Results of Production Trials with Beet and Lettuce in a Higher Plant Chamber

Report on Work Completed Under Canadian Space Agency Contract 9F007-010139/00/ST and European Space Agency MELiSSA Memorandum of Understanding TOS-MCT/2002/3161/In/CL (2002).

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Section 1.0: Report Summary

In the past year, the Controlled Environment Systems Research Facility (CESRF), University of Guelph, has been active in evaluating the performance of beet (*Beta vulgaris*) and lettuce (*Lactuca sativa*) in controlled environments. Beet and lettuce have been identified as candidate crops for inclusion in the MELiSSA pilot plant (MELiSSA General Working Meeting, November 29/30, 2001). While productivity data are available for these crops grown with basic cultural management, more information is still required relating to the performance of these crops under more advanced management strategies. More advanced strategies include integrated (multiple crops in a single chamber) and staged (multiple physiological stages) management.

The CESRF has focused research activity on beet (*Beta vulgairs* cv. Detroit Medium Red) and lettuce (*Lactuca sativa* cv. Grand Rapids) performance under staged and integrated production. It is the understanding of the CESRF team that work remains to be completed with wheat (*Triticum aestivum*) and that continued investigation with beet and lettuce is desirable.

The purpose of this annual report is to summarize information obtained in the production trials with beet and lettuce. While it is true that much of this information has already been presented in varying forms under the auspices of ESA-MELiSSA Technical Notes (TNs) and joint reports to ESA-MELiSSA and the Canadian Space Agency (CSA), the CESRF team believes that it would be useful to provide basic performance results in this annual report.

Results presented in this annual report are derived from a number of experiments performed in large full canopy sealed chambers. The studies are as follows:

a) Full canopy trials with batch planting of lettuce
b) Full canopy trials with batch planting of beet
c) Full canopy trials with staged planting of beet
d) Full canopy trials with integrated and staged planting of beet and lettuce

A summary of cultural conditions used in each of the studies is provided in Tables 1.1 – 1.3.

Table 1.1. Summary of experimental design and conditions for full canopy beet and lettuce batch experiments. Rep. refers to the replication number. The period of study in the chamber was proceeded by a common 21 day germination period in the greenhouse environment. Chamber leakage was estimated from compensation profiles for carbon dioxide in an empty chamber over a 24 hour period.

Parameter	Beet			Lettuce	
	Rep.1	Rep. 2	Rep. 3	Rep. 1	Rep. 2
Period of Study in Chamber (dd/mm/yr)	16/02/02 to 26/03/02	02/04/02 to 06/05/02	02/04/02 to 06/05/02	21/05/02to 14/06/02	21/05/02to 14/06/02
Length of Study (Days in Chamber)	38	33	33	24	24
Whole Chamber Harvest Data Collected	No	Yes	Yes	Yes	Yes
Light Intensity (PPF) $\mu molm^{-2}s^{-1}$	300-600	300-600	300-600	300-600	300-600
Relative Humidity (%)	75 ± 5	75 ± 5	75 ± 5	75 ± 5	75 ± 5
CO_2 Concentration $\mu L\ L^{-1}$	1000	1000	1000	1000	1000
Day/Night Temperature ^oC	26/20	26/20	26/20	26/20	26/20
Photoperiod hrs light day^{-1}	14	14	14	14	14
Chamber Leakage Rate (% volume day^{-1})	12	15	15	13	13

Table 1.2. Summary of experimental design and conditions for full canopy beet staged experiments. Rep. refers to the replication number. The period of study in the chamber was proceeded by a common 21 day germination period in the greenhouse environment. Chamber leakage was estimated from compensation profiles for carbon dioxide in an empty chamber over a 24 hour period.

Parameter	Rep.1	Rep. 2
Period of Study in Chamber (dd/mm/yr)	24/06/02 to 21/08/02	24/06/02 to 21/08/02
Length of Study (Days in Chamber)	58	58
Whole Chamber Harvest Data Collected	Yes by age class	Yes by age class
Light Intensity (PPF) $\mu molm^{-2}s^{-1}$	300-600	300-600
Relative Humidity (%)	75 ± 5	75 ± 5
CO_2 Concentration $\mu L\ L^{-1}$	1000	1000
Day/Night Temperature ^oC	26/20	26/20
Photoperiod hrs light day^{-1}	14	14
Chamber Leakage Rate (% volume day^{-1})	15	15

Table 1.3. Summary of experimental design and conditions for full canopy, integrated and staged beet and lettuce experiments. Rep. refers to the replication number. The period of study in the chamber was proceeded by a common 21 day germination period in the greenhouse environment. Chamber leakage was estimated from compensation profiles for carbon dioxide in an empty chamber over a 24 hour period.

Parameter	Rep.1	Rep. 2
Period of Study in Chamber (dd/mm/yr)	30/09/02 to 10/01/03	30/09/02 to 10/01/03
Length of Study (Days in Chamber)	102	102
Whole Chamber Harvest Data Collected	Yes by age class	Yes by age class
Light Intensity (PPF) $\mu molm^{-2}s^{-1}$	300-600	300-600
Relative Humidity (%)	75 ± 5	75 ± 5
CO_2 Concentration $\mu L\ L^{-1}$	1000	1000
Day/Night Temperature ^oC	26/20	26/20
Photoperiod hrs light day^{-1}	14	14
Chamber Leakage Rate (% volume day^{-1})	15	15

Section 2.0: General Materials and Methods

The following section summarizes the methods common to all investigations with beet and lettuce in the large full canopy chambers. Where appropriate, presentation of methods specific to a given experiment, particularly in the area of data analysis, is reserved for the section describing the results of that study. Below are the materials and methods used, which are common to all experiments.

Growth Chamber Facilities – Two large sealed environment chambers capable of determining the Net Carbon Exchange Rate (NCER) of full plant stands were used in all studies (Section 1.0, a-d). The chambers measure 4.5m x 3m and 2.5 m high. Heat exchangers and air handling equipment were integrated within the sealed environment. The glass topped chambers had externally mounted lighting with 9 x 600 W High Pressure Sodium (HPS) and 6 x 400 W Metal Halide (MH) lamps to provide a light level of, on average, 350 ± 16 µmoles m^{-2} s^{-1} PAR at stand height. For the purposes of this study, the hydroponics system described in the original paper was not used nor was the inner canopy lighting system. Additionally, the original LiCor model LI6262 Gas Analyser for CO_2/H_2O vapour was replaced by a California Analytical Instruments O_2 and CO_2 Analyser (Model 100P, Orange CA., USA). Thermal control was handled with externally supplied chilled water and steam routed through exchange coils mounted in an internal plenum at the rear of the chamber. Environment control was maintained by a computer control system (L.W. Anderson Software Consulting Ltd., Leamington, ON).

Experimental Design – The following is a summary of the experimental activity for batch, staged and integrated planted trials conducted in the large sealed chambers:

i. 2 replicate studies of batch planted lettuce

ii. 3 replicate studies of batch planted beet

iii. 2 replicate studies of staged planted beet

iv. 2 replicate studies of integrated and staged planting of beet and lettuce

Therefore a total of 9 independent replications using beet and lettuce were performed at the full stand level as summarized above. Each replicate was completed in one of the two sealed environment chambers. The studies described in this paper makes use of these replications with samples of NCER taken at 3 minute intervals throughout the study period. These studies are therefore treated as an analogue of a Split-Plot Design with chamber/replication as a main factor and time as a sub-factor.

Cultural Management - In all of the studies, beet and lettuce were germinated in a research greenhouse at the University of Guelph, using Rockwool© cubes. The plants remained in the cubes for a period of 21 days or until there was sufficient root exposure to facilitate transplanting into a deep water hydroponics system. During the germination period, seedlings were watered regularly with distilled water and once weekly with a dilute fertilizer solution (20-8-20 ppm N-P-K commercial mix having an Electrical Conductivity (EC) = 2.5 mS).

In the case of batch planted stands, following root exposure and true leaf emergence (21 days after seeding on average), 44 seedlings (of either lettuce or beet) were floated a circular plastic pool with a surface area of 2.5 m^2 and a volume of 220L of hydroponics solution. Seedlings, in their Rockwool© cubes, were placed in small holes cut from Styrofoam trays which were designed to float freely within the pools. Planting density was fixed at 17.6 plants m^{-2}. Any solution exposed

to light was shielded with black plastic film to minimize the growth of algae. The pool was positioned in the center of the chamber growing area at a distance of 1.5 m from the overhead lights. The nutrient solution was continuously aerated using internal chamber air and pump with a manifold of air lines and diffusers.

In the case of staged planted studies, seeds were sown at ten day intervals as described above. Following the 21 day emergence and early growth period, 11 seedlings were moved into each of the two sealed chambers. This procedure was repeated for the duration of the study period (e.g. 39 days after initial chamber closure in the case of the beet staged stand) which eventually resulted in 4 age classes being represented in a single chamber (full stocking). Once full stocking was attained in the chambers each subsequent planting of 11 new seedlings into the chambers (at each 10 day interval) was accompanied by the harvest of the 11 plants belonging to the most mature age class in the stand. This procedure maintained a uniform distribution for the 4 age classes. The same procedure was used for the integrated/batch production of beet and lettuce.

In both the batch and staged studies, plants were grown under a 14/10 hr light/dark (06:00 - 20:00) photoperiod coupled to a 26/20 ^{o}C day/night temperature. Atmospheric CO_2 concentrations were fixed at 1000 µL L^{-1} CO_2 as supplied through an external tank and mass flow controller. Average relative humidity in the chambers over all replications was 73% ± 5% with only dehumidification control using condensation coils. No significant accumulation of oxygen was noted because the chamber doors were opened for solution changeover.

The common nutrient solution used in this study had the following composition: 1.5 mM PO_4^{3-}, 3.62 mM Ca^{2+}, 4 mM NH_4^{+}-N, 11.75 mM NO_3^{-}N, 5 mM K^{+}, 2 mM SO_4^{2-}, 1 mM Mg^{2+}, 0.005 mM Mn^{2+}, 0.025 mM Fe^{3+} as Fe-DTPA, 0.0035 mM Zn^{2+}, 0.02 mM B^{3+}, 0.008 mM Na^{+},0.0008 mM Cu^{2+}, 0.0005 mM Mo^{6+}. This solution had an average EC of 1.9 mS. The pH of the solution was adjusted to approximately 5.5 with the addition of approximately 40 mL of a 1 M $NaHCO_3$ solution per pool. At the initial transplant of the seedlings, 220 L of nutrient solution was added to the pools prior to the chamber doors being sealed. Every five days after, the chamber doors were opened to replace the older solution with a fresh 220 L volume having the same composition as noted above. The solution change over procedure was common for both the staged and batch trials.

Net Carbon Exchange Data Collection - The net carbon gain of the developing stands was determined using a compensation technique. The computer controller maintained internal chamber CO_2 concentrations during the day-light hours so that any net carbon gain by the stand through photosynthetic activity was compensated by injections from an external tank. The volume and duration of CO_2 injections were used to estimate day time NCER. During the dark period it was not possible to remove CO_2 from the chamber to achieve static conditions, and as such, the difference in observed CO_2 and demand concentrations compensated for dark period respiration in the calculation of NCER. The sum of these NCER estimates over a 24 hour period (in moles C), yielded daily carbon gain (DCG). The estimates of DCG obtained on both the staged and batch stands were expressed on a per m^2 basis and divided by the daily PPF integral (17.5 mol PPF m^{-2} day^{-1}) to obtain the apparent stand quantum yield (AQY). The values of AQY were expressed in mol C m^{-2} day^{-1} mol^{-1} PPF m^{-2} day^{-1}, which reduced to mol C mol^{-1} PPF. The presentation of results relating to AQY for the beet canopy is reserved for Section 4.0.

Harvest Data – All plant material was harvested at the end of the study. Harvested material was pooled by chamber and partitioned into edible and non-edible biomass fractions. Leaf area was measured on 10 of the plants harvested using a Li-Cor 3100 Leaf Area Meter (Lincoln, NE, USA). Fresh weights were determined immediately on all plant material and dry weights were determined following 7 days in a drying oven at 65 ^{o}C. Chamber water balance was also

determined from evapotranspiration estimates and plant water content estimates derived from dry and fresh plant weights. At the time of writing not all harvest data were avilable.

Section 3.0: Results of Batch Planted Trials

Productivity and Yield - Beet

A summary of basic harvest data, including mean total fresh and dry weights of beet plants taken from three replicates is provided in Table 3.1. Water content of tissue and leaf area is also presented. There is a strong agreement (within 10%) of integrated carbon uptake estimates of biomass gain and those observed at harvest (Table 3.1).

Table 3.1. Harvest data for full stand beet experiments. Data presented are means for 20 plants collected over two chambers following harvest at 33 Days In Chamber (DIC) or 54 Days After Planting (DAP) (n=20 plants). Square brackets refer to the 95% upper (UCL) and lower (LCL) 95% confidence limits of the mean respectively. Harvest data for the first replication (at 38 days DIC) are not presented. The mean leaf area per plant from harvested material collected in both chambers is presented as a bracketed value. The mean total carbon gain as calculated from integrated carbon gain is also presented along with the observed error relative to harvest estimates.

Parameter	Fresh Weight at Harvest (g plant^{-1})	Dry Weight at Harvest (g plant^{-1})	Water Content (g plant^{-1})
Leaves (Area, cm^2 plant^{-1})	239.6 [214.9, 264.3] (1760.4)	14.7 [13.3,16.1]	224.9 [201.4, 248.3]
Beet Root	150.7 [123.7, 177.6]	13.6 [11.4, 15.7]	137.1 [112.2, 162.0]
Total Edible	390.3 [338.6, 441.9]	28.3 [24.7, 31.8]	362.0 [313.6, 410.3]
Total Inedible (Roots)	26.4 [22.1, 30.6]	1.7 [1.5, 1.9]	24.7 [20.6, 28.8]
Total	416.7 [360.7, 472.5]	30.0 [26.2, 33.7]	386.7 [334.2, 439.1]
Total (mol stand^{-1})	–	36.0 (Carbon)	Observed 34.6 (Error = -4.9%)

Dynamics in Daily Carbon Gain and Nutrient Uptake - Beet

The profile of the ln transformed accumulated carbon for the full beet stand of 44 plants is presented in Figure 3.1. The profiles of nutrient accumulation in the full beet stand of 44 plants is presented in Figures 3.1 – 3.4. These figures correspond to the accumulation profile of NO_3^- and PO_4^{3-} (Figure 31), Mg^{2+} and K^+ (Figure 32), Ca^{2+} and SO_4^{2-}, (Figure 33) and NH_4^+ and Na^+ (Figure 34). The ln transform data for C^{4+} is reproduced on each of these plots to facilitate visual comparison of slopes (relative uptake or relative growth). Modeled values refer to the simple linear regression of the ln transformed data on DIC.

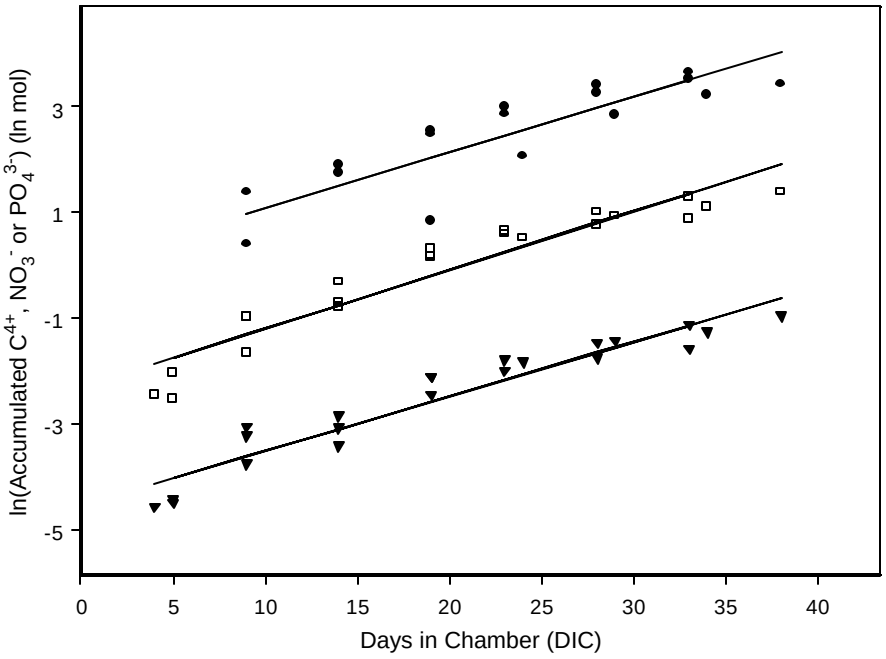

Figure 3.1. Plot of observed and model fitted ln transform of accumulated carbon (solid circle), nitrate (open square) and phosphate (solid triangle) for all replications of the beet study. Solid lines indicate the fitted model values.

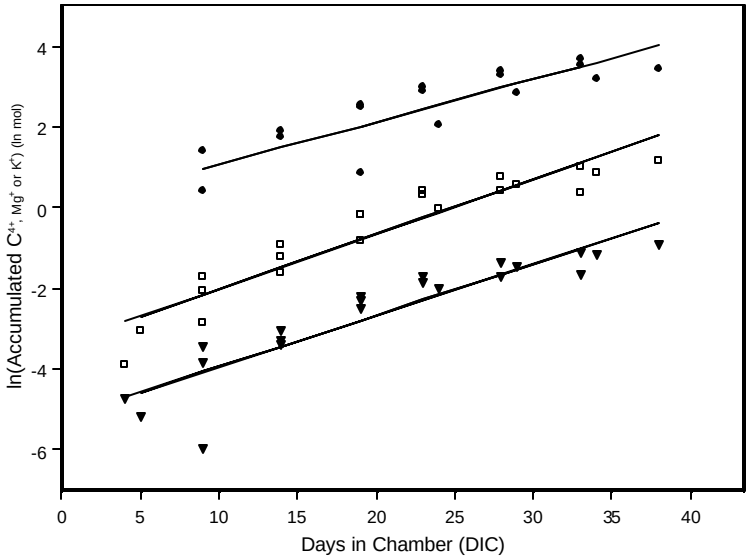

Figure 3.2. Plot of observed and model fitted ln transform of accumulated carbon (solid circle), potassium (open square) and magnesium (solid triangle) for all replications of the beet study. Solid lines indicate the fitted model values.

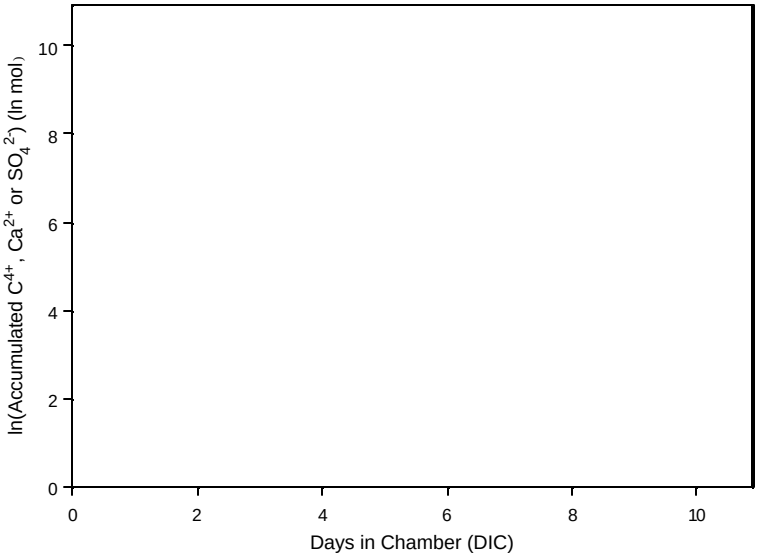

Figure 3.3. Plot of observed and model fitted ln transform of accumulated carbon (solid circle), calcium (open square) and sulphate (solid triangle) for all replications of the beet study. Solid lines indicate the fitted model values.

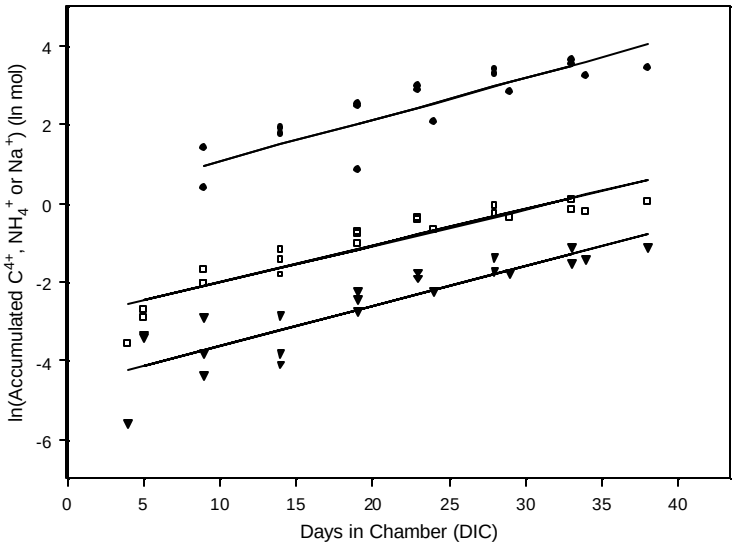

Figure 3.4. Plot of observed and model fitted ln transform of accumulated carbon (solid circle), ammonium (open square) and sodium (solid triangle) for all replications of the beet study. Solid lines indicate the fitted model values.

Table 3.2 summarizes the model (simple linear regression on ln-transform plots presented in Figure 3.1 – 3.4) predicted and mean observed accumulations in nutrients and carbon as well as the accumulation expressed as a percentage of total supply over the study period. In all cases less than 20% of the supplied nutrient was consumed by the beet crop. Given the low rates of consumption percentage, it is likely that no element was deficient over the course of the study. In addition to the percent consumption values, the accumulation ratio of nutrient uptake, expressed as total moles uptake per mole of carbon accumulated is presented for each ion. For nitrate, ammonium and potassium, this ratio was near 0.10. The ratio was considerably lower for phosphate and the micro-nutrients.

Table 3.2. Modeled nutrient and water accumulation data for full stand beet experiments. Bracketed values refer to the lower and upper 95% confidence intervals. Accumulation ratio refers to the moles of nutrient accumulated per mole of carbon sequestered, as calculated from model results. Water data presented is for total accumulation from pools (Total), water content in tissue as determined from harvest data (Tissue) and water lost from pools due to evapo-transpiration (ET). Total supply is calculated over the duration of the experiment. DIC refers to the number of Days in the Chamber. The observed total C^{4+} accumulation is from integrated carbon gain estimates as presented in Table 3.1.

Ion	Model Predicted Accumulation after 34 DIC (mol)	95% CI (mol)	% of Total Supply	Accumulation Ratio after 34 DIC
NO_3^-	4.4	(3.4,5.6)	20	0.12
NH_4^+	3.5	(1.0,1.6)	79	0.10
PO_4^{3-}	0.4	(0.3,0.4)	17	0.01
K^+	3.4	(2.5,4.8)	42	0.10
Mg^{2+}	0.4	(0.3,0.6)	26	0.01
Ca^{2+}	0.4	(0.2,0.7)	7	0.01
Na^+	0.3	(0.2,0.4)	38	0.01
SO_4^{2-}	0.2	(0.2,0.3)	8	0.01
H_2O (Total)	12863	(11048,14913)	15.0	–
H_2O (Tissue)	687	–	0.8	–
H_2O (ET)	12176	–	14.2	–
C^{4+}	**36.8**	**(27.4,49.4)**	–	**1**
C^{4+} (observed)	**34.8**	-	-	-

Dynamics in Water Uptake and Evapo-Transpiration - Beet

Over the course of crop development, it was estimated that nearly 12863 moles of water were utilized as a result of evapo-transpiration and plant accumulation (Table 3.3). It was determined that the crop held 687 moles of water at harvest (from dry and fresh weight measurements).

Therefore a total of 12176 moles of water loss from the reservoir is due to evapo-transpiration in the beet stand directly.

Results of a simple linear regression of water use on DCG are presented in Table 3.4. Significant models were obtained for total water use and transpiration and water accumulation in tissue as a function of accumulated carbon. Significant relationships between total water usage and Days in Chamber were also observed for the beet stand. Estimates of the slope derived from the regression of the ln transform of accumulated water use and carbon gain are presented in Table 3.5. This value is referred to as the Water Use Efficiency of productivity. Figure 3.5 presents the profile of ln transform of accumulated water use as a function of DIC for the beet stand. As is evidenced by the values in Table 3.5, this model is significant.

Table 3.3. Regression results for various models of water dynamic in full stand beet experiments. A_{water} refers to the accumulated total water lost from pools, $A_{trasnpiration+Tissue}$ refers to water accumulated by the canopy and lost due to transpiration. The parameters b_0 and b_1 refer to the model intercept and slope respectively. The r^2 value includes pure error. Indep. refers to the model independent variable.

Model Dependent Variable	Indep. Variable	b_0	b_1	p-value for b_1	t-value for b_1	r^2	Residual Standard Error
A_{water}	A_{carbon}	788.8	325.9	0.00	77.9	0.99	250
$A_{Transpiration+Tissue}$	A_{carbon}	0.0	325.9	0.00	77.9	0.99	250
$ln(A_{water})$	DIC	6.30	0.09	0.00	18.8	0.95	0.23

Table 3.4. Water use efficiency of productivity (WUE_{Pr}) for full stand beet experiments. Values of WUE_{Pr} were derived from the slope of regressions of A_{water} and A_{carbon}.

Variable	mol H_2O mol^{-1} C^{4+}	mol C^{4+} mol^{-1} H_2O	g C^{4+} Kg^{-1} H_2O
WUE_{Pr}	325.9	0.003	2.05

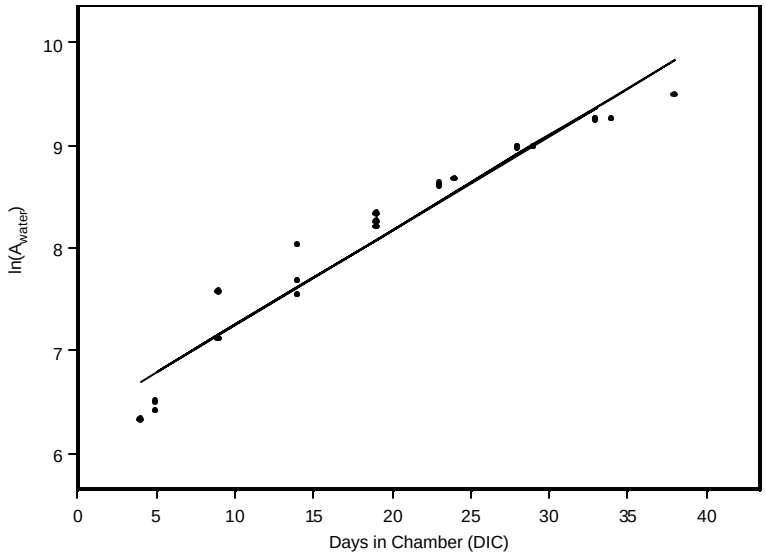

Figure 3.5. Plot of observed and model fitted ln transform of accumulated water use (A_{water}, solid circle) for all replications of the Beet study. Solid lines indicate the fitted model values.

Productivity and Yield - Lettuce

A summary of harvest data, including mean total fresh and dry weights of lettuce plants taken from two replicates is provided in Table 3.6. Water content of tissue and leaf area are also presented. There is a strong agreement (within 10%) of integrated carbon uptake estimates of biomass gain and those observed at harvest.

Table 3.5. Harvest data for full stand lettuce experiments. Data presented are means, 95% upper (UCL) and lower (LCL) confidence intervals (in square brackets) on 20 plants collected over two chambers following harvest at 24 Days In Chamber (DIC) or 45 Days After Planting (DAP). The mean total moles of carbon accumulated by the canopies is also presented. Mean leaf area of material harvested from both chambers is presented as a bracketed value. The mean total carbon gain as calculated from integrated carbon gain is also presented along with the observed error relative to harvest estimates.

Parameter	Fresh Weight at Harvest (g plant^{-1})	Dry Weight at Harvest (g plant^{-1})	Water Content (g plant^{-1})
Edible (Leaves) (Leaf Area cm^2 plant^{-1})	89.2 [77.1, 101.4] (1043.9)	4.3 [3.8, 4.8]	84.9 [73.2, 96.6]
Inedible (Roots)	17.4 [15.6, 19.1]	1.4 [1.2, 1.5]	16.0 [14.4, 17.6]
Total	106.6 [92.7, 120.5]	5.7 [5.0, 6.3]	100.9 [87.6, 114.2]
Total (mol stand^{-1})	–	7.7 (Carbon)	233.8
Total Observed Carbon Gain (mol)	–	8.0 (Carbon) (Error = +3.9 %)	–

Dynamics in Daily Carbon Gain and Nutrient Uptake - Lettuce

The profiles of ln transform of accumulated carbon and nutrient accumulation in the full lettuce stand of 44 plants is presented in Figures 3.6 – 3.9. These figures correspond to the accumulation profile of NO_3^- and PO_4^{3-} (Figure 3.6), Ca^{2+} and SO_4^{2-}, (Figure 3.7), Mg^{2+} and K^+ (Figure 3.8), and NH_4^+ (3.9). Plots for the ln transform of Na^+ accumulation are not presented, because poor uptake profiles were observed. The ln transform data for C^{4+} is reproduced on each of these plots to facilitate visual comparison of slopes (relative uptake or relative growth).

Table 3.7 summarizes the model predicted and mean observed accumulations in nutrients and carbon as well as the accumulation expressed as a percentage of total supply over the study period. In all cases less than 20% of the supplied nutrient was consumed by the lettuce crop. Given the low rates of consumption percentage, it is likely that no element was deficient over the course of the study but that such low uptake rates made model development, especially for the cases of ammonium and sodium, very difficult.

In addition to the percent consumption values, the accumulation ratio of nutrient uptake, expressed as total moles uptake per mole of carbon accumulated is presented for each ion. For nitrate and potassium, this ratio was near 0.10. The ratio was considerably lower for phosphate, ammonium and the micro-nutrients.

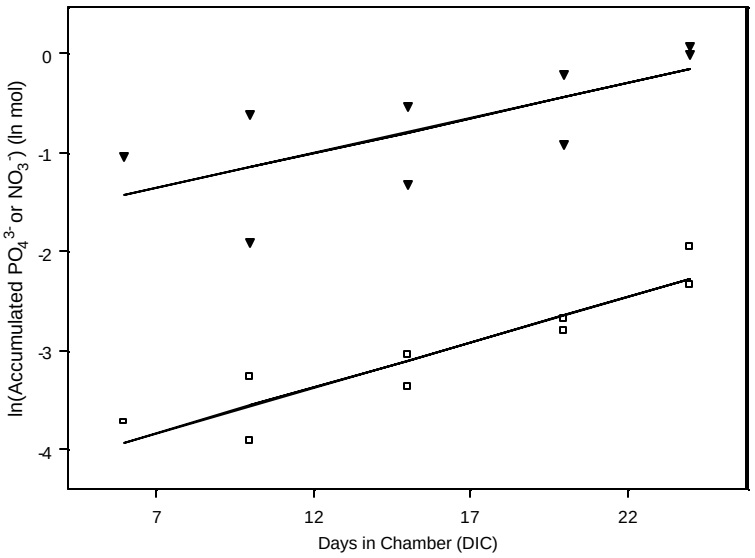

Figure 3.6. Plot of observed and model fitted ln transform of accumulated phosphate (open square) and nitrate (solid triangle) for all replications of the lettuce study. Solid lines indicate the fitted model values.

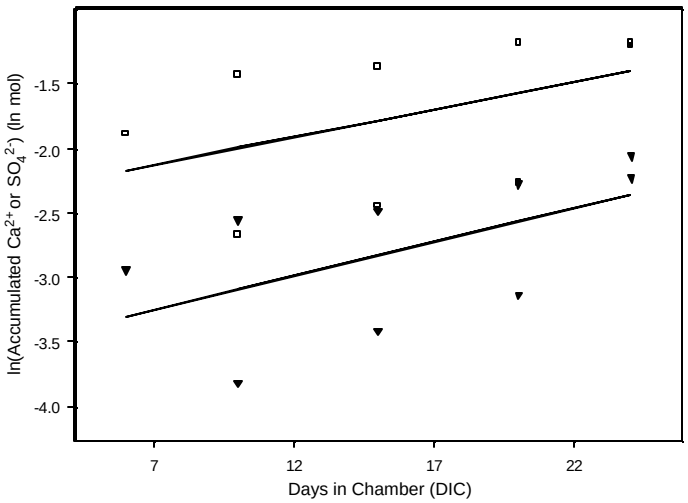

Figure 3.7. Plot of observed and model fitted ln transform of accumulated calcium (open square) and sulphate (solid triangle) for all replications of the Lettuce study. Solid lines indicate the fitted model values.

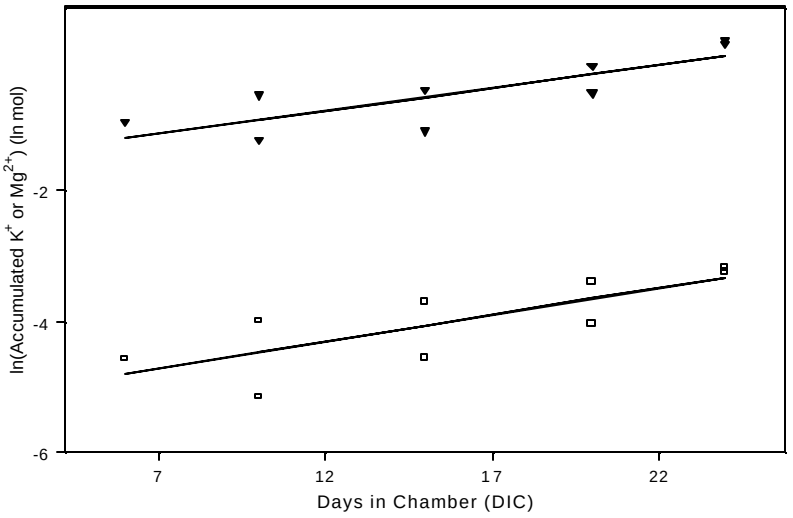

Figure 3.8. Plot of observed and model fitted ln transform of accumulated magnesium (open square) and potassium (solid triangle) for all replications of the Lettuce study. Solid lines indicate the fitted model values.

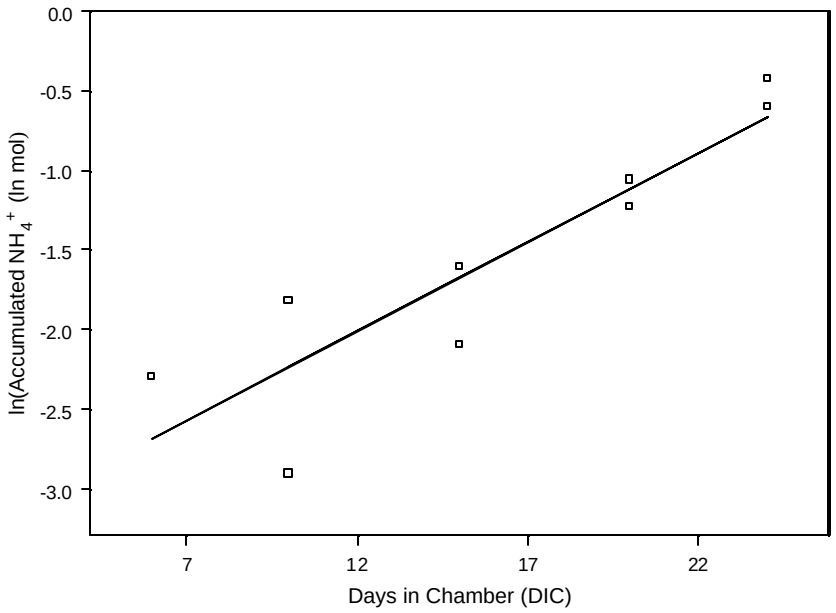

Figure 3.9. Plot of observed and model fitted ln transform of accumulated ammonium (open square) for all replications of the Lettuce study. Solid lines indicate the fitted model values.

Dynamics in Water Uptake and Evapo-Transpiration - Lettuce

Over the course of crop development, it was estimated that nearly 5526 moles of water were utilized by the lettuce stands, on average (Table 3.6). It was determined that the crop held 234 moles of water at harvest (from dry and fresh weight measurements). Therefore a total of 5292 moles of water loss from the reservoir is due to evapo-transpiration in the lettuce stand directly.

Results of the simple linear regression of water use on DCG are presented in Table 3.7 for the lettuce stand. Significant models were obtained for total water use and transpiration and water accumulation in tissue as a function of accumulated carbon. A significant relationship between total water usage and Days in Chamber (DIC) were also observed for the lettuce stand. Estimates of the slope derived from the regression of the ln transform of accumulated water use and carbon gain are presented in Table 3.8. This value is referred to as the Water Use Efficiency of productivity. Figure 3.10 presents the profile of ln transform of accumulated water use as a function of DIC for the lettuce stand. As is evidenced by the values in Table 3.10, this model is significant.

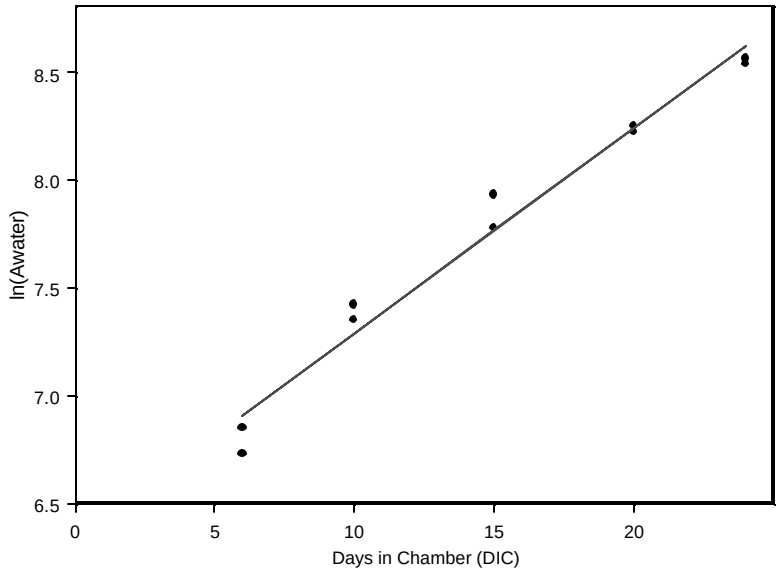

Figure 3.10. Plot of observed and model fitted ln transform of accumulated water use (A_{water}, solid circle) for all replications of the Lettuce study. Solid lines indicate the fitted model values.

Table 3.6. Modeled nutrient and water accumulation data for full stand lettuce experiments. Bracketed values refer to the lower and upper 95% confidence intervals. Accumulation ratio refers to the moles of nutrient accumulated per mole of carbon sequestered, as calculated from model results. Water data presented is for total accumulation from pools (Total), water content in tissue as determined from harvest data (Tissue) and water lost from pools due to evapo-transpiration (ET). Total supply is calculated over the duration of the experiment. DIC refers to the number of Days in the Chamber. The observed total C^{4+} accumulation is from integrated carbon gain estimates as presented in Table 4.7.

Ion	Model Predicted Accumulation after 24 DIC (mol)	95% CI (mol)	% of Total Supply	Accumulation Ratio after 24 DIC
NO_3^-	0.84	(0.50, 1.4)	0.05	0.10
NH_4^+	0.52	(0.35, 0.77)	0.17	0.06
PO_4^{3-}	0.10	(0.08, 0.13)	0.07	0.01
K^+	1.1	(0.76, 1.5)	0.19	0.13
Mg^{2+}	0.04	(0.02, 0.06)	0.04	0.004
Ca^{2+}	0.25	(0.14,0.44)	0.07	0.03
Na^+	0.01	(0.003, 0.02)	0.02	0.001
SO_4^{2-}	0.09	(0.05, 0.16)	0.04	0.01
H_2O (Total)	5526	(4964, 6186)	0.09	–
H_2O (Tissue)	234	–	0.004	–
H_2O (ET)	5292	–	0.09	–
C^{4+}	**8.4**	**(4.1,15.6)**	–	**1**
C^{4+} Observed	**8.0**	-	-	-

Table 3.7. Regression results for various models of water dynamic in full stand lettuce experiments. A_{water} refers to the accumulated total water lost from pools, $A_{Transpiration+Tissue}$ refers to water accumulated by the canopy and lost due to transpiration. The parameters b_0 and b_1 refer to the model intercept and slope respectively. The r^2 value includes pure error. Indep. refers to the model independent variable.

Model Dependent Variable	Indep. Variable	b_0	b_1	p-value for b_1	t-value for b_1	r^2	Residual Standard Error
A_{water}	A_{carbon}	2021.2	423.1	0.00	12.9	0.98	208
$A_{Transpiration+Tissue}$	A_{carbon}	0.0	423.1	0.00	12.9	0.98	208
$\ln(A_{water})$	DIC	6.3	0.1	0.00	17.9	0.98	0.11

Table 3.8. Water use efficiency of productivity (WUE_{Pr}) for full stand lettuce experiments. Values of WUE_{Pr} were derived from the slope of regressions of A_{water} and A_{carbon}.

Variable	mol H_2O mol^{-1} C^{4+}	mol C^{4+}mol^{-1} H_2O	g C^{4+}Kg^{-1} H_2O
WUE_{Pr}	423.1	0.002	1.3

Section 4.0: Results of Staged Planting Trials with Beet

RATIONALE

A significant cost (Equivalent System Mass, ESM) component of higher plant production is associated with the power consumption of lighting systems used to drive photosynthesis, as discussed, for example, by previous authors [1-2]. It is therefore imperative that crop production, for the purposes of providing life support commodities during an extended human presence in space (eg. air revitaliztion, potable water, food), makes efficient use of available power and artificial lighting systems. While some options exist for the reduction of crop production costs (ESM), including more efficient light delivery methods and technologies [3-5] there is also the possibility of improving crop lighting use efficiency through changes in cultural management at the stand level.

Previous studies [6-7] have examined the temporal dynamic in quantum yield (mol C fixed / mol absorbed photons, PAR) during the development of batch planted stands. Quantum yield was a factor in a higher level mechanistic model which was demonstrated to be useful in the prediction of stand carbon gain [7]. The implication of these authors' work is that the manipulation of stand quantum yield may provide the key to reducing the production costs of crop stands in controlled environments.

A large proportion of scientific investigation in controlled environment crop production for life support applications has been restricted to batch planted scenarios. A number of notable exceptions occur. Reportedly, the Russian Bios-3 trials used a conveyer type system which required the planting and harvest of crops at regular intervals [8]. This cultural strategy, hereafter referred to as staged planting, resulted in a uniform age distribution of the stand, with a range of age classes represented. Other authors have demonstrated that staged planting is a means to dampen long term dynamics in stand carbon gain relative to that of batch stands [9-11]. While these studies have identified the utility of the staged cultural management strategy for the stabilization of air revitalization capacity of stands, there remains the need to investigate the impacts of such a strategy on crop production costs and system trade.

This section develops an empirical model for the dynamic in apparent quantum yield of batch and staged planted beet stands. Since it is possible that increases in stand quantum efficiency may result under staged planting scenarios, the developed empirical models for beet are used to project the implications of staged planting on crop production cost. Cost changes are then examined within the context of trade studies with physico-chemical life support systems.
empirical model development

DATA ANALYSIS AND MODEL DEVELOPMENT – Data from both the staged and batch stands were used to develop an empirical model of the dynamic in AQY. In the case of the batch stand data, AQY values from the entire period of stand development were modeled using a non-linear Gompertz function having the form:

$$AQY(t) = S \cdot \exp(-e^{(B-K \cdot t)}) + e \qquad [4.1]$$

where t is the number of days since the initial chamber closure, and where S, B and K are parameters estimated by the non-linear regression algorithm and where e is a vector of model errors [13]. This model was used as it is a popular choice for modeling logistic growth in plant s.

The 95% confidence intervals for prediction were also determined using algorithms in the S-Plus Software [14].

A linear model was used in the case of the staged stand data. In this case, however, only data from the recovery period after full stocking were used. Because the a description of the methods used to fit the linear model makes use of results described in the next section, a summary of the methods used to analyze the staged stand data is reserved.

RESULTS

APPARENT STAND QUANTUM YIELD - Figures 4.1 and 4.2 depict the mean of Apparent Stand Quantum Yield (AQY) data for the mean of replicates from each of the batch and staged trials, respectively. These plots span the period of initial chamber closure (Day 0) to the period of harvest (Day 29 for the batch stand), and extends to the second harvest of the mature age classes for the staged stand (Day 39). It is important to note that AQY in this context is determined from NCER and DCG and therefore accounts for photorespiration and dark respiration of the stand. Table 4.1 summarizes the basic yield information collected for the staged beet stand.

An examination of Figure 4.1 illustrates the large range in AQY throughout the period of batch stand development. A maximum AQY (AQY_{max}) of 0.043 mol C mol^{-1} PPF is achieved at approximately 27 days after planting. In the growth period before AQY_{max} is achieved, there is a region of inefficiency. As discussed by previous authors this region is a result of incomplete absorption of incident light by the developing canopy which has a lower leaf area index than at canopy closure [6]. There is a subsequent stabilization in AQY_{max} following canopy closure at which time there is maximal absorption of incident light and no net increase in AQY with stand development. It is expected that if the stand was not harvested, the period of stability in AQYmax would be followed by a decrease in efficiency associated with stand senescence.

In contrast, an examination of Figure 4.2 indicates an increase in the staged stand's AQY, which parallels that of the batch stand, until the point of harvest of the first mature age class (Day 29). However, following the initial harvest of the most mature age class and the planting of new seedlings, there is a reversion of the stand's AQY to levels at or near those realized 10 days prior to the initial harvest. The stand then enters a 10 day period of 'recovery' at which time AQY_{max} is achieved a second time. This cycling in stand AQY, once full stocking of each age class is reached, is expected to continue in perpetuity if there are no major perturbations in environment conditions or crop health. Studies are continuing which will look at extended periods of full stand.

RATES OF STAND RECOVERY AND DETERMINATION OF AQY BOUNDS - It is apparent that the staged stand has higher AQY (during the period of full stocking) when compared to the early phases of the batch stand. To examine this idea further, data from the period of the staged stand recovery (from one harvest point to the next) were subjected to a simple linear regression having the form:

$$AQY = b_0 + b_1 \cdot (DICY) + e \qquad [4.2]$$

where DICY is the number of days into the recovery period (ranging from 0 at harvest/planting, 9 at next harvest/planting), where ßo and ß1 are the model intercept and slope respectively and where e is a vector of model errors. This procedure allowed for a determination of the mean of the minimum (AQYmin) and maximum (AQYmax) quantum yield for the cycling period and for the fully stocked staged stand and the slope or rate of recovery in AQY between harvest periods. The

results of this linear regression model were used to project the total quantity of carbon fixed for the same PPF integral but over repeated harvest and cycling periods.

Figure 4.3 presents a plot of the linear regression fit and the upper and lower 95% confidence intervals for the predicted AQY on any given day in the cycle period. Table 4.1 presents key findings of the regression model and those obtained from the non-linear regression on the batch stand data.

Statistic	Value
Staged Stand Data	
bo (p-value)	0.024 (0.00)
b1 (p-value)	0.002 (0.00)
df-error	14
r2	83 %
Batch Stand Data	
S (t-value)	0.049 (60.9)
B (t-value)	1.8 (38.7)
K (t-value)	0.14 (28.8
df-error	22

Table 4.1. Key findings of the regression of AQY on DICY (days into harvest/plant cycle) for the staged stand and for the non-linear regression performed on the batch stand data. Bracketed values indicate associated p-or t- values, df refers to the degrees of freedom of error. The values bo and b1 refer to the estimates for the intercept and slope respectively, while the values of S, B, K are those estimated by the non-linear regression on the Gompertz Model.

An examination of Table 4.1 indicates that the linear model slope was significant for the staged stand. This result indicates symmetry in the recovery rates in AQY between harvest periods in the staged stand. Further the slope estimate (bo) gives insight into the minimum (AQYmin) immediately following harvest and planting.

As mentioned above, the linear regression model was used to project the total quantity of carbon fixed for the same PPF integral but over repeated harvest and cycling periods. This allowed for the comparison of the staged planting regime to the batch planted regime. The details are as follows. First, the projection assumes that the staged stand is fully stocked and that there are no end effects. Secondly, for the purposes of comparison to batch stand data, it is assumed that a common initial starting point is shared by the batch and staged stands. This is to say that the day of the first harvest and planting in the staged stand following full stocking is the same as the starting date for development of a batch planted stand.

Data from the batch stand profile in AQY (Figure 4.1) were used to calculate the total amount of net carbon gained by the stand under a fixed daily PPF integral of 17.5 mol m^{-2} day^{-1} (the product of AQY and the daily PPF integral yields DCG) for a 30 day in-chamber growth period. Similarly, the linear regression results described above were used to calculate the total amount of net carbon gained by the staged stand while allowing the AQY to cycle, as predicted by the linear regression model. A total of three cycles were simulated (30 days).

It is estimated that the staged stand would have a net carbon gain of over the 30 day period (given the assumptions noted above) of 15.0 mol C m-2 , with a lower and upper 95% confidence estimate (derived from the regression confidence limits) of 14.5 and 15.5 mol C m^{-2} respectively. In contrast, the batch stand is estimated to accumulate 10.3 mol C m-2, with a lower and upper 95% confidence estimate (as derived from the non-linear regression confidence limits) of 10.1

and 10.5 mol C m-2 respectively, over the same 30 day period. From these results, it is easy to see that at the given daily PPF integral of 17.5 mol m-2 day-1, the batch stand has a net carbon gain which is between 27% and 35% lower than the expected net carbon gain of the staged stand. Given the same production area and fixed production costs between the staged and batch stands, it seems that the staged stand is more cost efficient at fixing carbon.

As eluded to earlier in this paper, the cost differences in net carbon gain between the two cultural strategies are likely related to differences in light interception by the stands. When the batch planted stand is young, there is incomplete absorption of incident light due to a lower leaf area index. As the batch stand develops, however, canopy closure is achieved and mutual shading of leaves, due to higher a higher leaf area index, results in lower quantum yields. This effect is augmented by higher respiration rates in heterotrophic (dissimilating) plant parts (hypocotyl and roots). In contrast, the staged stand has a quantum yield which cycles about a higher mean value (0.032 mol C mol^{-1} PPF). As a whole, the staged stand is more efficient at light absorption due to its greater average leaf area than that of the pre-closure period in the batch stand, but insufficient leaf area to diminish net carbon gain returns to light investment. In other words, the staged stand maintains a leaf area which has a higher absorption of incident radiation but is not so large that mutual shading increases respiratory carbon losses.

IMPLICATIONS OF STAGED PRODUCTION ON TRADE STUDIES

In trade studies consideration must be dually given for the combined effects of any increased labour cost (in ESM) and reductions in the cost (in ESM) of productivity (increases in quantum efficiency) associated with staged planting. Previous studies have identified the cost for a system of higher plant chambers using results from optimized menu studies [2]. In that body of work the cost of a higher plant system for food, air revitalization and potable water supply was determined for a Mars mission of 1800 days in length and a 6 member crew, with no end effects. Estimates of system cost obtained from these studies were based on crop productivity rates obtained with batch culture under nominal environment conditions. For the purposes of this discussion then, nominal ESM costs obtained in that study are abbreviated as ESM_{BR} or ESM_{PC}. These ESM costs included a fixed component and a time dependent component. More detailed information on the assumptions involved in the calculation of ESM estimates are available from the author.

There is some debate with regards to whether a staged planting scenario would be more labour intensive than a batch production scenario. The original batch planted production system included 5.7 hrs of labour per day [15]. It is therefore possible to partition the time independent components of the original ESM costing and include the time-dependent component of labour. The base cost of higher plant based, bioregenerative system (BR) was 58518 kg ESM (including mass and power requirements but using nominal productivity and stand quantum efficiency). This includes accounting for the fact that time-independent components were pro-rated to the original mission length of 1800 days Therefore the total mission cost associated with any additional labour due to a staged planting scenario can be given by:

$$ESM_{BR} = 58518 + \left(\frac{5.7 + H}{0.5}\right) \cdot T \qquad [4.3]$$

where ESM_{BR} is the mission cost (kg ESM) for a life support system, including air revitalization (CO_2 removal and O_2 production) and food for a BR system, H is the number of additional hours required per day to manage the staged system, 0.5 is the labour cost equivalency (0.5 hrs kg^{-1} ESM), T is the number of days into the a mission and ESM_{BR} is the total mission bioregenerative cost in kg ESM. Further, it has been shown that the physico-chemical (PC) food system, including

the use of prepackaged food for six crew members (as on the ISS) is 13.8 kg ESM day^{-1} [16]. Included in the time-dependent components of the total mission cost assuming physico-chemical (PC) systems alone, are the logistic and labour costs of PC equipment for air revitalization. The total cost of the PC approach, including air revitalization, was shown to be:

$$ESM_{PC} = 812 + 14 \cdot T \qquad [4.4]$$

where ESM_{PC} is the mission cost (kg ESM) for a life support system, including air revitalization (CO_2 removal and O_2 production) and food for a PC system, T is the number of days into a mission and ESM_{PC} is the total mission PC system cost in kg ESM [15].

Additionally, the increases in crop quantum yield and associated cost reductions (translated to kg ESM kg^{-1} crop yield, dwb), observed for the beet canopy under staged planting suggest that overall decreases in system cost on the order of 10 % to 30 % are realistic. Further if optimization of chamber infrastructure and mechanization are pursued, reductions in ESM cost may reach 50%. Such additional reductions may be achieved with the use of more efficient lighting sources, reduction in hydroponics system volume and further enhancements in cultural management strategies.

Figure 4.4 presents a summary of the total bioregenerative system and total PC system costs as a function years into a mission extended beyond the initial 1800 days, for values reductions in BR system cost ranging from 10 % to 50%. Additional the effect of an additional single hour per day (H=1) and an additional 3 hours per day (H=3) has been included based on a ESM cost reduction on the order of 40%. This was done to illustrate the impacts of a reasonable increase in labour requirement associated with staged planting when applied in combination with attainable reductions in overall system cost associated with increases in apparent quantum yield. It is useful to note here that experience gained with managing staged stands suggests that an additional labour requirement greater than 3 hours per day is unrealistic in a practical setting. This is so because the planting and harvesting of small areas needed to fulfill a single planting and harvest cycle is not overly time consuming. In fact, it has been possible in the course of these studies to plant and harvest a 2.5 m^2 production area of beet managed under staged production in less than 0.5 hrs in a 10 day period. This suggests an additional labour requirement of no more than 3 hours for the staged crop. Further, the benefits of repeated plant maintenance tasks on crew psychology are not evaluated here.

An examination of Figure 4.4 illustrates that no breakeven point (within a mission length of 30 years) exists for BR and PC systems for reductions in BR system cost up to 10%. Cost breakeven point in this context refers to the number of days into the mission at which the total ESM_{BR} equals ESM_{PC}. This point also corresponds to the intersection of the ESM_{BR} and ESM_{PC} profiles. Breakeven points do exist for cost reductions in the BR system within the range of 20% to 50%. Obviously decreases in the time to breakeven is decreased with decreasing BR costs. For a cost reduction of 50%, for example, the breakeven point is found to occur near a mission length of 9 years.

Increasing labour requirement associated with staged planting, increases the mission cost at different rates, and thereby extends the point of the intersection of the ESM_{BR} and ESM_{PC} profiles. The profile of ESM_{BR} for an additional labour requirement of H=1 hr (at an ESM reduction of 40%) intersects with the PC cost profile near 18 years while the profile of ESM_{BR} for an additional labour requirement of H=3 hrs (at an ESM reduction of 40%) does not intersect the PC cost profile within a mission duration of 30 years. It is reasonable that the additional labour requirement of the staged planting canopy is nearer to 1 than 3 hours per day, if not near, 0.

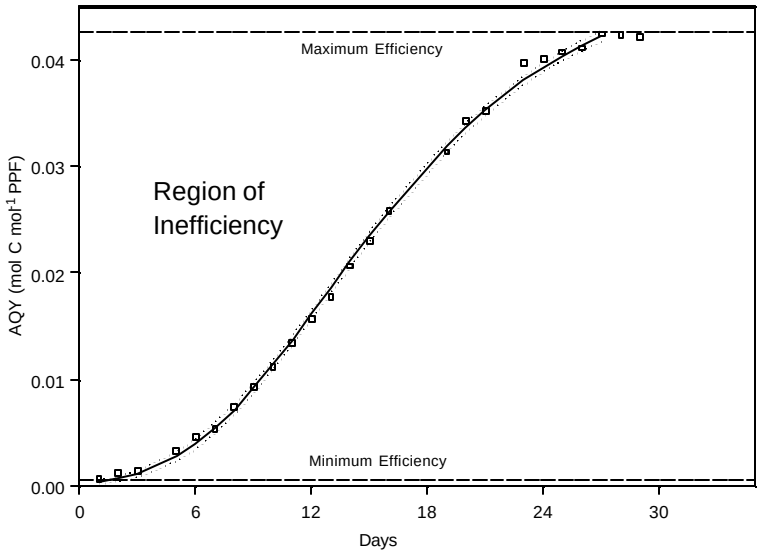

Figure 4.1. Dynamic in apparent quantum yield (AQY) for the batch planted stand as a function of days since initial chamber closure. The solid line indicates the fitted values obtained from the non-linear regression fit of the Gompertz function, while dotted lines indicate the upper and lower 95% confidence limits. Dashed lines indicate the maximum and minimum apparent quantum yields.

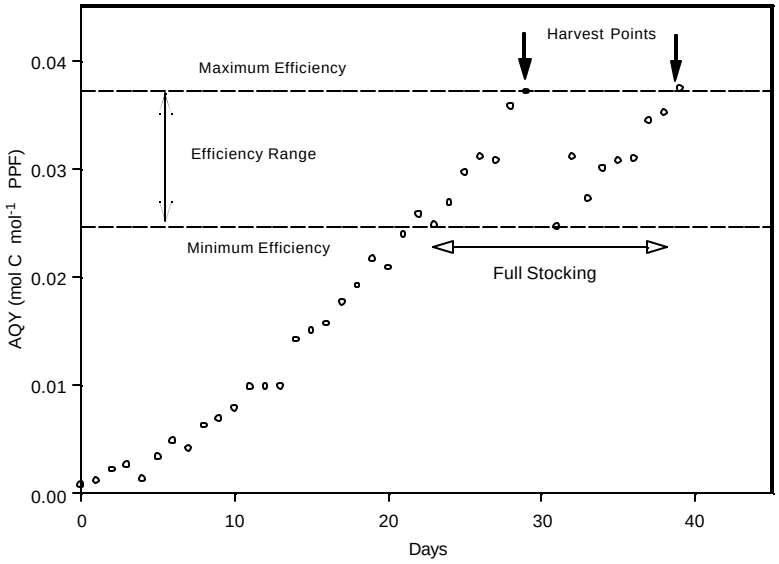

Figure 4.2. Dynamic in apparent quantum yield (AQY) for the staged planted stand as a function of days since initial chamber closure. Dashed lines indicate the maximum and minimum apparent quantum yields following full chamber stocking

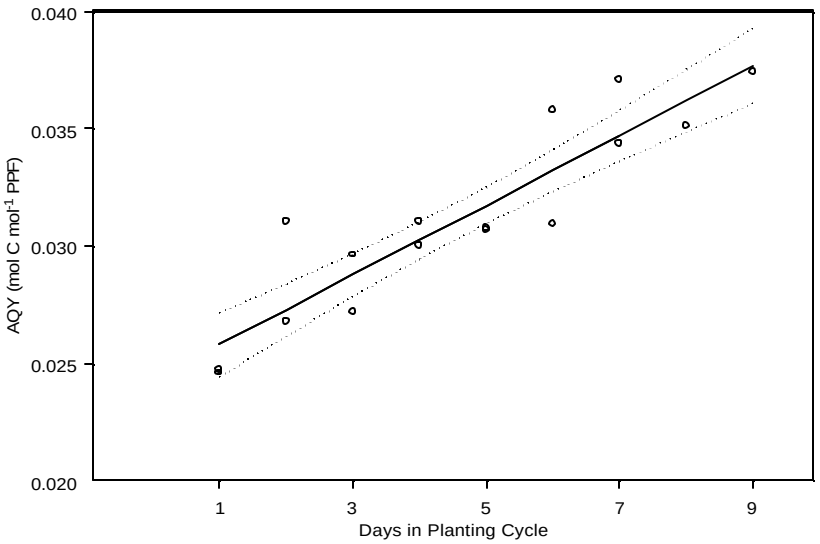

Figure 4.3. Changes in the stand apparent quantum yield (AQY) during the recovery period between plantings and harvest in a staged stand. Solid line is the line of best fit for a simple linear regression model while dotted lines are the upper and lower 95% confidence limits of prediction.

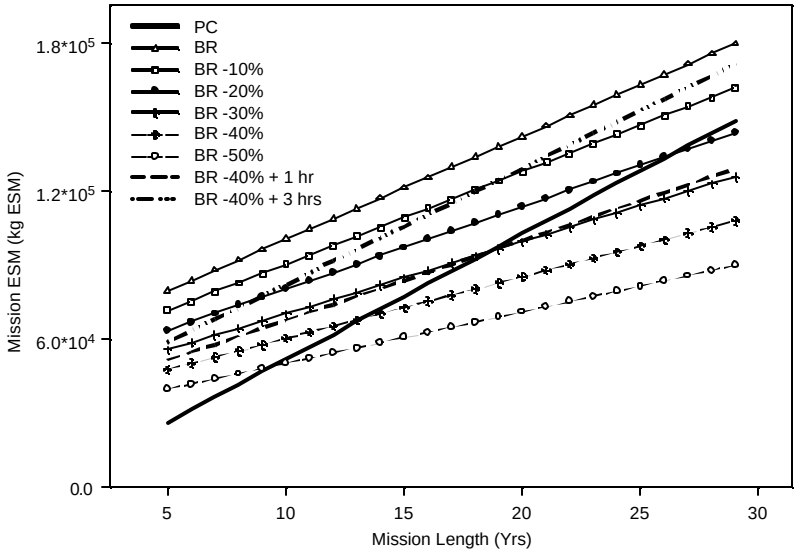

Figure 4.4. Bioregenerative (BR) and physico-chemical (PC) system mission costs (kg ESM) for varying mission lengths and cost reductions. Cost reductions for BR systems are expressed on a negative percentage change basis. Profiles for the ESM cost reduction of 40% are also plotted with additional labour requirements of 1 hr (+ 1 hr) or 3 hrs (+ 3 hrs) per day.

Section 5.0: Results of Integrated Planting Trials with Beet and Lettuce

The purpose of this experiment was to evaluate the effect of multiple crops with rotational planting on the daily net carbon exchange rate (NCER) and daily water production (evapotranspiration) within a sealed environment. Two of the three MELiSSA candidate crops, beet and lettuce, were continuously grown with a ten day staggered planting interval, resulting in a plant canopy with all representative stages of physiological growth within a common atmosphere.

CARBON DYNAMIC

Atmospheric management based on batch-type production scenarios would result in large fluctuations in carbon assimilation capabilities as crops are planted, harvested, and planted again [**Error! Reference source not found.**]. When beet and lettuce were combined in a staggered planting system, by the time all physiological stages were present at 50 days after initial planting, a trend towards a more stable carbon assimilation uptake profile was observed (Figure 5.1).

Application of a general linear model to the NCER results of each 10-day planting interval showed a downward trend in overall productivity (Figure 5.2). Although this would negate the hypothesis that staggered planting improves atmospheric stability, the downward trend can be attributed to reduced irradiation during the last four cycles (light curve studies) and to a nutrient solution deficiency or allelopathic interaction which resulted in a decline in beet health and vigor. Although carbon uptake showed a declining trend in this experiment, improved management practices to alleviate nutrient imbalance and allelopathic interaction should serve to provide steady productivity.

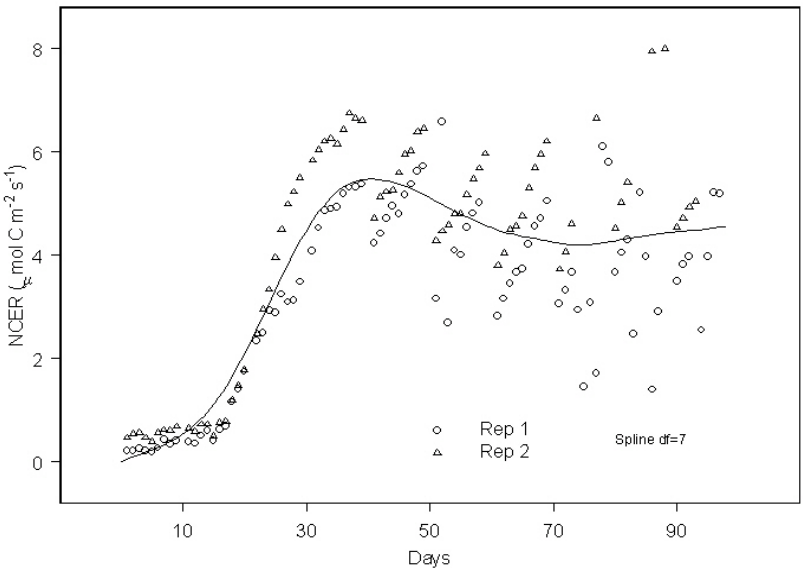

Figure 5.1 Daily net carbon exchange rate (NCER) for staggered beet and lettuce grown over a 100 day period. A simple spline algorithm was utilized to show the basic trend in NCER.

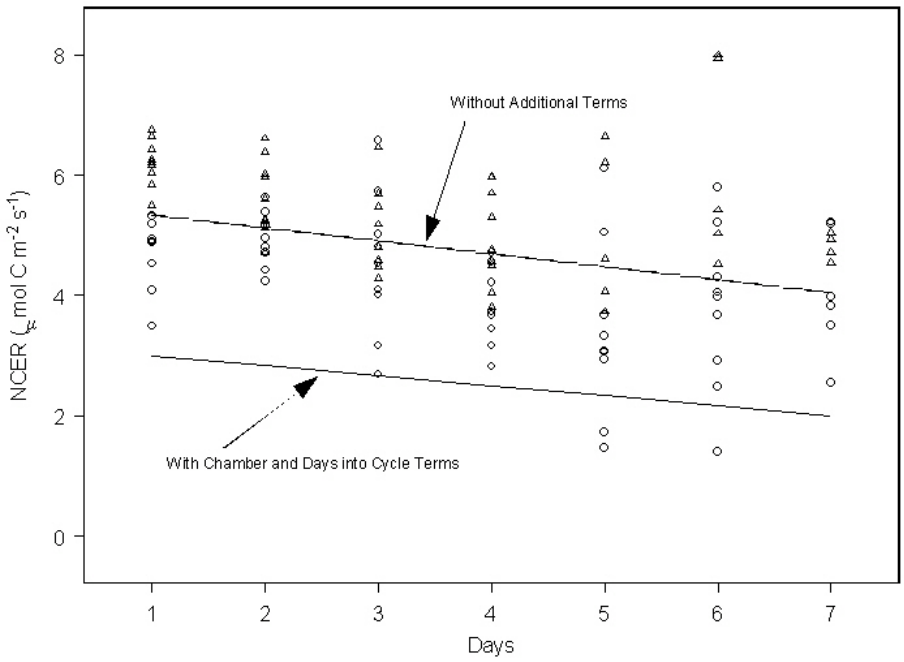

Figure 5.2 Integrated data set after full representation of all age classes with staggered planting of beet and lettuce. Each 10-day growth cycle was plotted and general linear model applied to the results.

EVAPO-TRANSPIRATION

During the initial crop establishment phase, transpiration steadily increased to a peak of approximately 6.5 L day^{-1} at 50 days after the start of the experiment. The rate of evapotranspiration then declined somewhat, and became steady during the later period where all phases of growth were represented in the chamber. Production during this period was approximately 6 L day^{-1}.

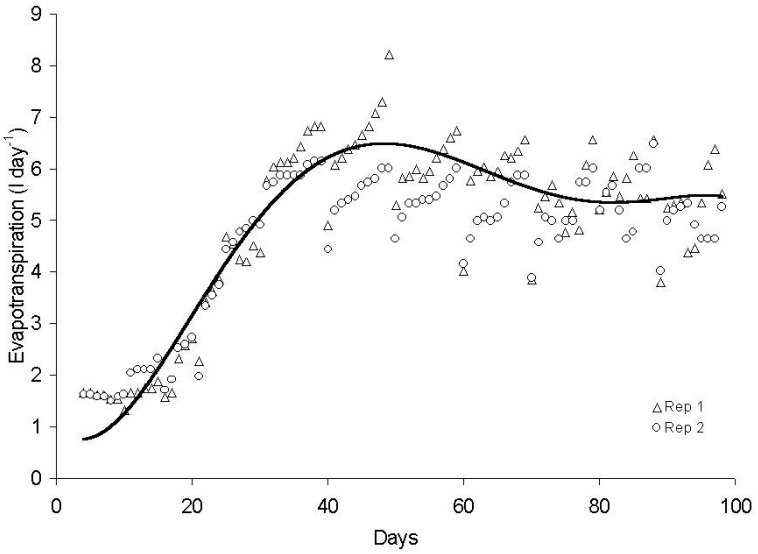

Figure 3.5 Daily evapotranspiration for staggered beet and lettuce with polynomial curve fitted to demonstrate the trend in water production.

Section 6.0: Update on the Controlled Environment System Research Facility and Hypobaric Chamber Specifications

The new 900 m^2 (8600 ft^2) Controlled Environment Systems Research Facility located within the Bovey Building complex at the University of Guelph has been completed. A total of 14 hypobaric chambers are now online and in the initial phases of testing. The facility hosts 5 large full canopy chambers each having a growing volume of 1m (width) x 1.8m (height) x 2.2m (depth). Additionally, there a 9 smaller, cylindrical chambers having dimensions of 1.6m (high) and 0.4m (diameter). The control system common to both the large and small chambers is provided by Argus Controls (White Rock, British Columbia) and is currently being configured. Preliminary results demonstrate the capability to depressurize to 5 KPa with a control bandwidth of 0.1 KPa. The new microbiological, analytical, calibration, and system control laboratories are now fully equipped and occupied by numerous CES faculty, technicians, and students.

At the present time, the research foci related to chamber development include: stress physiology and water relations are reduced pressure (10 kPA to 100 kPa), assessment of crop productivity and yield and atmospheric composition management. Studies in plant response to reduced pressure were completed using pepper plants and psychrometers.

Table 1. Large Hypobaric Chambers (5 chambers in total)

1. Dimensions:
   - a: Volume = 3879 L (1 m x 2.2 m x 1.8 m) per chamber
   - b: Plant Growing Area = 2.2 m^2 (1 m x 2.2 m) per chamber

2. Materials used:
   - a: Stainless Steel 316 (walls, floor, valves, plumbing)
   - b: Laminated Tempered Glass (roof)
   - c: Heresite (oxidation barrier on fans, heat exchangers, motor parts)
   - d: Viton (O-rings, solenoid seats)

3. Analyzers:
   - a: California Analytical Gas Analyzer for CO_2/O_2
   - b: Gas Chromatograph/Mass Spectrometer (Varian Saturn 2000)
   - c: Dionex DX500 HPLC Ion Chromatograph

4. Lights:
   - a: Six 1000 W High Pressure Sodium (HPS) lamps per chamber
   - b: Light level: 0 to 1500 µmol m^{-2} s^{-1} PPF at bench height

5. Sensors:
   - a: Hydroponic system
     - 1) Electrical Conductivity (two per chamber)
     - 2) pH metres (two per chamber)
   - b: Chamber
     - 1) Aspirated Air Humidity sensors (two per chamber)
     - 2) Aspirated Air Temperature sensors (two per chamber)
     - 3) Root Zone Temperature sensors (two per chamber)
     - 4) LiCor Quantum Sensor (two per chamber)

6. Environment Control:
   - a: Temperature (15 to 45 ºC) $\pm$ 0.2 ºC
   - b: CO_2 Concentration (10 to 5000 ppm) $\pm$ 10 ppm
   - c: O_2 Concentration (18 to 25 %)

d: Relative Humidity (50% to 95%) $\pm$ 5%
e: Pressure (5 kPa to 100 kPa)

Table 2. Small Hypobaric Chambers (9 chambers in total)

1. Dimensions:
   a: Volume = 245 L (1.6 m high x 0.4 m diameter) per chamber
   b: Plant Growing Area = 0.13 m^2 (0.4 m diameter) per chamber

2. Materials used:
   a: Stainless Steel 316 (walls, floor, valves, plumbing)
   b: Acrylic (roof)
   c: Heresite (oxidation barrier on fans, heat exchangers, motor parts)
   d: Viton (O-rings, solenoid seats)

3. Analyzers:
   a: California Analytical Gas Analyzer for CO_2/O_2
   b: Gas Chromatograph/Mass Spectrometer (Varian Saturn 2000)
   c: Dionex DX500 HPLC Ion Chromatograph

4. Lights:
   a: One 1000 W High Pressure Sodium (HPS) lamp per chamber
   b: Light level: 0 to 1500 µmol m^{-2} s^{-1} PPF at bench height

5. Sensors:
   a: Aspirated Air Humidity sensors (one per chamber)
   b: Aspirated Air Temperature sensors (one per chamber)
   c: Root Zone Temperature sensors (two per chamber)
   d: LiCor Quantum Sensor (one per chamber)

6. Environment Control:
   a: Temperature (15 to 45 ºC) $\pm$ 0.2 ºC
   b: CO_2 Concentration (10 to 5000 ppm) $\pm$ 10 ppm
   c: O_2 Concentration (18 to 25 %)
   d: Relative Humidity (50% to 95%) $\pm$ 5%
   e: Pressure (5 kPa to 100 kPa)

Section 7.0: Acknowledgements References and Abbreviations

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Acronyms

AQY – Apparent Quantum Yield
B - Parameter estimate in Gompertz function
ßo – Model intercept
ß1 – Model slope
BR - Bioregenerative
DCG – Daily Carbon Gain
e - a vector of model errors
EC – Electrical Conductivity
ESM – Equivalent System Mass
ESM_{BR} / ESM_{PC} - Equivalent System Mass of Bioregenerative (BR) and Physico-Chemical (PC) life support systems
dwb – dry weight basis
H – Number of additional labour hours per day in a staged production scenario
K - Parameter estimate in Gompertz function
NCER – Net Carbon Exchange Rate
PPF – Photosynthetic Photon Flux
S – Parameter estimate in Gompertz function

Table 4.1. Harvest data from staggered planting trials with beet. DIC at Harvest refers to the number of days in the chamber before harvest. Beet Root Biomass refers to the biomass of the enlarged beet hypocotyls. Inedible Biomass refers to root biomass. All values are expressed on a dry weight (dwb) per plant basis and are averages taken over two chambers. Bracketed values indicate lower and upper 95% confidence interval bounds for a sample size n=22 (11 plants per chamber).

DIC at Harvest	Leaf Area (cm^2 $plant^{-1}$)	Shoot Biomass (g dw $plant^{-1}$)	Beet Root Biomass (g dw $plant^{-1}$)	Edible Biomass (g dw $plant^{-1}$)	Inedible Biomass (g dw $plant^{-1}$)	Inedible: Edible	Total Biomass (g dw $plant^{-1}$)
10	34 [26, 42]	0.29 [0.23, 0.35]	0.04 [0.03, 0.05]	0.33 [0.26, 0.40]	0.08 [0.06, 0.10]	0.23 [0.18, 0.39]	0.41 [0.33, 0.49]
20	133 [87, 180]	1.24 [0.82, 1.61]	0.25 [0.17, 0.33]	1.46 [0.99, 1.93]	0.25 [0.16,0.34]	0.18 [0.13, 0.21]	1.71 [1.16, 2.25]
30	693 [532, 855]	7.50 [5.69, 9.30]	4.18 [3.01, 5.34]	11.67 [8.78, 14.55]	1.14 [0.82, 1.45]	0.11 [0.09, 0.13]	12.81 [9.64, 15.98]
40	1186 [908, 1463]	15.00 [11.94, 18.23]	16.30 [12.30, 20.39]	31.42 [24.54, 38.31]	1.79 [1.38, 2.21]	0.07 [0.04, 0.09]	33.22 [25.98, 40.47]