The Control of Carbon Dioxide Concentration and Effects of Carbon Dioxide Concentration on *Lactuca sativa* L. CV. 'Grand Rapids' Growth in Relation to Changing Photosynthetic Photon Flux Density.

by

Gordon Douglas Grant

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LACTUCA SATIVA L.

CV. 'GRAND RAPIDS' GROWTH IN RELATION TO CHANGING

PHOTOSYNTHETIC PHOTON FLUX DENSITY

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FORWORD

This thesis was written in paper style according to the regulations specified in the 1976 Plant Science Thesis Guide, section 3. The thesis "The Control of Carbon Dioxide Concentration and Effects of Carbon Dioxide Concentration on _Lactuca Sativa L._ CV. 'Grand Rapids' growth in relation to changing "Photosynthetic Photon Flux Density"." consists of two manuscripts:

1. Microprocessor based conductimetric Carbon Dioxide Analyser/Controller.
2. Affects of Carbon Dioxide Concentration and Photosynthetic Photon Flux Density on the early growth of 'Grand Rapids' lettuce.

The former has been submitted for publication in _HortScience_ and the latter has been submitted for publication in the _Journal of the American Society of Horticultural Science_.

ABSTRACT

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A two phase study was undertaken to examine effects of CO_2 analyser/controller capable of regulating CO_2 concentrations in controlled environment growth chambers. A microprocessor was used to provide proportional control of CO_2 concentrations. A second CO_2 analyser/controller was custom designed by Agricultural Canada Engineering and Statistical Research Institute based on the principles of empirical gas analysis. The two controllers were used to monitor and control six carbon dioxide concentrations under varying photosynthetic photon flux density (six values). Both controllers functioned satisfactorily. The conductimetric controller had a response time of 3 minutes and an accuracy of control of 3.5 %.

The second phase of the study was an analysis of the effects of varying CO_2 concentration and PPFD on the early growth of 'Grand Rapids' lettuce. Lettuce plants were grown

in 10.2 cm pots under eighteen treatment combinations organized into three experiments. Both CO_2 concentrations and PPFD had a significant effect on lettuce plant growth. Increasing CO_2 concentration would compensate somewhat for slow growth under low PPFD conditions. Optimum CO_2 concentrations for plant growth varied with the ambient PPFD. Under low PPFD conditions during the winter (approximately 150 $uE.m^{-2}.s^{-1}$) a commercial lettuce grower may wish to supplement CO_2 concentrations to 33 or 38 $mmol.m^{-3}$ whereas under higher PPFD conditions during spring (300 - 325 $uE.m^{-2}.s^{-1}$) supplemental CO_2 concentrations of 42 to 44 $mmol.m^{-3}$ are more optimal.

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LIST OF ABBREVIATIONS

CO_2	-	carbon dioxide
IRGA	-	infrared gas analyser
KWh	-	kilowatt hour
lx	-	lux
m	-	milli
mol	-	mole
PAR	-	photosynthetically active radiation
PI	-	photosynthetic irradiance
PPFD	-	photosynthetic photon flux density
ppm	-	parts per million
u	-	micro
vphm	-	volume parts per hundred million
vpm	-	volume parts per million

INTRODUCTION

Suggestions that supplemental carbon dioxide (CO_2) in the plant atmosphere would improve crop production were first made over 90 years ago (Wittwer and Robb 1964). However, it has only been during the last two decades that the attention of the scientific community has focused seriously on various aspects of plant growth and development in relation to CO_2 concentration. In 1979 guidelines were established for the monitoring and control of CO_2 in controlled environments (Pallas 1979). The guidelines established by the Controlled Environments Working Conference recommended that concentrations of CO_2 be reported for studies undertaken in controlled environment facilities (Tibbitts and Kozlowski 1979).

Control and monitoring of CO_2 concentrations in growth rooms has generally been effected with the use of infrared gas analysers (IRGA) (Bailey et al. 1970). These units are expensive and their response is non-linear at higher CO_2 concentrations. Conductimetric analyser/controllers were developed by Bowman (1968) and Slack and Calvert (1972) and refined by Kimball and Mitchell (1979). With the advent of low cost microprocessors and microcomputers the question arises as to whether their use in a conductimetric controller will further enhance controller performance while maintaining facility of use for the researcher. One aspect of the current research effort was to develop a microcomputer based CO_2 analyser/controller of sufficient precision to be used in controlled environment rooms and which could be assembled by a plant science researcher with limited technical background from materials generally available in the research lab or readily available from general supply houses. To achieve this aim a microcomputer based conductimetric controller was designed and built based on a conductimetric controller designed by Kimball and Mitchell (1979). A series of performance tests were run to ensure that the desired precision could be achieved. In order to have a comparison controlled system and to facilitate concurrent experiments with three CO_2 concentrations, ambient and two elevated concentrations, a second controller was custom designed by Agriculture Canada, Engineering and Statistical Research Institute, Ottawa. This low-priced IRGA based unit consisted of dual, filter isolated, infra-red wave bands and a 50-cm folded radiation path. Commercial marketing of the unit is contemplated, consequently a full description is not available.

Scientific interest in CO_2 effects has been on-going for the last two decades. Many experiments have been performed with the intent of studying CO_2 concentration effects but have in actuality been performed with poor control of the

CO_2 concentration (Calvert 1972, Knecht and O'Leary 1974, Kretchman and Howlett 1970). In one study the range of control achieved varied from 500 to 2000 ppm (approximately 21 to 83 $mmol.m^{-3}$) for a set concentration of 1500 ppm (approximately 62 $mmol.m^{-3}$) (Kretchman and Howlett 1970). Research has been able to establish a positive effect of elevated ambient CO_2 concentration on crop growth yet little research has been accomplished to quantify the relationship (Pallas 1979, Wittwer and Robb 1964). As well, recent work has emphasized the necessity of considering CO_2 supplementation as part of a multifactorial study (Krizek et al. 1974). Temperature, vapor pressure deficit, and PPFD have been observed to influence plant response to CO_2 concentration (Weibe and Lorenz 1982, Lee and Whittingham 1974, Cavalchini and Odone 1969).

The aim of the second part of the current research effort has been to clarify the effects of CO_2 concentration on plant growth when photosynthetic photon flux density (PPFD) is included in the plant response model. A question of special interest to commercial greenhouse agriculture is whether CO_2 supplementation can be used to overcome the efects of low PPFD. A question of similar importance is whether the same effects on growth can be achieved with moderate increases in CO_2 concentration as are observed with higher increases in CO_2 concentration.

In order to investigate these questions a crop which has been demonstrated to respond favorably and dramatically to CO_2 concentration and PPFD was required. An investigation into previous research efforts found that *Lactuca sativa* L. responded well and in addition was of some agronomic significance (Wittwer and Robb 1964, Kretchman and Howlett 1970). It was for these reasons that 'Grand Rapids' lettuce, a commercial greenhouse leaf lettuce was selected as a suitable test material. Lettuce plants were grown in growth rooms under different combinations of PPFD and CO_2 concentration. A range of PPFD values were chosen to approximate values common to winter and spring conditions.

LITERATURE REVIEW

Units of Measure

Krizek (1979) cites twelve different units of measure used to report concentrations of carbon dioxide in scientific literature. At the Controlled Environments Working Conference held in Madison, Wisconsin, in March 1979, this problem was addressed and the units of $mmol.m^{-3}$ or $umol.m^{-3}$ were recommended for adoption as the units to report carbon dioxide concentrations in scientific literature (Krizek 1979). The rationale behind this comes from the International System of Units (S.I.) wherein the defined base quantities of a substance are moles (mol). The base unit for volume is defined as $length^{-3}$ that is $metre^{-3}(m^{-3})$. Concentration would then be expressed as $mol.m^{-3}$ with the appropriate prefix such as umol or mmol (Krizek 1979). In order to facilitate comparison of research work reported in different units of concentration an approximation of carbon dioxide concentration is provided in parenthesis in units of $mmolCO_2.m^{-3}$.

Historically plant researchers have reported radiation levels in photometric units (foot candle or lumens.m-2) which are units of measure defined by the spectral sensitivity of the human eye (Shibles 1976). Several researchers have suggested a number of reasons for this but current measurements of radiant energy should be over wavelengths and spectral sensitivites relevant to photosynthesis (McCree 1979). In fact, the use of the word 'light' in plant photosynthesis studies is incorrect as light refers to radiation visible to the human eye and is therefore not relevant to plant studies.

The Committee on Crop Terminology of the Crop Science Society of America has defined terminology suitable for reporting radiation levels relevant to photosynthesis (Shibles 1976). There are three basic definitions. Photosynthetically active radiation (PAR) is defined as radiation over the wave bands of 400 to 700 nm. Photosynthetic photon flux density is defined by the number of photons in 400 to 700 nm (PAR) band incident upon a unit surface area.$^{-1}$unit time^{-1}. The reccommend unit is $nE.s^{-1}.cm^{-2}$ but $uE.m^{-2}.s^{-1}$ would more closely follow the S.I. system. An einstein (E) is defined as 1 mole of photons. Photosythetic irradiance (PI) is the energy flux density of PAR incident unit time.$^{-1}$ unit surface area^{-1}. The recommended unit is $nW.cm^{-2}$ but W.m-2 would more closely follow the S.I. system. McCree (1979) observed that PPFD was a better measurement for photosynthetic activity than PI as the primary events in photosynthesis are photochemical. The author of this thesis has chosen to report radiation levels in PPFD and in units of $uE.m^{-2}.s^{-1}$. In this literature review radiation levels are reported as the original authors reported them as comparisons and conversions between different measurement and instrument systems are not accurate (McCree 1979b).

Plant Response to Carbon Dioxide Supplementation

It is well documented that 'normal' 330 ppm (14 mmol.m^{-3}) ambient carbon dioxide (CO_2) concentrations limit photosynthetic fixation except at reduced photosynthetic photon flux densities (PPFD) (Kretchman and Howlett 1970, Wettwer and Robb 1964). This review will cover some of the theoretical and practical aspects of plant response and in particular the response of lettuce (Lactuca sativa) to CO_2 enrichment. As well, some of the interrelationships between PPFD, temperature, and CO_2 concentration will be reviewed.

A wide range of CO_2 concentrations have been utilized in commercial and research applications. Lettuce plants have been grown in supplemental CO_2 concentrations in a range from 600 ppm to 6000 ppm (25 - 254 mmol.m^{-3}) (Hand 1980, Kim et al. 1975). Great Lakes '366' lettuce plants showed responses to CO_2 within 20 days of planting and increases in plant mass were manifest up to 3000 ppm (127 mmol.m^{-3}). Plants grown in 6000 ppm (254 mmol.m^{-3}) CO_2 had similar masses as those grown in 3000 ppm (127 mmol.m^{-3}) (Kim et al. 1975) Zatyko (1971) grew head lettuce during the late winter in greenhouses enriched to 0.1, 0.3, or 0.5 % CO_2 (42,127, 212 $mmol.m^{-3}$) and observed that plants were 39-75 % heavier in yield than controls at 'normal' CO_2 concentrations. A plateau was reached at 0.3 % CO_2, which raised the mean head weight from 70 to 122.5 g. Thus it would seem that there is an optimum CO_2 concentration for which a positive response in plant growth or yield can be expected. Some evidence in support of a hypothesis that this optimum varies with the plant species, PPFD, and day temperature in the plant growth facility will be presented in this review.

A concentration of 400 ppm (17 $mmol.m^{-3}$) is often the control concentration used by plant researchers (Knecht and O'Leary 1974, Madsen 1974). This CO_2 concentration is not always indicative of concentrations commonly found in commercial greenhouses. Concentrations as low as 150 ppm (6 $mmol.m^{-3}$) to 180 ppm (8 $mmol.m^{-3}$) have been measured in non-enriched greenhouses (Wittwer and Robb 1964, White 1978). At low concentrations the CO_2 compensation point for C_3 plants is approached and little net photosynthesis will occur (Hicklenton and Jolliffe 1978, Wittwer and Robb 1964). The economic benefits described in the literature may be underestimated due to 'normal' greenhouse CO_2 concentrations being lower than the 'normal' ambient global atmospheric concentrations. Several researchers consider a CO_2 concentration of 1000 ppm (42 $mmol.m^{-3}$) to 1500 ppm (63 $mmol.m^{-3}$) to be optimum for plants in the reproductive phase and 2200 ppm (93 $mmol.m^{-3}$) optimum for plants in the vegetative phase of growth (Madsen 1970, Wittwer and Robb 1964). Went (1979) pointed out that these optimum CO_2 concentrations may be of little meaning as plants absorb CO_2 at noticeably different rates at different times of the day and under different physiological conditions (Krizek 1979). Studies where the duration of the period of enrichment have been varied indicated that the optimum benefit from CO_2 supplementation occured when supplementation is maintained for the entirety of the light period. Calvert and Slack (1976) demonstrated that by successively shortening the duration of the daily enrichment period, lower yields of tomatoes (*Lycopersicon esculentum*) were obtained. Ending the enrichment period earlier in the afternoon had less of a detrimental effect on yield than did beginning the enrichment period later in the morning. This was primarily due to the lower rates of photosynthesis of tomato plants in the late afternoon from diminishing light levels (Calvert and Slack 1976).

Many researchers have found a positive correlation between supplemental CO_2 and yield in tomatoes with increases in yield varying from 25 to 71 % (Calvert 1972, Hicklenton and Jolliffe 1978, Kretchman and Howlett 1970, Madsen 1974). Others have estimated tomato fruit yield increases to be 43 % (Wittwer and Robb 1964). Johnston (1972) tested sixteen different varieties of head lettuce in the fall in a greenhouse enriched to 600 ppm (25 $mmol.m^{-3}$). Average increase in mass of the plants was 30 %. Krizek *et* al. (1974) observed a 2 to 4.6 fold increase in plant mass for head lettuce, tomatoes, and cucumbers (Cucumis sativus) after 15 days from planting. The seedling environment was 'programmed' for rapid growth. Irradiance, CO_2 concentration and temperature were all increased to values greater than that normally recommended for optimum growth of the plants. Two groups of control plants were used, one set in a growth chamber at 400 ppm (17 $mmol.m^{-3}$) CO_2 and the other set in a greenhouse without supplementary light or CO_2 and a normal temperature regime. Growth of plants in the high CO_2, higher light, and high temperature growth room was as 10 to 25 times that measured for plants of all three species in the greenhouse (Krizek *et* al. 1974). Frydrych (1981) grew lettuce plants with a supplemental CO_2 concentration of 200 $uL.L^{-1}$ (8 $mmol.m^{-3}$) and supplemental light. The increase in overall plant mass was 49 %. Dullforce (1966) observed final dry weight increases of 26 % for head lettuce plants grown in a CO_2 supplemented atmosphere. The researcher commented that this same increase in growth could be obtained in the control plants if they were planted 4 or 5 days earlier.

Hand (1980) grew winter head lettuce in CO_2 concentrations varying from 800 vpm to 1600 vpm (33 - 68 $mmol.m^{-3}$) and observed an increase in the mass of marketable heads of 21 to 31 %. The increase in mass was due to a greater dry matter content per unit leaf area. Hand's research involved varying ethylene concentrations in the CO_2 supplemented atmosphere. Plants exposed to 50 vphm ethylene and 1600 vpm CO_2 showed an increase in head mass of 27 % compared to 31 % observed in plants grown with 1600 vpm CO_2 (68 mmol.m^{-3}) and no ethylene. The implications of this are that growers using CO_2 burners may be unaware of detrimental effects caused by ethylene pollution in the greenhouse. This may be due to a partial masking of the harmful effects of ethylene by the positive effects if CO_2 supplementation on the head lettuce mass. Others have reported an antagonistic effect of elevated CO_2 concentration on ethylene symptoms. Uota (1969) observed that a 10 % CO_2 concentration prevented ethylene-induced sleepiness of carnation blooms. The author noted that the CO_2 was inhibiting the biological synthesis of ethylene in the plant.

With tomato plants a 180 % increase in the rate of photosynthesis can be expected with a 225 % increase in the CO_2 concentration above 'normal' ambient levels (Hicklenton and Jolliffe 1978). Ho (1977) reported a 20 % increase in the rate of carbon fixation in plants grown in CO_2 supplemented atmospheres. The relationship of rates of photosynthesis and CO_2 concentration in the plant atmosphere was quantified as being linear over the range of 100 ppm to 1000 ppm (4 - 42 mmol.m^{-3}) under 'normal' day light conditions. As a result, Lee and Whittingham (1970) concluded that CO_2 was limiting photosynthesis under 'normal' daylight conditions in the greenhouse. Supplemental CO_2 has been reported to improve the CO_2 utilization efficiency of tomato plants (Hicklenton and Jolliffe 1978). Decreases in the chlorophyll content of tomato leaves grown in CO_2 enriched atmospheres substantiate this observation (Madsen 1974). As well, respiratory losses of CO_2 were observed to be a smaller proportion of net photosynthetic gain in chrysanthemums (Chrysanthemum morifolium) grown in an atmosphere supplemented to 1500 ppm (63 $mmol.m^{-3}$) CO_2 versus those grown in a 325 ppm CO_2 (14 $mmol.m^{-3}$) atmosphere (Hughes and Cockshull 1972). Heath and Meidner (1967) observed a decline in both the CO_2 compensation point and light compensation point for 'Grand Rapids' lettuce grown in a CO_2 supplemented atmosphere. Hence at relatively low light intensities additional CO_2 may be improving the photosynthetic efficiency of the plant by a reduction in the light compensation point which would enable the plant to make better use of the available light.

An increase in percent carbon fixed to sucrose with a corresponding drop in percent carbon fixed to glycine and serine in tomato leaves growing in a CO_2-enriched atmosphere has been demonstrated (Lee and Whittingham 1974). Goldsworthy (1969) observed a similar reduction in glycolate formation which may reduce the rate of photorespiration and therefore improve the efficiency of CO_2 utilization. Since sucrose is the primary transport form of carbon from leaves, the obvious deduction is that there should be an increase in carbon transport from leaves with increasing CO_2 concentrations in the plant atmosphere. Ho (1977) observed such an increase in the order of 40 % in tomato plant leaves grow in a CO_2 supplemented atmosphere.

Classical growth analysis applied to CO_2 enrichment studies has shown that mean unit growth rate of leaves increased with CO_2 concentration in chrysanthemum plants yet there was no effect of supplemental CO_2 on mean specific leaf area, mean leaf weight, mean leaf area ratio or final leaf area (Hughes and Cockshull 1972). Hurd (1968) observed increases in relative growth rate (RGR) and net assimilation rate (NAR) in tomato plants grown in CO_2 supplemented atmospheres. Dullforce (1966) observed similar increases for head lettuce grown in a low light and a CO_2 supplemented environment. However RGR still decreased as the lettuce plants became older and more complex with leaves increasingly shading one another (Dullforce 1966, Holsteign 1981). Dullforce (1966) postulated that this decrease in RGR may be due to a reduction in diffusion rates of CO_2 into the leaves and perhaps through closure of the stomata. More recent work does not support this. Stomatal resistances in apical leaves of tomato plants were observed to be equal to those observed in lower leaves of plants grown in a CO_2 enriched atmosphere (Hicklenton and Jolliffe 1978). Plants grown in a non-enriched atmosphere had lower stomatal resistances in apical leaves than in lower leaves, thus indicating an increase in stomatal resistance with CO_2 concentration, yet increasing CO_2 concentration improves RGR. Jones and Mansfield (1970) observed partial closing of stomata in lettuce plants exposed to a 1000 ppm (42 $mmol.m^{-3}$) CO_2 supplemented atmosphere. The authors noted no evidence of acclimatization of the stomata to high CO_2. They suggest that further benefits from CO_2 supplementation could be obtained if stomatal closure were prevented during CO_2 supplementation could be obtained if stomatal closure were prevented during CO_2 supplementation. Nevertheless, it becomes obvious that increasing CO_2 concentration must improve plant productivity by some means other than just an improvement in the CO_2 concentration gradient. This is based on the observation that as the concentration gradient is improved there is a corresponding increase in resistance to CO_2 flux.

Large differences in net photosynthetic rates in response to CO_2 have been measure in different genotypes of tomatoes (Nilwik _et_ al. 1982). Differences between 150 - 209 mg $CO_2 \cdot m^{-2}$ were recorded in ten different genotypes at low light fluxes and 'normal' CO_2 concentrations and at high light fluxes and high CO_2 concentrations. Carbon dioxide compensation points were observed to vary between genotypes and to vary within genotypes under different light and CO_2 treatments. Thus cultivars of a species can be expected to be more or less suited to CO_2 suppplementation depending on how the physiological status of the plant changes in terms of light compensation points in response to increasing CO_2 concentrations.

Young leaves of tomato plants were observed to be more responsive to CO_2-enrichment than older leaves and earlier growth was observed to be greater (Hicklenton and Jolliffe 1978). Leaf expansion in lettuce, tomatoes, and cucumbers was enhanced by supplemental CO_2 and an increase in lateral bud formation for all three species was observed (Krizek et al. 1974). Tomato leaves in a CO_2 supplemented atmosphere were observed to be thicker by 5 to 8 % (Hurd 1968). Studies with head lettuce plants indicated that average leaf size of lettuce plants in CO_2 enriched and non-enriched atmospheres are the same (Dullforce 1966). Carbon dioxide supplementation did not effect head diameter, leaf length or rate of leaf maturation in lettuce (Cavalchini and Odone 1969). Yet head masses were increased by 20.75 % on average and heart width by 9.06 % on average.

Extended daylength was demonstrated to increase head weight and leaf number and shorten leaf length of head lettuce plants but only when used in conjuction with high (1700 ppm, 72 $mmol.m^{-3}$) CO_2 (Cavalchini and Odone 1969). With 'normal' atmospheric CO_2 concentrations extended daylength increased the number of heart leaves but the effect was more pronounced at high CO_2 concentrations. A positive interaction between light level and CO_2

concentration was observed in chrysanthemum plants with an increase in unit leaf growth rate, final total dry mass and final total flower mass (Hughes and Cockshull 1972).

A number of research efforts have been directed towards the question of whether PPFD or CO_2 concentration in the growth facility is the more limiting factor to plant growth (Ho 1977, Hurd 1968, Hurd and Thornley 1974, Lee and Whittingham 1974). It was observed that under winter light levels rates of carbon fixation were similar in plants grown in CO_2 enriched and non-enriched atmospheres in greenhouses (Ho 1977). However, when experiments were performed with high light levels tomato leaves had a 72-100 % higher rate of carbon fixation when in a CO_2 enriched atmosphere (Ho 1977). It is apparent then that light is limiting in winter greenhouses. Ho made the observation that leaves in the CO_2 enriched atmosphere had a less dramatic response to changing light levels.

Research of others has shown that relatively small increases in low light levels correspond to substantial increases in CO_2 concentration in terms of their effects on the photosynthetic rate (Lee and Whittingham 1974). Others have confirmed this response (Hicklenton and Jolliffe 1978, Hurd 1968). Hicklenton and Jolliffe (1978) were able to demonstrate a beneficial interaction between CO_2 concentration and light intensity. In an atmosphere supplemented to 1500 ppm (63 $mmol.m^{-3}$) with a light flux of 5,382 lx the same rate of growth occurred in tomato plants as was observed under 16,500 lx and 400 ppm (17 $mmol.m^{-3}$) CO_2 concentration. In work with 'Grand Rapids' lettuce an optimum light flux for maximum leaf area was observed at 0.3 to 0.4 KWh $m^{-2}.day^{-1}$ (Craker and Seibert 1983). The authors went on to suggest that leaf area was more sensitive to photoperiod than to irradiance level. But it is apparent that this statement is not supported by the research methods employed as irradiance level and duration were not differentiated from each other. Plants under different irradiance durations did not receive the same daily integrated quantum flux. Cavalchini and Odone (1969) presented evidence from research with head lettuce supporting the above hypothesis. In high CO_2 concentration treatments an interaction between duration and intensity of irradiance was observed. Twelve hour light durations gave the largest head masses when applied at a medium light intensity but 18-hour duration gave the largest head masses at high intensity. The authors noted that beneficial effects of supplemental lighting in terms of intensity and duration were only manifest when supplemental CO_2 was applied. Best results were obtained when all three factors of supplemental CO_2 concentration, light intensity, and light duration were combined.

Temperature has been shown to bring about a rise in the CO_2 compensation point of lettuce from 70 ppm (3 $mmol.m^{-3}$) to 150 ppm (6 $mmol.m^{-3}$) with a temperature rise from 6 C to 22 C (Weibe and Lorenz 1982). At a low light flux of 5 klx maximum rates of photosynthesis occurred at 6 C while the optimum temperature for leaf growth was much higher at 16 C. Stokes (1978) established a standard temperature regime for winter greenhouse head lettuce production as 10 C day and 4 C night temperature. When supplemental CO_2 was added to the greenhouse atmosphere, increases in head mass were obtained with a day temperature of 13 C. Hughes and Cockshull (1972) observed positive interactions of temperature, CO_2 concentration and light intensity for greenhouse chrysanthemums. Tomato fruit manifest a similar temperature and CO_2 concentration interaction. Yields of fruit were improved when the CO_2 concentration and day temperature were increased but yields are reduced if only day temperature was elevated (White 1978).

It becomes apparent then that the effects of CO_2 concentration on plant growth and development cannot be studied in isolation if relevent conclusions are to be drawn. Temperature and PPFD have been clearly demonstrated to form significant interactions with CO_2 concentration. As well, the physiological age and genotype of the plant influence the plant response to CO_2 supplementation. Although many researchers have observed interactions between PPFD and CO_2 concentration, relatively little progress has been made to quantify this relationship.

Monitoring and Control of Carbon Dioxide

Pallas (1979) listed six methods which had been used to monitor and to varying extents control carbon dioxide (CO_2) concentrations in plant growth structures. These were: absorption of infrared energy, electrochemistry, photochemistry, interferometry, gas chromatography, and liquid scintillation spectrometry. Of these techniques, infrared gas analysis and electrochemical, including pH and conductimetric techniques, lend themselves most readily to adoption in continuous monitoring and control situations. The principle features of different CO_2 monitoring systems were summarized in Table 1.

Many researchers are of the opinion that monitoring of CO_2 in controlled environment chambers is essential and control highly desirable (Pallas 1979). The need for CO_2 regulation in a controlled environment chamber is dependent on the relationship of the size of the chamber and the material in the chamber (Hellmer and Giles 1979). Hellmers and Giles (1979) state that in a matter of a few hours after lights had come on C_3 plants had lowered the CO_2 concentration to 150 ppm and C_4 plants to 50 ppm. In a fully loaded chamber the calculated rate of decline in CO_2 concentration was observed to be 1 % of the chamber volume per minute. Large fluctuations can be observed in chambers. Carbon dioxide concentration increases rapidly as an investigator enters the chamber. Even to maintain a fixed

TABLE 1

A Comparison of the Methods Described for Measuring the Concentration of CO_2 in Air (Bowman 1968).

Method	Maximum sensitivity vpm	Sample size ml	Time for one determination min	Control
Infra-red absorption	0.05	1000	1	Yes
Electrical conductivity of alkali solution	2	100	0.5	Yes
Electrical conductivity of deionized water	10	50	1	Yes
Equilibrium pH of alkali solution	20	1000	30	No
Titration of alkali solution	50	300	5	No
Chemical absorption (indicator tube)	50	100	3	No
Chemical absorption (volumetric)	50	20	5	No
Gas chromatography	50	1	2	Difficult
Optical interferometer	60	100	0.5	No
Katharometer	200	200	2	Yes

'normal' ambient CO_2 concentration an air exchange rate of 75 % of the volume of the chamber per hour is necessary (Hellmer and Giles 1979).

The simplest method of CO_2 control was by the use of a time clock system. With this approach estimates of the rate of CO_2 use on a per hour or per half-day basis were calculated. The volume or mass of CO_2 required to maintain this concentration for the growth facility was derived. A timer was then set in conjunction with the output from a CO_2 generator or the flow rate of CO_2 gas from a tank. Checks were made of the CO_2 concentration with disposable sampling tubes (Badger and Poole 1979). This method of control was not that reliable or precise a means, as it does not take into account changes in the rate of CO_2 usage by the crop or changes in the rate of CO_2 loss from the plant growth structure. At the Glasshouse Crops Research Institute, England, CO_2 gas was injected at a constant rate of 50 lb/acre/hour into glasshouses. The mean concentration was observed to be 1230 vpm (51 $mmolCO_2.m^{-3}$) with no wind and 750 vpm (31 $mmolCO_2.m^{-3}$) when there was a 10 mph wind (Slack and Calvert 1972). Thus it is quite conceivable that growers are either under or overshooting the optimum CO_2 concentration set for a particular crop.

The use of infrared gas analysers (IRGA) by plant researchers for CO_2 regulation is well established (Pallas 1979). He suggests that IRGA offers the potential for the greatest precision of control. A drawback in the use of

IRGA in the commercial greenhouse is the high sensitivity of the IRGA to water vapour when the 2.7 um band is not filtered out (Sestak 1971). Interference by water vapour can be avoided by filtering with lead telluride optical 'wedge' filters placed over the detector cell windows (Bowman 1968). The use of optical filters instead of a drying system was demonstrated to improve the response time of a complete IRGA system by approximately 40 %. This was due to a reduction in sweep volume brought about by the removal of the drying system (Bowman 1968b). He used an IRGA at the heart of a 6-stage proportional controller system designed for use in plant research facilities. Performance was within 2 % of full scale of the IRGA. The author notes that absolute accuracy of the system was limited by that of the analysed gas mixtures used for calibration (Bowman 1968b). IRGA has been used in conjunction with microcomputers to optimize CO_2 control in plant growth facilities. The microcomputer was used to compare the CO_2 concentration measured by the IRGA to a preprogrammed set level. The computer would then calculate the injection rate in terms of number of seconds open per minute. The microcomputer was programmed to adjust the calibration of the IRGA system to correspond to an analysed gas mixture supplied to the system (Hellmers and Giles 1979).

Conductimetric CO_2 gas analysers are based on the principle that electrical conductivity of water increases proportionally with the dissolved CO_2 concentration (Kimball and Mitchell 1979). In most systems air from the plant growth facility is bubbled through a column of deionized water. Some of the CO_2 in the air is dissolved in the water. The CO_2 charged water is then passed through a flow through conductivity cell which is the actual sensing device of the system (Pallas 1979). Most systems are designed to be recirculating and use a bed of deionizing resin to remove the CO_2 from the water (Bowman 1968). Conductimetric controllers are considered to be limited in accuracy to $\pm$15 $uL.L^{-1}$ at 30 $uL.L^{-1}$ CO_2 (0.6 $mmolCO_2.m^{-3}$ at 12 $mmolCO_2.m^{-3}$) (Pallas 1979). Bowman observed that less than 5 % of the CO_2 content of the air was dissolved by the deionized water (Bowman 1968b). Response time for a conductimetric controller was observed to be 2.5 minutes for a 90 % change in output after a step change in CO_2 concentration (Kimbal and Mitchell 1979).

Conductimetric controllers vary in sensitivity to temperature. Responses had varied from 0.25 % of full scale to 1.5 % per C (Slack 1974, Bowman 1968b). The degree of temperature sensitivity was of a smaller magnitude than one would expect due to the opposite responses of electrical resistance and solubility of CO_2 to changing temperature. As temperature increases there was a corresponding decrease in solubility of CO_2 in water and an increase in conductivity. These two effects tended to cancel out each other (Bowman 1968b).

Long term studies with conductivity type CO_2 controllers indicate a drift in calibration with time (Slack 1974). This was due primarily to a decrease in the efficiency of the deionizing resin with time and the accumulation of dust in the solvent system (water) of the controller. Reports with another conductivity CO_2 controller indicated weekly drifts of ± 10 % from the set level but no long term drift (Kimball and Mitchell 1979).

An electrochemical system has been developed for monitoring CO_2 concentrations in fluids or air. The system uses a pH electrode and a Ag-AgCl reference electrode surrounded by a tris(hydroxymethyl)amino-methane buffer. Carbonic anhydrase was added to the buffer solution as a catalyst. The detector and buffer solution was covered with a 3 mil (76.2 um) silastic membrane which was highly permeable to CO_2 (Ryes _et_ al. 1967). The system provides continuous monitoring of CO_2 in air as well as that dissolved in liquids. Response time was observed to be quite rapid with less than 2 seconds required to indicate a 98 % step change in CO_2 concentration.

An alkali solution (NaOH) has been used instead of deionized water. With this approach the electrical conductivity of the solution was measure before and after air from the plant growth facility was bubbled through it.

The sensitivity of the system was observed to be approximately 2 ppm (Bowman 1968). However a large negative temperature coefficient of 2 % of full scale per C was observed. The researcher noted that flow rates of the sensing fluid and gas from the plant growth facility must be maintained constant and that the NAOH solution must be replenished often.

Conclusion

In conclusion one can readily appreciate the complex nature of plant response to varying CO_2 concentrations. The level of PPFD significantly effects plant response to CO_2. It was for this reason that experiments were designed to further illucidate the relationship of CO_2 and PPFD.

In order to maintain adequate control of CO_2 concentrations in the growth rooms it is necessary to have accurate and precise CO_2 monitoring and control equipment. From the literature reviewed it became apparent that a conductimetric analyser/controller system offered a reasonable compromise between ease of construction and level of precision and accuracy necessary for growth room experimentation. For these reasons a conductimetric system was constructed.

MICROPROCESSOR BASED CONDUCTIMETRIC CARBON DIOXIDE ANALYSER/CONTROLLER[1]

1. Received for publication _______________.

2. The inclusion of trade names is for the pupose of clarification and does not constitute an endorsement by the authors.

Abstract

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Additional index words: controlled environment, microcomputer, gas analysis

Abstract: A conductimetric carbon dioxide analyser/controller utilizing a microcomputer was designed, built and tested. A phototransistor was incorporated to distinguish between day and night periods. A proportional control program which varies the duration of the carbon dioxide injection period was written to reduce oscillations around the control concentration. Oscillations were reduced from 6 % to 3.5 %.

Introduction

Pallas (1979) voiced the opinion of many researchers that monitoring of carbon dioxide (CO_2) in controlled environment chambers is essential and control highly desirable if controlled environment studies are to be more meaningful and precise. The most common system used for CO_2 analysis and control has been the infrared gas analyser (IRGA) (Pallas 1979). IRGA's are rather expensive however and require an on-going recalibration program if their accuracy is to be maintained (Bowman 1968). A number of researchers have investigated lower cost alternatives and in particular conductimetric systems (Bowman 1968, Slack and Calvert 1972, Kimbal and Mitchell 1979). Kimbal and Mitchell (1979) improved upon designs of Slack and Calvert (1972) and Bowman (1968) by incorporating a temperature compensating thermistor into the controller circuit. For controlled environment studies this feature may not always be necessary if the CO_2 analyser/controller unit is calibrated at the day temperature of the growth room since there is not likely to be large daytime oscillations in temperature in the growth room (Salisbury 1979). Conductimetric analyser/controllers have been used a conductivity meter/controller to control the CO_2 concentration in the plant growth facility (Bowman 1968, Kimbal and Mitchell 1979). In order to improve the versatility of the controller a small microcomputer was used as the controller in the system described in this article.

A water pump was added to improve the lag and response times of the system in order to make better use of the microcomputer and reduce oscillations in CO_2 concentration due to the control method.

Description

The conductimetric CO_2 analyser/controller can be divided into two basic sub-systems, the sensor sub-system and the analyser/controller sub-system. The sensor sub-system is similar in design to that described by Kimbal and Mitchell (1979). Sensor operation is based on the principle that electrical conductance of deionized water increases with the concentration of ions in the water. The basic operation of the recirculating sensor sub-system is described by Kimball and Mitchell (1979). The sensor described by Kimball and Mitchell (1979) was based on the entrainment of water by rising air bubbles to drive the recirculation system. The current system uses an impeller pump to circulate the water.

The analyser/controller system consists of a Motorola MC6800 microprocessor to:

1. transform conductivity values into CO_2 concentrations
2. determine whether or not additional CO_2 needs to be injected
3. determine the lenght of the injection and wait period required.

A digital LED display of the current CO_2 concentration in the growth facility is displayed. As well, a radiation sensing circuit is incorporated to distinguish between day and night periods.

Construction

The sensor (Figure 3.1) was constructed from readily available materials. The air pump was a small diaphram aquarium pump. Air flow rates were monitored and set at 100 $mL.min^{-1}$ with a Gilmont size 11 rotameter. The bubble column consisted of a 30 cm length of CPVC rigid PVC plastic tubing (12.7 mm ID) filled with 6 mm glass beads to increase the contact area area between the air bubbles and the deionized water. Joints with the PVC tubing were sealed with plastic cement. Fifteen cm of Tygon R3603 (6.4 mm ID) flexible tubing connected their separation chamber to the conductivity cell. A Markson Science Inc. model 1100 conductivity cell was connected to a Markson conductivity meter which provided an analog output to the microcomputer. Water flow rates were monitored and controlled with a flow meter and by adjusting the pumping rate of the impeller pump to a rate of 80 $mL.min^{-1}$ for the system. A Barnstead D8902 ultra-pure demineralizing cartridge equiped with hose fittings was used to remove CO_2 from the water. Water flowed from the bottom to the top of the cartridge to prevent packing of the resin in order to reduce resistance to water flow of the system. After passing through the deionizing column water was returned to the bubble column via a 70 cm length of tygon tubing.

The CO_2 analyser/controller section (Figure 3.2) consists of a HeathKit model ET-3400 microcomputer. The computer is configured with a Motorola MC6800 microprocessor, equipped with a hexidecimal input keypad, six 7-segment LED's, bread-board area, and 0.5K of RAM. A 1K ROM monitor allows the user to enter and debug machine code programs.

A 741 operational amplifier is used for signal conditioning of the conductivity meter output prior to input into an Analog Devices ADC0804 analog/digital (A/D) converter. Digital output from the converter was inputted to the A port of a Motorola MC6821 peripheral interface adapter (PIA) which functions as an interface to the microprocessor. The phototransistor circuit is interfaced through the CA2 input of the PIA. An analog output of the actual CO_2 concentration was provided by the Motorola MC1408L8 digital/analog (D/A) converter to a strip chart recorder. Carbon dioxide control was achieved with a simple on/off solenoid gas valve connected to a compressed CO_2 tank. The input signal to the solenoid was through the CB2 output of the PIA into a mechanical relay switch. The signal to the relay was conditioned by a power transistor (M2N4124).

A short machine language program which occupied less than 500 bytes was stored in the RAM. Input from the A/D was transformed into actual CO_2 concentration with a look-up table in the RAM and displayed on the LED's and outputted to the strip chart via the D/A. The desired control level was entered through the keypad and stored in the RAM. Proportional control was achieved by varying the duration of the on time of the solenoid valve in response to the difference between the set concentration of CO_2 and the actual CO_2 concentration measured in the growth facility by the sensor.

Performance

The CO_2 conductivity sensor was tested at three different flow rates of air and water. Analysis of variance was performed (Table 3.1) to determine the effects of water and air flow rates on the conductivity meter reading. Water flow rate was found to be significant at the 90 % confidence level but the air flow rate which appears to have some effect on meter reading was not significant. An increase in water flow rate from 40 to 80 $mL.min^{-1}$ while air flow rate was maintained at 60 $mL.min^{-1}$ reduced the meter reading by 15 % for a calibrated gas of 47.84 $mmol.m^{-3}$ CO_2. An increase in air flow rate from 60 to 100 $mL.min^{-1}$ with a water flow rate of 40 $mL.min^{-1}$ brought about an increase in the meter reading by 11 % for the same calibrated gas.

A water pump was not initially included in the design of the conductivity sensor. The water flow due to the entrainment of water by the air bubbles was observed to be approximately 5 $mL.min^{-1}$, this gave a response time for a 90 % change in meter reading after a step change in CO_2 concentration from 0 $mmol.m^{-3}$ to 47.84 $mmol.m^{-3}$ of greater than 5 minutes. Response times with the water pump installed varied from 4.5 minutes for a flow rate of 40 $mL.min^{-1}$ to 3 minutes for a flow rate of 80 $mL.min^{-1}$.

The relationship of CO_2 concentration and electrical conductivity can be approximated by a cubic function (Kimbal and Mitchell 1979). When the cubic function, f(CO_2 concentration) = $conductance^3$ + intercept, was fitted to calibration data, an R^2 of 0.89 was observed (Figure 3.3). The sensitivity of the system was calculated from the 1^{st} derivative of the calibration equation at a CO_2 concentration of 47.84 $mmol.m^{-3}$ and observed to be 49.26 $mmolCO_2.m^{-3}.umhos^{-1}$. This gives a sensitivity of 0.0203 $umhos.mmolCO_2^{-1}.m^{-3}$.

Test of the amount of oscillation around a control setting were made with the use of an IRGA. Initial oscillations were observed to be 6 % for a control setting of 26 $mmol.m^{-3}$ for a simple on/off control system in the controller program. When the proportional control subroutine was written into the program oscillations were reduced to 3.5 % for a control setting of 27 $mmol.m^{-3}$.

Conclusion

A conductimetric controller is a practical alternative to IRGA monitoring and control of CO_2 in air. The use of a microcomputer for the controller subsystem enhances the versatility and performance of the controller. Improvements and modifications are easily facilitated as demonstrated by the addition of a simple light sensitive circuit to prevent CO_2 supplementation during the night. The use of a microcomputer enables a degree of 'intelligence' to be incorporated into the controller. The controller can respond to the characteristics of the growth facility and adjust the duration of CO_2 injection when it senses the CO_2 concentration approaching the set concentration. The techniques of programming microcomputers and designing simple circuits using integrated circuits are not above the abilities of the plant researcher and with the decreasing costs of microcomputers and integrated circuits the future of micro-electronics in agricultural research looks promising.

TABLE 3.1

Analysis of Variance for Effects of Water and Air Flow Rates on the Natural Logarithm of Conductivity Meter Reading.

SOURCE	DF	SS	MS	F-VALUE
Model	8	10.402	1.300	6.66*
Water	2	9.203	4.602	23.57*
Air	2	0.8251	0.413	2.11
Water*Air	4	0.3740	0.094	0.48
Error	981	191.517	0.1952	
Total	989	201.919		

*significant at the 90 % confidence level

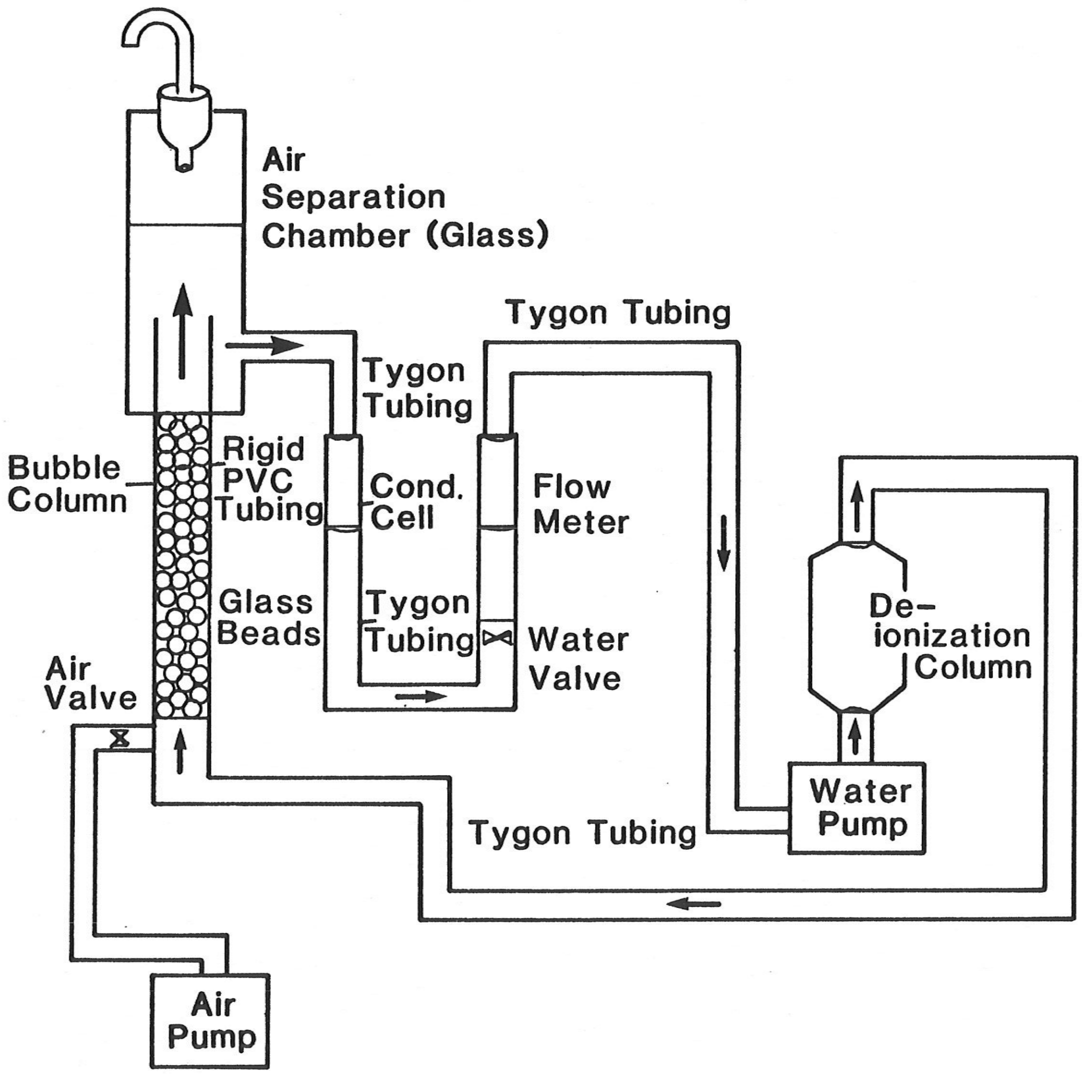

Figure 3.1: Schematic diagram of the conductimetric sensor.

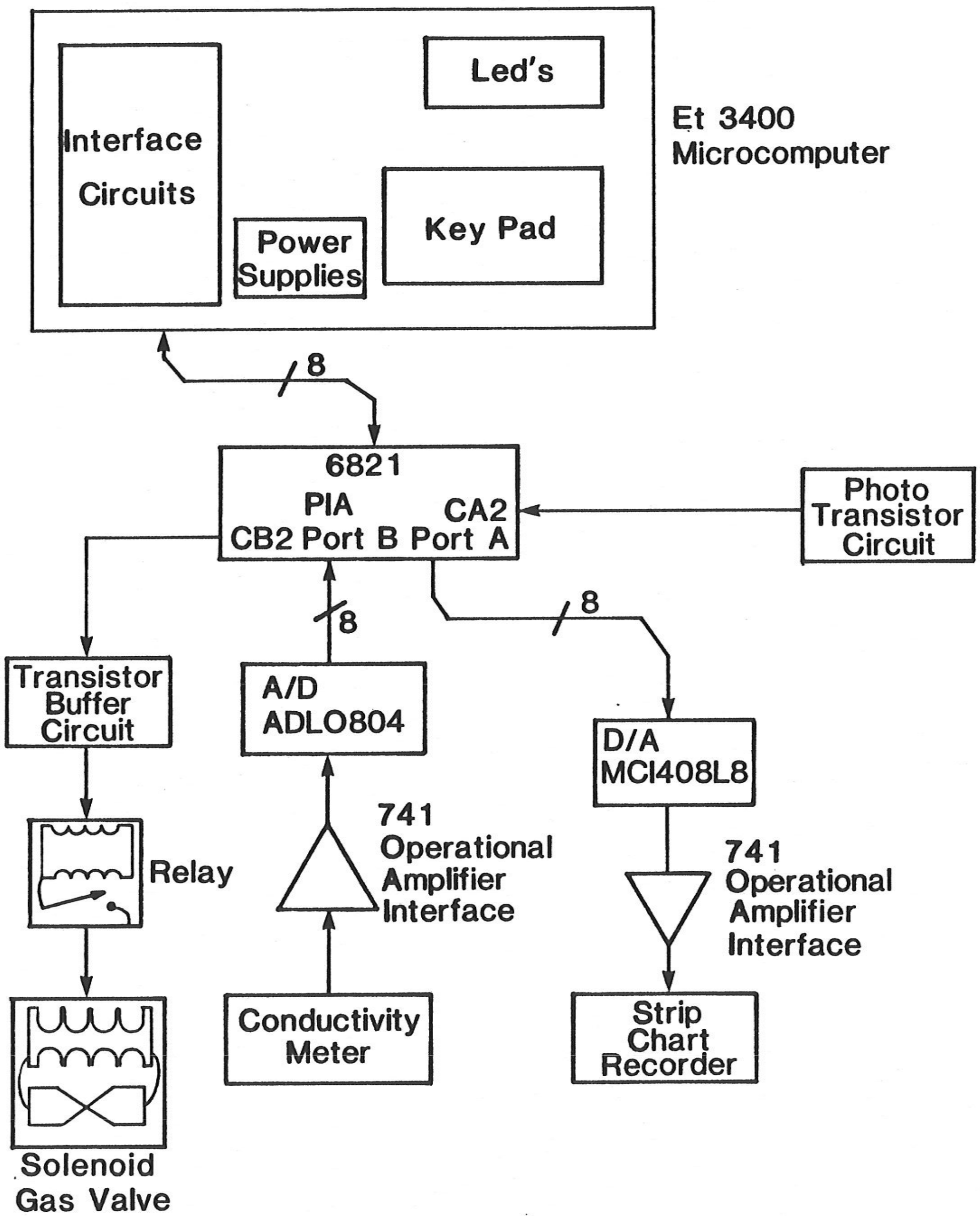

Figure 3.2: Schematic diagram of the microcomputer controller.

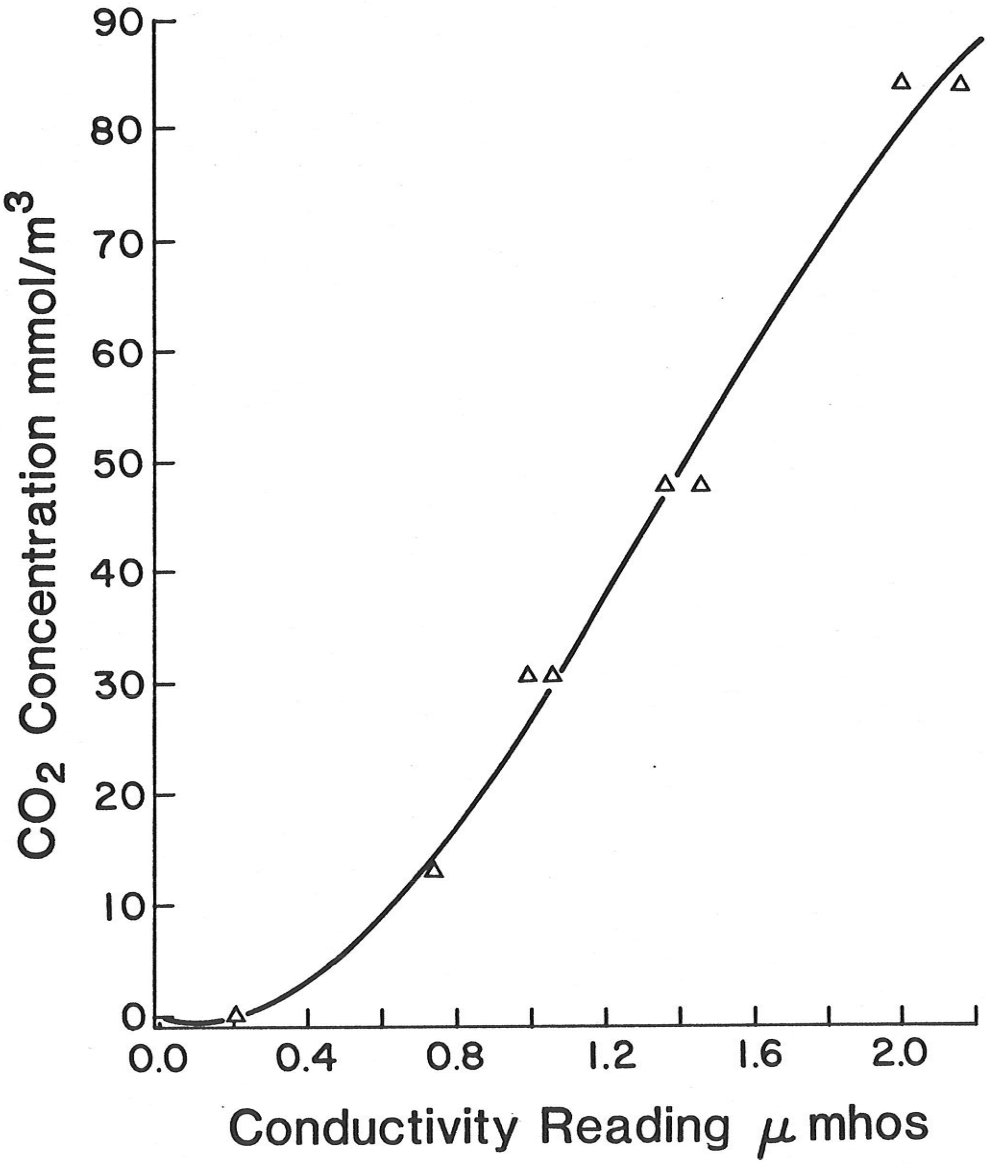

Figure 3.3: Calibration curve for the conductimetric sensor.

EFFECTS OF CARBON DIOXIDE CONCENTRATION AND PHOTOSYNTHETIC PHOTON FLUX DENSITY ON THE EARLY GROWTH OF 'GRAND RAPIDS' LETTUCE.[1]

Footnotes:

1. Received for publication ______________.

2. Conversion values of carbon dioxide concentration into units of $mmol.m^{-3}$ are approximate and are provided to facilitate comparison between different research efforts.

3. The inclusion of trade names is for the purpose of clarification and does not constitute an endorsement by the authors.

4. Custom designed by Dr. E. Brach, Agriculture Canada, Engineering and Statistical Research Institute, Ottawa, Ontario, Canada.

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Abstract

'Grand Rapids' lettuce (Lactuca sativa L.) plants were grown in controlled environment chambers under six photosynthetic photon flux densities (PPFD) (150, 175, 225, 300, 325 $uE.m^{-2}.s^{-1}$) and six carbon dioxide (CO_2) concentrations (14, 25, 33, 38, 42, 44 $mmol.m^{-3}$). Plants were harvested six times at weekly intervals and fresh and dry mass determinations of lettuce top growth were made up to 39 days past emergence. Both CO_2 and PPFD significantly effected lettuce plant fresh and dry mass. Regression analysis indicated larger gains in growth accrue from increases in PPFD than from CO_2 concentration. Even under low PPFD conditions CO_2 concentration increased dry mass by 85 to 93 % and fresh mass by 57 to 68 %. Largest day mass gains of 228 % were recorded for high PPFD and high CO_2 concentration. Hence operators of commercial winter lettuce greenhouses may choose to vary the level of CO_2 supplementation in responses to ambient PPFD as it changes during the progression from winter to spring plants.

Introduction

Much research has been conducted which documents the positive effect of carbon dioxide (CO_2) concentration on lettuce plant growth. Lettuce plants have been grown in atmospheres with supplemental CO_2 concentrations varying from 600 to 6000 ppm (25 to 254 $mmol.m^{-3}$)[2] (Hand 1980, Kim *et* al. 1975). Increases in lettuce mass with supplemental CO_2 have varied from 30 to 460 % (Johnston 1972, Krizek et al. 1974). Several researchers have observed an interrelationship between irradiance (PAR) and CO_2 concentration (Krizek et al. 1974, Frydrych 1981, Heath and Meidner 1967). Heath and Meidner (1967) observed a decline in CO_2 and light compensation points of 'Grand Rapids' lettuce plants exposed to supplemental CO_2.

Ho (1977) observed that rates of carbon fixation were similar in tomato plants (*Lycopersicon esculentum* MILL.) grown in CO_2-enriched and non-enriched greenhouses during low irradiance (photosynthetically active radiation) of the winter. Under high irradiance levels plants in the enriched atmosphere had a 72 to 100 % higher rate of carbon fixation. Ho (1977) observed that leaves of plants in the supplemental CO_2 treatments manifested a less dramatic response to changing radiation levels. The question arises; does an increase in CO_2 concentration partially overcome the effect of low photosynthetic photon flux density (PPFD) on plant growth?

Research has demonstrated that small increases in low irradiance levels correspond to substantial increases in CO_2 concentration in their effects on the rate of photosynthesis (Lee and Whittingham 1974). Hicklenton and Jolliffe (1978) observed a beneficial interaction between CO_2 concentration and radiation level. In an atmosphere supplemented to 1500 ppm (64 mmol.m^{-3}) CO_2 and an illuminance of 5,382 lux similar growth rates occurred in tomato plants as were observed for plants under 16,500 lux and 400 ppm (17 mmol.m^{-3}) CO_2 concentration.

Dullforce (1966) investigated the question of the use of supplemental CO_2 to overcome the effects of reduced irradiance levels in winter greenhouse head lettuce production. Although increases in head masses of 26 % were reported the question could not be fully answered as only two CO_2 concentrations and one irradiance level were used. The authors of this paper have attempted to better clarify the relationship between CO_2 concentration and PPFD in the growth of 'Grand Rapids' lettuce, a leaf lettuce.

Materials and Methods

Three identical walk-in growth rooms were used simultaneously to grow plants under three CO_2 concentrations and two PPFD's. 'Grand Rapids' lettuce plants were grown under 2.4 m x 1.2 m light banks with Sylvania VHO Gro-lux wide-spectrum[3] fluorescent tubes spaced 10.2 cm apart. Plants were grown under six different PPFD's over three experiments. Densities maintained were 150, 175, 225, 275, 300, and 325 uE.m^{-2}.s^{-1}. These values were chosen to approximate PPFD common in Manitoba greenhouses during the winter to spring period. Flux densities were set and monitored with the use of a Licor model LI-185A quantum meter equipped with a quantum sensor. Measurements were made biweekly at the top of the plant canopy. PPFD values were corrected biweekly to the desired level by adjustment of the light canopy. Readings were averaged over the entire fluorescent tube bank. A 16-hour day 8-hour night photoperiod was maintained for all experiments.

Carbon dioxide concentrations in the growth rooms were monitored and maintained with the use of an IRGA controller[4] and a conductimetric controller (Grant and Lacroix 1983). One room was designated as the ambient control concentration for each experiment, no supplemental CO_2 was added and the CO_2 concentration of the air in the room was monitored with a Beckman model 215 IRGA for part of each experiment. Carbon dioxide concentrations maintained were 25, 33, 38, 42 and 44 $mmol.m^{-3}$ with the control room concentration observed to be 14 $mmol.m^{-3}$ for each experiment. Variation of CO_2 control within rooms was approximately $\pm 1-2$ $mmol.m^{-3}$. Supplemental CO_2 was supplied from liquid CO_2 tanks through 9.5 mm Tygon R3603 tubing to the ventilation fans located on the ceiling of the growth room.

Air temperatures were set to 23 ± 0.5 C day and 15 ± 0.5 C night temperature for all growth rooms. Temperatures were determined by the use of a shielded YSI thermistor probe with readings taken at the plant canopy level. No control of humidity was maintained. Relative humidity was observed to fluctuate from 80 % shortly after watering to 50 %

several hours later for one growth room at the end of experiment three. Plants were watered once daily with tap water.

Plants were direct seeded or transplanted into 10.2 cm diameter green plastic pots. Pots were filled with an unsterilized soil mix of 1 soil: 1 peat: 1 sand. Lettuce plants were fertilized twice weekly with 0.9 g of 20-20-20 water soluble fertilizer with trace elements per plant (0.18 g N, 0.08 g P, 0.15 g K). Plants in the first experiment were directly seeded into pots. Plants in the second and third experiments were seeded into a flat and after 5-6 days transplanted into plastic pots in each growth room. Emergence varied from 3-4 days between experiments. Twice weekly, plants were randomly redistributed under the bank of fluorescent tubes to minimize the effects of varying PPFD under different areas of the light source.

In experiment one, five lettuce plants were randomly removed from each treatment every three days for measurement of fresh mass and dry mass of the top growth. In experiments two and three plants were randomly sampled once weekly. Analysis was conducted at intervals of six days for experiment one and weekly intervals for experiments two and three. Plants were grown for 42 to 56 days but only the first 39 days after emergence were used for analysis.

Results and Discussion

Each experiment was analysed separately. Effects of CO_2 concentration and PPFD on dry mass are presented in Table 4.1. Analysis of variance was performed and both CO_2 concentration and PPFD were found to have a highly significant effect on dry mass gain of lettuce plants for all three experiments. The interaction of CO_2 by PPFD was calculated to be significant for two of the three experiments. Comparison of means of the dry mass for 3 experiments at the final harvest indicated an increase in dry mass of the plants with both increasing CO_2 concentration and PPFD (Figure 4.1). For a particular PPFD an increase in CO_2 concentration brought about an increase in dry mass. A trend of increasing RGR with CO_2 concentration was observed but analysis of variance did not indicate a significant effect of CO_2 concentration or PPFD on RGR (Table 4.2). An initial doubling of CO_2 concentration above normal ambient levels (14 $mmol.m^{-3}$) had a more profound effect on increases in dry mass production than a further increase of 11 to 17 $mmol.m^{-3}$ CO_2 (Table 4.3). The trend in dry mass response seemed to indicate an ultimate limiting of increases in dry mass in response to increasing CO_2 concentration indicating a PPFD limiting effect. A similar effect for PPFD was observed. Initial increases in PPFD at normal ambient CO_2 concentrations (14 $mmol.m^{-3}$) had a similar effect on lettuce dry mass production as did increases in PPFD to 40 and 325 $uE.m^{-2}.s^{-1}$ whereas at higher CO_2 concentrations increases in PPFD effected positive increases in dry mass. Hence at higher PPFD, normal CO_2 concentration appears to be limiting dry mass production.

Although analysis of dry mass production is of value in terms of scientific interest, fresh mass production is the primary parameter of interest to a commercial producer of greenhouse lettuce. Therefore, a separate analysis of fresh mass response to CO_2 concentration and PPFD was undertaken. Analysis of variance demonstrated a significant effect of CO_2 concentration on fresh mass production for all three experiments (Table 4.4). The PPFD was not significant nor was the interaction of CO_2 concentration and PPFD. One may wonder though if the effect of PPFD on fresh mass may not be confounded by increases in the transpiration rates with increasing PPFD which would tend to offset any positive effects on fresh mass growth. There is some evidence for this as analysis of variance of the ratio of fresh mass:dry mass indicated a significant effect of PPFD but not for CO_2 concentration (Table 4.5). The growth response, expressed as fresh mass, to increasing CO_2 concentration is similar to that observed for changes in dry mass. Increases in fresh mass are more dramatic for moderate increases in CO_2 concentration above normal ambient than for larger increases in CO_2 concentration (42 $mmol.m^{-3}$) (Table 4.6). A reduction in the rate of increase of fresh mass production was observed for some high CO_2 concentration treatments. Moderate increases in CO_2 concentration to 33 $mmol.m^{-3}$ for most PPFD treatments produced the largest plants (Figure 4.2).

Results concerning the effects of CO_2 concentration on the ratio of fresh mass:dry mass appear to be inconclusive. At some PPFD treatments there was observed a decrease in the ratio and at other flux densities there was an increase in the ratio with increasing CO_2 concentration (Figure 4.3).

A number of linear and quadratic models were studied to quantify the relationship of CO_2 concentration and PPFD on the rates of lettuce growth. For both fresh and dry mass it was calculated that a quadratic model did not significantly improve the fit of the model, therefore a linear model which was significant in both cases was used. A better fit was obtained when fresh and dry masses were transformed into natural logarithms. Improvement in the coefficient of determination (R^2) for fresh mass was from 0.78 to 0.93 when natural logarithm transformed data were used, and from 0.70 to 0.94 for dry mass after data transformation. In order to derive an overall growth constant for each treatment, log transformed data were fitted to the linear model:

$$\text{Ln(Fresh or Dry mass)} = B_0 + B_1 * X$$

where B_0 is the intercept

B_1 is the parameter equivalent to the growth constant

X is the number of days past emergence.

The first derivative was calculated for each modelled treatment in order to derive the overall rate of change in mass of the lettuce plant per unit time. In fact this is just B_1 as B_0 disappears during differentiation. Hence eighteen growth constants were calculated, one for each treatment of the three experiments. Analysis of variance indicated a significant interaction term for dry mass but not for fresh mass. Regression analysis of the response surface did not indicate a significant interaction term with the estimate for the interaction parameter one to two orders of magnitude less than the other parameters of CO_2 and PPFD. Growth constants (G_d) for natural log transformed dry mass were fitted to a linear model by least squares method. The linear model with estimated parameters is:

$$G_d = 0.00244CO_2 + 0.00065PPFD$$

Under low PPFD conditions (150 $uE.m^{-2}.s^{-1}$) the calculated rate of change in lettuce growth attributed to a doubling in CO_2 concentration from normal ambient concentrations (14 $mmol.m^{-3}$) was 2.83 $mg.day^{-1}.mmol(CO_2)^{-1}$ which results in an overall increase in the rate of growth of 39.7 mg(dry mass).day^{-1}. Doubling the PPFD from 150 to 300 $uE.m^{-2}.s^{-1}$ at 14 $mmol.m^{-3}$ CO_2 concentration has an associated rate of change of 0.779 $mg.day^{-1}.(uE\ m^{-2}.s^{-1})^{-1}$ for an overall increase in the rate of growth of 116.8 mg (dry mass).day^{-1}

more than twice the rate increase observed for a doubling of CO_2 concentration. Under moderate PPFD conditions (200 $uE.m^{-2}.s^{-1}$) a further increase in PPFD to 300 $uE\ m^{-2}.s^{-1}$ under normal ambient CO_2 concentrations has an associated rate of change of 0.791 $mg.day^{-1}.(uE.m^{-2}.s^{-1})^{-1}$ for an overall increase in the growth rate of 79.1 mg (dry mass).day^{-1}. Whereas doubling the CO_2 concentration from 14 to 28 $mmol.m^{-3}$ under higher PPFD (300 $uE.m^{-2}.s^{-1}$) conditions has an associated rate of change of 3.12 $mg.day^{-1}.mmolCO_2^{-1}$ for an overall increase in the rate of growth of 43.7 mg (dry mass).day^{-1}. Hence both CO_2 concentration and PPFD have a positive effect on lettuce plant dry mass production but greater benefits appear to accrue from increases in PPFD (Figure 4.4).

The linear model for the response of the fresh mass growth constant (expressed in natural logarithms) with parameter estimates is:

$$G_f = 0.00232\ CO_2 = 0.00064\ PPFD$$

This results in a rate for a doubling of CO_2 concentration from 14 to 28 $mmol.m^{-3}$ CO_2 at low PPFD conditions (150 $uE.m^{-2}.s^{-1}$) of 2.68 $mg.day^{-1}.mmolCO_2^{-1}$ for an overall increase of 37.5 mg (fresh mass) day^{-1}. A comparison of the linear models developed for dry mass and fresh mass indicate that the parameters for both CO_2 concentration and PPFD are quantitatively very similar, hence calculations developed for dry mass response will also apply to the fresh mass apply to the fresh mass response. It would seem therefore that fresh mass response is a reflection of the dry mass response.

Conclusion

Both CO_2 concentration and PPFD positively effect the growth of 'Grand Rapids' lettuce. The effects of PPFD appear to be greater than the effects of CO_2 concentration. However under low PPFD conditions increasing CO_2 concentration has a positive effect on lettuce growth and would appear therefore to compenate somewhat for slow growth under reduced PPFD conditions. The ultimate response of lettuce to increased CO_2 concentration appears to be a function of and is therefore limited by the PPFD environment in which the lettuce plants are grown. A commercial winter greenhouse lettuce produced may wish therefore to adjust CO_2 concentrations in the greenhouse several times during the growing season. As the PPFD increases through the growing period optimum CO_2 concentrations for maximal growth will also increase. During low PPFD conditions (winter) CO_2 concentrations of 33 to 38 mmol $CO_2 \cdot m^{-3}$ may provide optimal growth. Whereas at during higher PPFD conditions (spring), CO_2 concentration of 44 mmol $CO_2 \cdot m^{-3}$ may be more appropriate.

TABLE 4.1

Highlights of Analysis of Variance of Effects of CO_2 Concentration and PPFD on Lettuce Plant Final Dry Mass.

SOURCE	D.F.	MEAN SUM OF SQUARES		
		EXPERIMENT		
		1	2	3
MODEL	10	69.223^{z}	130.480^{z}	219.447^{z}
CO_2 Conc.	2	2.420^{z}	20.857^{z}	41.164^{z}
PPFD	1	2.137^{z}	35.843^{z}	12.279^{z}
CO_2 Conc. * PPFD	2	0.071	2.320^{y}	3.125^{x}
ERROR	169	0.145	0.748	1.349
CORRECTED TOTAL	179			

^{z}significant at the 99 % confidence level
^{y}significant at the 95 % confidence level
^{x}significant at the 90 % confidence level

TABLE 4.2

Highlights of Analysis of Variance of Effects of CO_2 Concentration and PPFD on Relative Growth Rate of Lettuce Plants from emergence to 39 days past emergence.

SOURCE	D.F.	MEAN SUM OF SQUARES		
		EXPERIMENT		
		1	2	3
MODEL	10	0.0518^{z}	0.0348^{z}	0.0489^{z}
Days from Emergence	5	0.0990^{z}	0.0688^{z}	0.0974^{z}
CO_2 Conc.	2	0.0051	0.0007	0.0008
PPFD	1	0.0049	0.0004	0.0001
CO_2 Conc. * PPFD	2	0.0041	0.0000	0.0000
ERROR	25	0.0066	0.0009	0.0010
CORRECTED TOTAL	35			

^{z}significant at the 99 % confidence level.

TABLE 4.3

Effect of CO_2 Concentration and PPFD on Final Dry Mass of Lettuce Plant Tops Harvested 39 Days After Emergence. Values are Expressed as Percent of Ambient CO_2 Concentration Control and Lowest PPFD.

CO_2 CONCENTRATION ($mmol.m^{-3}$)	PPFD ($uE.m^{-2}.s^{-1}$) 150	175	225	275	300	325
14 (Normal)	0	13	66	32	66	56
25	77					141
33			123		199	
38		50		63		
42	68	26		52		188
44			180		245	

TABLE 4.4

Highlights of Analysis of Variance of Effects of CO_2 Concentration and PPFD on Lettuce Plant Fresh Mass.

SOURCE	D.F.	MEAN SUM OF SQUARES		
		EXPERIMENT		
		1	2	3
MODEL	10	9630.869^z	11564.214^z	17816.139^z
CO_2 Conc.	2	416.092^z	1207.979^z	2660.669^z
PPFD	1	50.711	33.056	32.934
CO_2 Conc. * PPFD	2	6.417	100.156^x	69.706
ERROR	169	23.963	35.041	83.533
CORRECTED TOTAL	179			

^{z}significant at the 99 % confidence level
^{y}significant at the 95 % confidence level
^{x}significant at the 90 % confidence level

TABLE 4.5

Highlights of Analysis of Variance of Effects of CO_2 Concentration and PPFD on Ratio Fresh:Dry Lettuce Plant Mass.

SOURCE	D.F.	MEAN SUM OF SQUARES		
		EXPERIMENT		
		1	2	3
MODEL	10	24.227[z]	96.377[z]	101.171[z]
CO_2 Conc.	2	17.679[x]	3.340	3.110
PPFD	1	94.132[z]	608.075[z]	93.794[z]
CO_2 Conc. * PPFD	2	10.166	24.825[z]	11.704
ERROR	169	6.277	1.684	9.065
CORRECTED TOTAL	179			

[z] significant at the 99 % confidence level
[y] significant at the 95 % confidence level
[x] significant at the 90 % confidence level

TABLE 4.6

Effect of CO_2 Concentration and PPFD on Final Fresh Mass of Lettuce Plant Tops Harvested 39 Days After Emergence. Values are Expressed as Percent of Ambient CO_2 Concentration Control and Lowest PPFD.

CO_2 CONCENTRATION ($mmol.m^{-3}$)	PPFD ($uE.m^{-2}.s^{-1}$) 150	175	225	275	300	325
14 (Normal)	0	7	39	2	33	18
25	59					46
33			121		122	
38		42		31		
42	59	28		28		72
44			87		108	

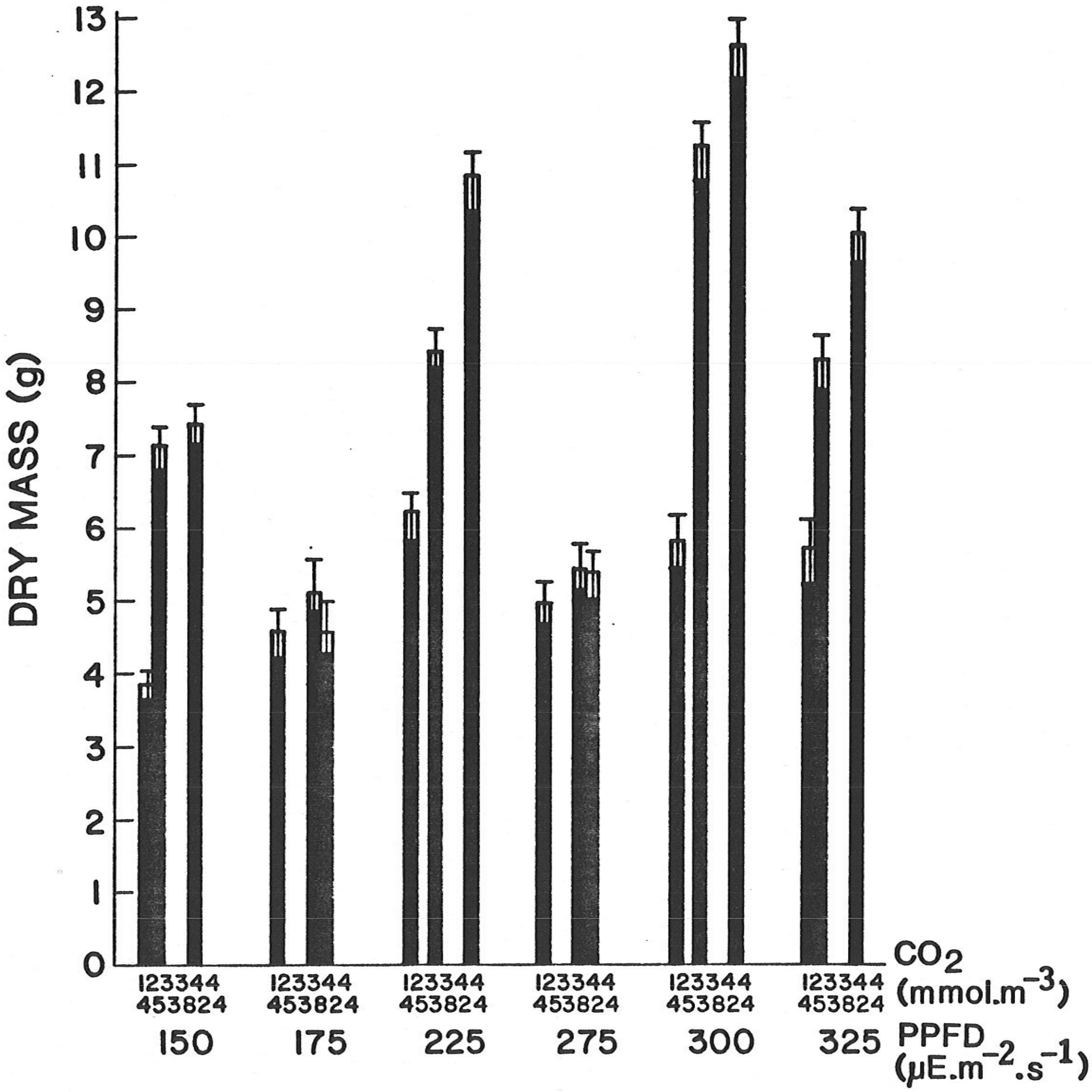

Figure 4.1: Average final dry mass of lettuce plants grown under varying CO2 and PPFD harvested 39 days past emergence. Segments represent 95% confidence limits.

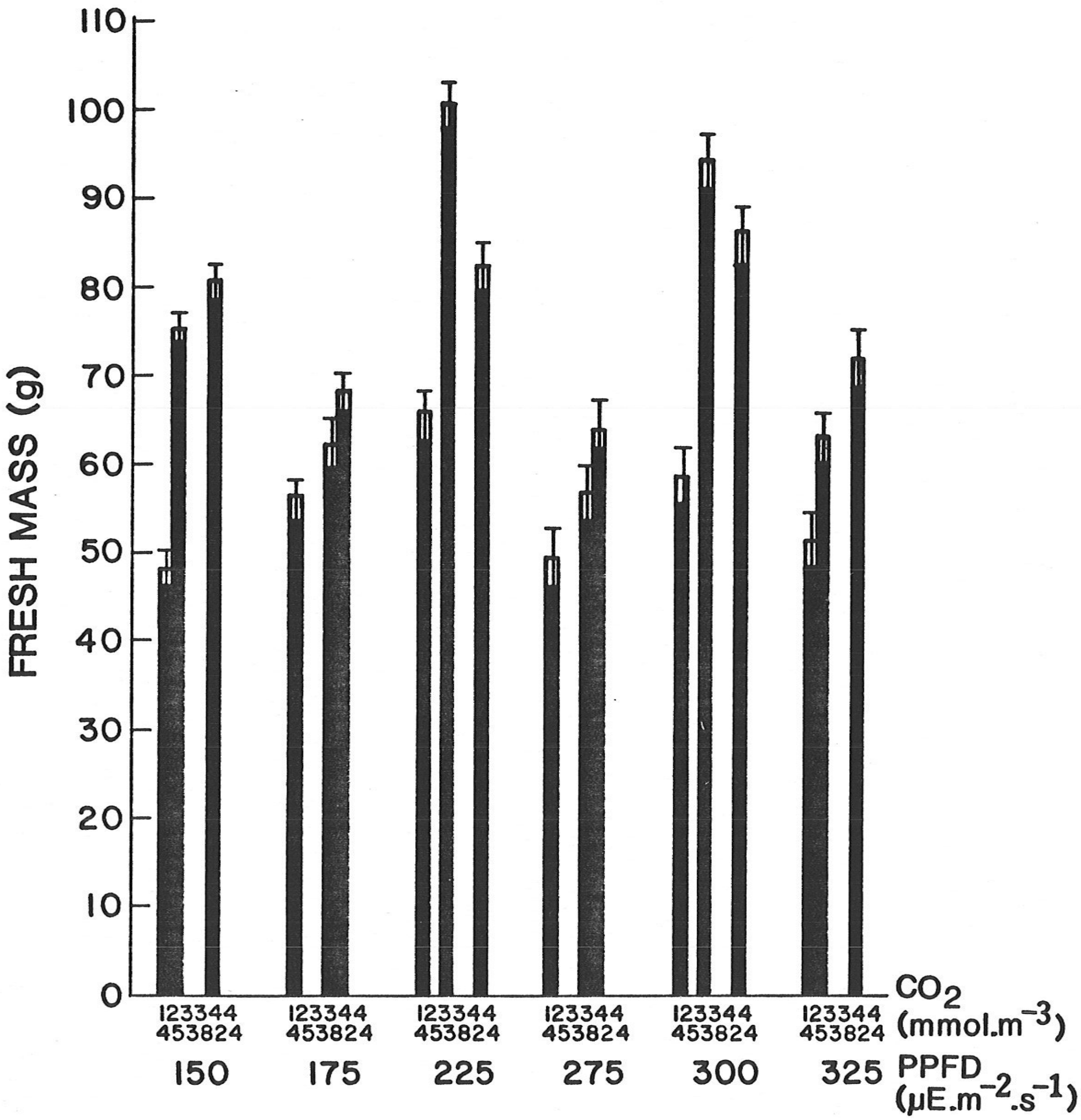

Figure 4.2: Average final fresh mass of lettuce plants grown under varying CO2 concentration and PPFD harvested 39 days past emergence. Segments represent 95% confidence limits.

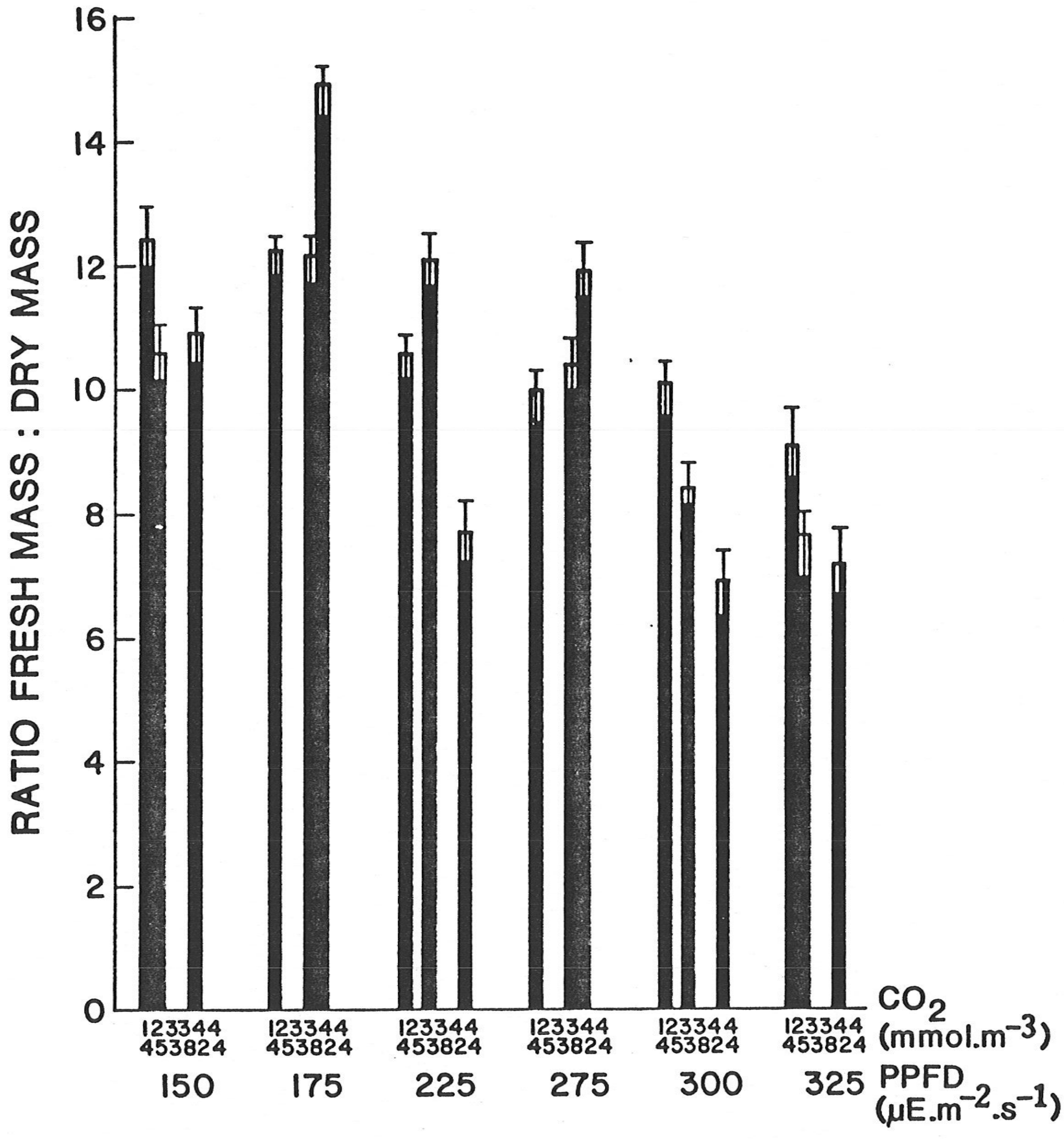

Figure 4.3: Average fresh:dry mass ratio of lettuce plants grown under varying CO2 concentration and PPFD harvested 39 days past emergence. Segments represent 95% confidence limits.

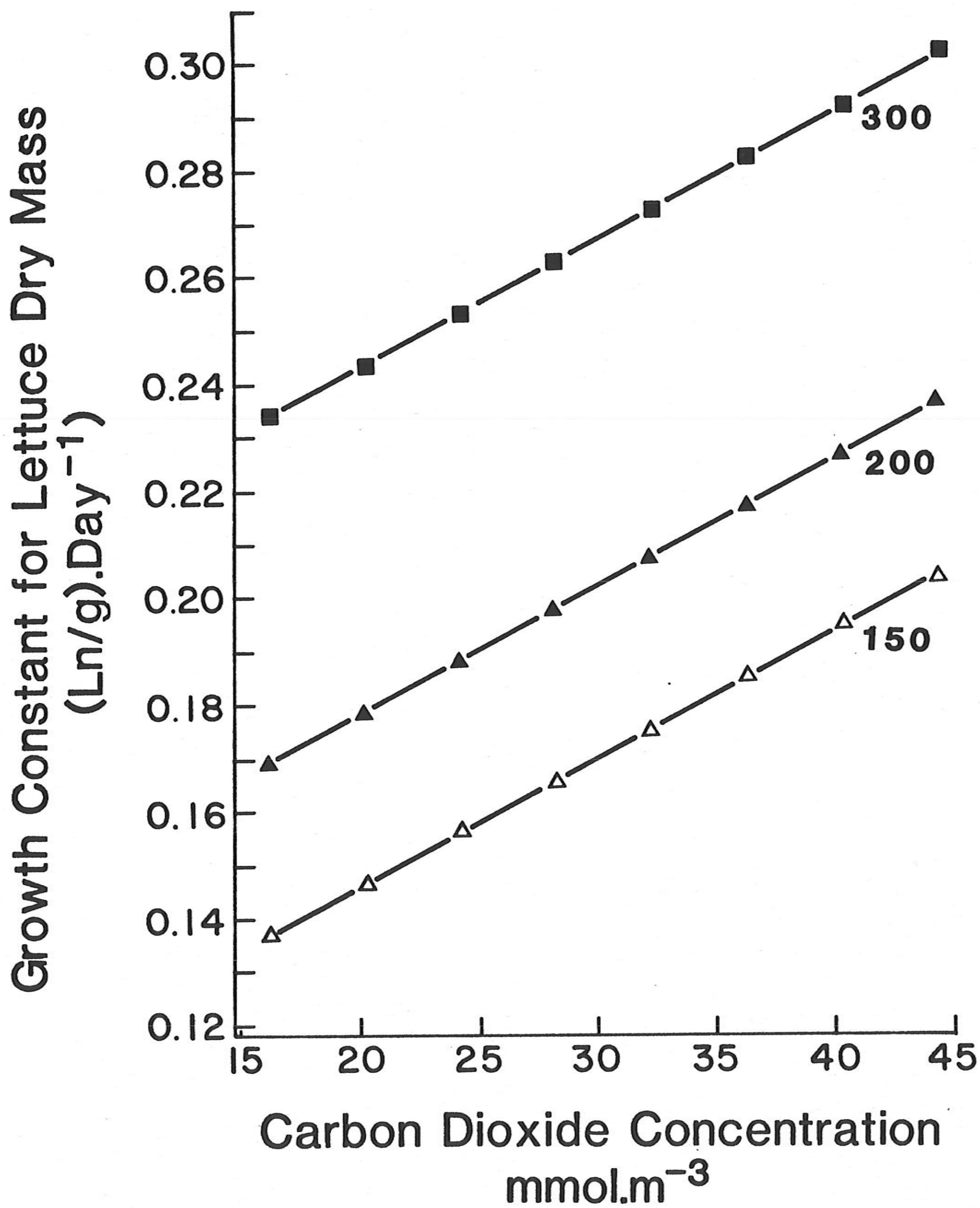

Figure 4.4: Effects of CO_2 concentration on the interpolated growth constant of Ln(dry mass) under varying PPFD (uE.m^{-3}.s^{-1}).

GENERAL DISCUSSION

Two different CO_2 monitoring and control systems were utilized in the author's current research: an IRGA developed at the Agriculture Canada Engineering and Statistical Research Institute, Ottawa, Canada and a conductimetric system developed by the author. The IRGA is a custom built, self-contained CO_2 controller with a digital display indicating current CO_2 concentration of the atmosphere in which the unit is placed. Since the infrared beam and receiver are open to the growth facility atmosphere there is no need for a pump to move air into the sensor. The designer of the equipment stated that the sensitivity of the unit was ± 1 ppm (± 0.0416 mmol $CO_2 . m^{-3}$) at 20 C (Brach 1982). This was not verified by the author. The main advantage of the unit is the low maintenance that it requires. Except for occasionally cleaning the reflecting mirror no maintenance of the unit was required. The unit was observed to have a response time of approximately 1 second.

The conductimetric controller is described in a previous section of this thesis. The sensitivity of the sensor was 49.26 mmol $CO_2 . m^{-3} . umhos^{-1}$. The controller hardware/software was programmed to respond to changes in

CO_2 concentration of 0.42 mmol $CO_2.m^{-3}$. The assembly language program of the controller is included in appendix 1. Accuracy of control was 3.5 % or 0.95 mmol $CO_2.m^{-3}$ at a control concentration of 27 mmol $CO_2.m^{-3}$. It is interesting to note that the minimum standard deviation in dry mass observed for five plants sampled at 39 days past emergence was 0.2843 g. This resulted in a 95 % confidence interval of $\pm$353.0 mg of plant dry mass. The effect of CO_2 concentration on the rate of dry mass production was calculated to be 2.8 $mg.day^{-1}(mmol\ CO_2.m^{-3})^{-1}$ at the lowest PPFD treatment and 3.1 $mg.day^{-1}(mmol\ CO_2.m^{-3})^{-1}$ at the highest PPFD. Hence the magnitude of an increase in CO_2 concentration necessary to produce an effect on lettuce plant grown in these series of experiments larger than the 95 % C.I. was $\pm$3.2 mmol $CO_2.m^{-3}$ at the low PPFD and $\pm$2.9 mmol $CO_2.m^{-3}$ at the high PPFD. Thus the controllers need only be precise to this level as further precision is lost through natural variation in growth of plants within the same sample. Both the IRGA and conductimetric controller were below this level. Although the conductimetric controller is not as precise as the IRGA it will function with the necessary level of precision for control and monitoring of CO_2 concentration in controlled environments and greenhouses. Controller sensitivity varies inversely with response time. Therefore if greater precision is desired, the water flow in the system can be reduced which increases the response time. A reduction in water flow rate increases the contact time between the sampled air and the deionized water which results in a greater movement of CO_2 from the air to the deionized water.

The use of a microprocessor in the controller facilitates these adjustments through modification of the controller software to compensate for a 'fast' or 'sluggish' sensor. The feasibility of measurement of CO_2 flux from individual leaves by the unit has not been determined. The advantage of the conductimetric controller is that it can be readily assembled from inexpensive materials by the plant researcher. The use of a microcomputer as the controller subsystem opens up possibilities for data aquisition interfaces with other computer and data storage systems. Hence two relatively precise CO_2 analyser/controllers were available for experimental work.

Growth data on lettuce plants were collected for eighteen different treatment combinations of CO_2 concentration and PPFD. Growth data of fresh and dry mass is presented in Table B.1. Current work substantiates claims for a positive effect of CO_2 concentration on the growth of 'Grand Rapids' lettuce. Liebig's 'Law of the Minimum' appears to accurately describe the relationship of CO_2 concentration and PPFD on lettuce plant growth. Carbon dioxide and PPFD have interdependent positive effects on plant growth. Hence plants grown in a 150 $uE.m^{-2}.s^{-1}$ environment may significantly benefit from increases in CO_2 concentration and may reflect rates of growth similar to a moderate PPFD (225 $uE.m^{-2}.s^{-1}$) without CO_2 supplementation. It becomes readily apparent however that continued increases in CO_2 concentration have less and less effect on plant growth and will not be able to manifest rates of growth in lettuce plants corresponding to substantial increases in PPFD, i.e., doubling the PPFD. Under high PPFD conditions the effect of increasing CO_2 concentration appears to be linear and does not appear to have reached a saturation point by 44 mmol $CO_2.m^{-3}$ (Figure 5.1). The relationship between CO_2 concentration and PPFD is obviously more complex than a linear relationship even though there is no statistical support for this from analysis of the current data.

There is a noticeable trend for a positive effect of CO_2 concentration and PPFD on the RGR (Table 5.1). Yet there was no observed statistical significance for the factors. This lack of significance may be due to the small magnitude of the changes in RGR observed with the treatment combinations. Dullforce (1966) observed for lettuce plants an initial increase in RGR with days from seeding followed by a decline in RGR as the plants mature and there is more leaf material shaded, reducing the overall efficiency of plant dry matter production. A similar trend was observed in the author's research work. This overall trend may mask the quantitatively less predominant effects of changing CO_2 concentration and PPFD. When compounded over several weeks

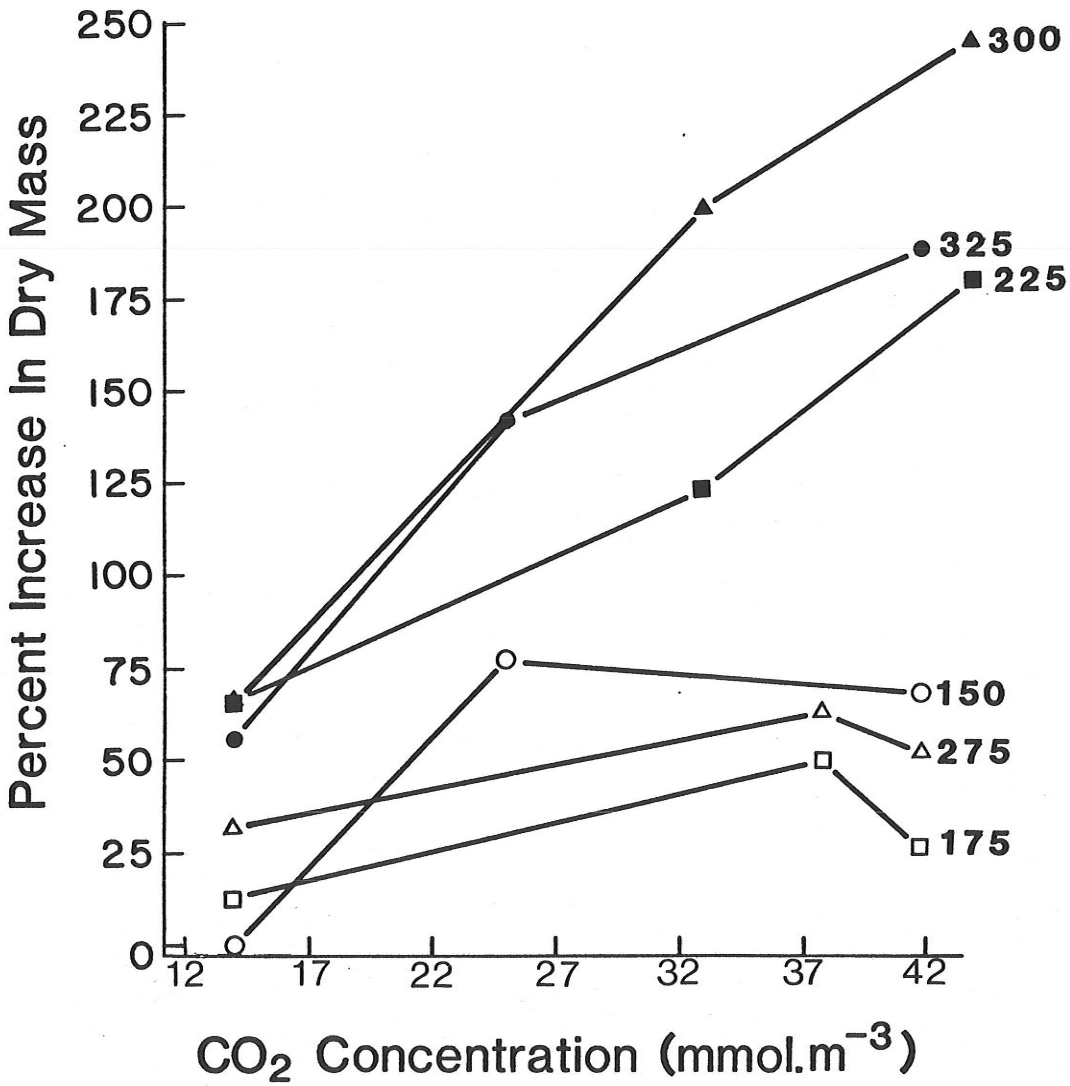

Figure 5.1: Comparison of lettuce plant final dry mass response to changing CO_2 concentration under different values of PPFD ($uE.m^{-2}.s^{-1}$) for three experiments.

of growth the end result is significant differences in plant mass from statistically insignificant changes in RGR.

There appears to be a trend for increasing CO_2 concentration to positively effect the ratio of fresh mass:dry mass, particularly at the mid-range PPFD treatments. The effect may be a result of a reduction in the transpiration rate due to closure of the stomata in response to increasing CO_2 concentration. Jones and Mansfield (1970) observed partial stomatal closure in lettuce plants in response to increasing CO_2 concentration from 330 to 880 ppm (14 to 37 mmol $CO_2 \cdot m^{-3}$). There appears to be an inverse relationship between PPFD and the ratio of fresh: day mass. However, as stated previously the effects of PPFD and CO_2 concentration on the fresh mass:dry mass ratio may have been confounded by increased rates of evapotranspiration with increased radiation intensity under higher PPFD treatments. The possible effects of CO_2 concentration on the fresh mass:dry mass ratio have some interesting implications for the greenhouse lettuce producer. It is lettuce fresh mass which is marketed to consumers. Plants with a high fresh mass:dry mass ratio are more tender and may be more desirable to consumers. As well, increases in the fresh mass:dry mass ratio increase plant fresh mass above increases in plant dry mass production hence larger plants with a higher water content may be produced even under low PPFD conditions.

TABLE 5.1

Mean RGR Values for Lettuce Plants Harvested from 2 to 39 Days Past Emergence.

CO_2 CONCENTRATION ($mmol.m^{-3}$)	PPFD ($uE.m^{-2}.s^{-1}$) 150	175	225	275	300	325
14 (Normal)	0.1942	0.3020	0.2040	0.1943	0.2028	0.2035
25	0.2090					0.2123
33			0.2113		0.2177	
38		0.1941		0.1933		
42	0.2098	0.1933		0.1976		0.2172
44			0.2167		0.2213	

CONCLUSION

Both the IRGA and the conductimetric systems functioned satisfactorily as CO_2 analyser/controllers. It is quite feasible to monitor and control CO_2 concentrations in controlled environment growth facilities to a level of precision necessary for scientific research using low cost equipment.

The custom built 'low cost' IRGA analyser/controller worked well with little maintenance and no repair required.

The conductimetric controller can be readily assembled by a researcher. Through the use of a microcomputer and some simple electronics an intelligent controller can be developed which is capable of responding to the physical characteristics of the growth facility. Further enhancements of the analyser/controller are facilitated through changes in programming and the addition of firmware modules.

Both CO_2 concentration and PPFD were demonstrated to have a positive effect on lettuce plant growth. Under low PPFD conditions there appeared to be a limit to the positive effect of CO_2 concentration on plant growth. Therefore during periods of low PPFD, maximum benefits of CO_2 enrichment will occur at moderate CO_2 concentrations from 25 to 38 mmol. $CO_2 . m^{-3}$. Commercial greenhouse operators must therefore adjust CO_2 concentrations in response to changing light fluxes in the greenhouse. During the winter months when light is limiting (approximated by the 150 $uE.m^{-2}.s^{-1}$ PPFD treatments) CO_2 concentrations of 33 to 38 mmol $CO_2 \cdot m^{-3}$ may be optimal for lettuce plant growth where as in late spring (approximated by the 300 to 325 $uE.m^{-2}.s^{-1}$ PPFD treatments) CO_2 concentrations of 44 mmol $CO_2 \cdot m^{-3}$ may provide optimal growth. Responses reported in this thesis are specific for leaf lettuce, in order to ascertain optimal CO_2 concentration in relation to PPFD for other greenhouse crops research on the specific crop is required.

Although there was no statistical support, there appeared to be a trend for increasing CO_2 concentration to increase the ratio of fresh mass:dry mass of lettuce plants. An increase in the fresh mass:dry mass ratio improved the fresh yield of lettuce plants which would be of economic significance to commercial greenhouse lettuce producers.

Statistical analysis indicated that the relationship of PPFD and CO_2 concentration on lettuce plant growth could be described most appropriately by a linear model. However this ignores the plateau effect of CO_2 concentration at low PPFD's. Therefore it appears that the response of lettuce plants to PPFD and CO_2 concentration are linear until either PPFD or CO_2 concentration become the limiting resource.

RECOMMENDATIONS FOR FURTHER STUDY

The use of 'low cost' IRGA and conductimetric CO_2 analyser/controllers were demonstrated to be feasible for use in controlled environment growth facilities. Possibilities for further work are in the area of commercial implementation. How many sensing points are required per hectare of greenhouse interior to maintain a reasonable level of within house variation of CO_2 concentration? Most growers who use supplemental CO_2 obtain it from the burning of fossil fuels. An area to be investigated therefore is the suitability of these controllers for the regulation of fosil fuel CO_2 generators. How does the duration of the on/off cycle influence the rate of evolution of pollutants and given this what level of precision can be exercised while attempting to minimize pollutant levels?

The current research effort uncovered several avenues for further plant research. The issue of the effects of CO_2 concentration on fresh mass and in particular the water content of the plant as expressed as the fresh mass:dry mass ratiohas not been clarified or resolved. Do increases in CO_2 concentration above 'normal' ambient levels increase the water content of lettuce plants and if so, how is this effected? These questions have some economic significance to commercial producers. A practical area of research would be the feasibility of varying CO_2 concentration to hasten or reduce growth rates to meet market dates for a particular crop cycle. A grower may find it useful to manipulate the CO_2 concentration in a lettuce greenhouse in response to unforeseen changes in climate which may force the crop ahead or behind schedule.

A better description of the CO_2 PPFD interaction is required. Perhaps individual plant studies of short duration with more stringent control of CO_2 concentration and PPFD are in order. This would also allow the possibility of study of any hysteresis effects in lettuce plants in response to changing CO_2 concentration and PPFD. As well, such factors as temperature and vapour pressure deficit need to be incorporated into experiments. Manipulation of the vapour pressure deficit in relation to CO_2 concentration and PPFD offers some interesting possibilities in terms of effects on stomatal closure.

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Appendix A

APPENDIX I. MOTOROLA M6800 ASSEMBLY LANGUAGE PROGRAM FOR CONDUCTIMETRIC CO_2 ANALYSER/CONTROLLER

```
M68SAM IS THE PROPERTY OF MOTOROLA SPD. INC.
   COPYRIGHT 1974 TO 1976 BY MOTOROLA INC

MOTOROLA M6800 CROSS ASSEMBLER, RELEASE 1.3
          MODIFIED IAMC VER: 1.0

 00001                      NAM     CONTROL     NAME OF PROGRAM
 00002      00F7     OFF    EQU     $F7         MASK FOR OFF
VALVE
 00003      0008     ON     EQU     $08         TURNS VALVE ON
 00004      FE20     OUTBYT EQU     $FE20
 00005      FCBC     REDIS  EQU     $FCBC       OUTPUT ROUTINES
TO LED'S
 00006      8000     PIADR  EQU     $8000       PORT A DATA
REGISTER
 00007      8002     PIBDR  EQU     $8002       PORT B DATA
REGISTER
 00008      8001     PIACR  EQU     $8001       PORT A C/S
REGISTER
 00009      8003     PIBCR  EQU     $8003       PORT B C/S
REGISTER
 00010               *
 00011               *
 00012               *      START
 00013 0000                 ORG     $0000
 00014 0000 0001     LEVEL  RMB     1
 00015 0001 D4       CO2HI     FCB    $D4
 00016 0002 19       CO2LOW FCB     $19
 00017 0003 0115     CO2TAB FDB     TAB-$19
 00018 0005 0001     CO2     RMB     1           CO2
CONCENTRATION
 00019 0006 0002     TABTEM RMB     2 TEMP      STORAGE FOR TABLE
ADDRESS
 00020 0008 01E9     TEMPTB FDB     TVAL
 00021               *
 00022               *         INITIALIZE
 00023               *
 00024 000A 4F              CLR A
 00025 000B B7 8001         STA A PIACR         SET PORT A TO
INPUT
 00026 000E B7 8003            STA A PIBCR         SETUP PORT B
TO INPUTS
 00027 0011 B7 8000            STA A PIADR
 00028 0014 B7 8002            STA A PIBDR
 00029               *
 00030 0017 86 06              LDA A #$6        SET   CA1 FOR
INPUT ON
 00031 0019 B7 8001            STA A PIACR      RISING  EDGE
```

```
 00032 001C 86 34                LDA A #$34     SET  CB2 TO
RESPOND AS BIT3
 00033 001E B7 8003              STA A PIBCR    OF  PORT B C/S
REG
 00034                 *
 00035                 *
 00036 0021 BD 004C BEGIN  JSR   COND        BEGIN MAIN
PROGRAMMING LOOP
 00037 0024 BD 0056              JSR   THERM    GET  THERMISTER
VALUE
 00038                 *
 00039                 *
 00040 0027 BD 0060              JSR   TRANS    TRANSFORM  DATA
INTO CO2 CONC.
 00041                 *              AND DEGREES C.
 00042 002A BD FE20              JSR   OUTBYT  DISPLAY  CO2
CONC
 00043 002D 97 05                STA A CO2
 00044 002F 17                   TBA
 00045 0030 BD FE20              JSR   OUTBYT    DISPLAY
TEMPERATURE
 00046                 *
 00047 0033 BD 008D              JSR   CONTRL  REGULATE  CO2
CONCENTRATION
 00048                 *
 00049 0036 B6 8002          LDA A PIBDR      CHECK IF IT IS
NIGHT
 00050 0039 49               ROL A            CHECK IF BIT 7 IS
ON - NIGHT
 00051 003A 24 0B                BCC   MSKIP
 00052 003C B6 8003              LDA A PIBCR   MAKE  SURE
VALVE IS OFF
 00053 003F 84 F7                AND A #OFF
 00054 0041 B7 8003              STA A PIBCR

 00055 0044 BD 0121              JSR   NIGHT    IF  SO DO NOT
ADD ANY CO2
 00056                 *
 00057 0047 BD FCBC MSKIP        JSR   REDIS    RESET  LED'S
 00058 004A 20 D5                BRA   BEGIN    START  THE
PROCESS AGAIN
 00059                 *
 00060                 *
 00061
*****************************************************
 00062                 *
 00063                 *   SUBROUTINE COND
 00064                 *
 00065                 *
```

```
 00066 004C B6 8000 COND   LDA A PIADR     GET CONDUCTIVITY
VALUE
 00067 004F 4D                TST A           WAIT A COUPLE
OF CLOCK CYCLES
 00068 0050 B1 8000           CMP A PIADR   HAS  A/D
STABILIZED ?
 00069 0053 26 F7             BNE   COND    IF   NOT READ
AGAIN
 00070 0055 39                RTS
 00071                *
 00072                *
 00073
****************************************************
 00074                *
 00075                *   SUBROUTINE THERM
 00076                *
 00077 0056 F6 8002 THERM  LDA B PIBDR     READ THERMISTER
VALUE FROM PO
 00078 0059 4D                TST A           WAIT A FEW
CYCLES
 00079 005A F1 8002           CMP B PIBDR   HAS  A/D
STABILIZED ?
 00080 005D 26 F7             BNE   THERM   IF  NOT READ
AGAIN
 00081 005F 39                RTS
 00082                *
 00083                *
 00084
****************************************************
 00085                *
 00086                *   SUBROUTINE TRANS
 00087                *
 00088 0060 81 02   TRANS  CMP A #CO2LOW   IS CO2 CONC. LESS
THAN TABLE
 00089 0062 2D 16             BLT   TRTEM
 00090 0064 81 01             CMP A #CO2HI  IS   CONC. GT
THAN TABLE RANGE
 00091 0066 2E 12             BGT   TRTEM
 00092                *
 00093 0068 CE 0003           LDX   #CO2TAB POINT  TO CO2
LOOK UP TABLE
 00094 006B DF 06             STX   TABTEM
 00095 006D 9B 07             ADD A TABTEM+1      ADD
INCREMENT TO POINTER
 00096 006F 97 07             STA A TABTEM+1
 00097 0071 24 03             BCC   TSKP1   CARRY  OVERFLOW
TO HIGH
 00098 0073 7C 0006           INC   TABTEM  BYTE  OF
ADDRESS
 00099                *
 00100 0076 DE 06   TSKP1     LDX   TABTEM  POINT  TO CO2
VALUE
 00101 0078 A6 00             LDA A ,X
 00102                *
```

```
 00103                  *
 00104 007A CE 0008 TRTEM      LDX   #TEMPTB POINT  TO T
CONVERSION TABLE
 00105 007D DF 06              STX   TABTEM
 00106                  *
 00107 007F DB 07              ADD B TABTEM+1      ADD
INCREMENT TO POINTER
 00108 0081 D7 07              STA B TABTEM+1
 00109 0083 24 03              BCC   TSKP2   ADD  CARRY TO
HIGH ORDER BYTE
 00110 0085 7C 0006            INC   TABTEM
 00111                  *
 00112 0088 DE 06   TSKP2      LDX   TABTEM  POINT  TO
TEMPERATURE VALUE
 00113 008A E6 00              LDA B ,X
 00114 008C 39                 RTS

 00115                  *
 00116                  *
 00117
*****************************************************
 00118                  *
 00119                  *   SUBROUTINE CONTRL
 00120                  *
 00121 008D 96 05   CONTRL LDA A CO2        GET CURRENT CO2
CONC.
 00122 008F 91 00              CMP A LEVEL
 00123 0091 22 1F              BHI   NOCO2      IF HIGHER DO
NOT ADD ANY MORE
 00124                  *
 00125                  *
 00126                  *   GREENHOUSE NEEDS MORE CO2
 00127                  *
 00128 0093 F6 8003            LDA B PIBCR   IS  VALVE ON ?
 00129 0096 C1 08              CMP B #ON
 00130 0098 27 05              BEQ   LVCO2   YES  - DO NOT
TURN VALVE ON
 00131                  *
 00132 009A CA 08              ORA B #ON     NO     - TURN ON
 00133 009C F7 8003            STA B PIBCR
 00134                  *
 00135 009F 8B 0B   LVCO2      ADD A #11     IS     CO2 CONC
WITHIN 10 PPM ?
 00136 00A1 19             DAA              CHANGE VALUE INTO
DECIMAL
 00137 00A2 91 00              CMP A LEVEL
 00138 00A4 22 07              BHI   CLOSE   YES  - LEAVE ON
THEN WAIT
 00139                  *
 00140 00A6 86 0F              LDA A #15     LEAVE  VALVE ON
FOR 30 SECS.
 00141 00A8 BD 0100            JSR   DELAY   THEN  TURN
VALVE OFF
```

```
 00142 00AB 20 12                BRA   CONRTN  THEN  LEAVE
ROUTINE AND CHECK AC
 00143                 *
 00144                 *
 00145 00AD 86 0A   CLOSE        LDA A #10     CLOSE  TO
DESIRED LEVEL
 00146 00AF BD 0100              JSR   DELAY   LEAVE  ON FOR
20 SECS.
 00147                 *
 00148 00B2 F6 8003 NOCO2        LDA B PIBCR   TURN  VALVE OFF
 00149 00B5 C4 F7                AND B #0FF    FOR  1 MINUTE
 00150 00B7 F7 8003              STA B PIBCR
 00151 00BA 86 1E                LDA A #30
 00152 00BC BD 0100              JSR   DELAY
 00153                 *
 00154                 *
 00155                 *
 00156 00BF 39      CONRTN RTS                 LEAVE ROUTINE
 00157                 *
 00158                 *
 00159
*****************************************************
 00160                 *
 00161                 *    SUBROUTINE DELAY
 00162                 *
 00163 0100                   ORG   $0100
 00164 0100 81 01   DELAY        CMP A #1 CHECK  IF DELAY IS
ONLY 1 SEC LONG
 00165 0102 27 17                BEQ   DLAST   IS  SO THEN SET
TIMING ACCORDINGL
 00166                 *
 00167 0104 CE C34F DLP1   LDX   #49999 OUTSIDE  LOOP - 2
SEC MULTIPLES
 00168 0107 01                   NOP
 00169                 *
 00170 0108 08      DLP2   INX                 INNER LOOP - 20
CYCLES LONG
 00171 0109 09                   DEX
 00172 010A 09                   DEX
 00173 010B 01                   NOP
 00174 010C 01                   NOP
 00175 010D 26 F9                BNE   DLP2    REPEAT  UNTIL 1
SEC HAS ELAPSED
 00176                 *
 00177 010F 01                   NOP
 00178 0110 CE C34F              LDX   #49999  USE  UP SOME
MORE CYCLES
 00179 0113 4A                   DEC A
 00180                 *
 00181 0114 81 01                CMP A #1        CHECK FOR
LAST SECOND OF DELA
 00182 0116 22 EC                BHI   DLP1
```

```
 00183 0118 4D                    TST A           CHECK IF LAST
SEC DELAY IS FI
 00184 0119 27 05                 BEQ    DLYFIN  IF   SO THEN
LEAVE DELAY LOOPS
 00185 011B CE C34D DLAST         LDX    #49997  ON   LAST SEC
DELAY READJUST TIMI
 00186 011E 20 E8                 BRA    DLP2     ACCOUNT  FOR
TIME USED TO ENTER AN
 00187                *
 00188 0120 39        DLYFIN RTS                LEAVE ROUTINE
 00189                *
 00190                *
 00191
*****************************************************
 00192                *
 00193                *    SUBROUTINE NIGHT
 00194                *
 00195 0121 01        NIGHT   NOP
 00196 0122 86 96     NLOOP   LDA A #150
 00197 0124 BD 0100           JSR   DELAY
 00198 0127 B6 8002           LDA A PIBDR
 00199 012A 49                ROL A
 00200 012B 25 F5             BCS   NLOOP
 00201 012D 39                RTS
 00202                *
 00203                *
 00204
*****************************************************
 00205                *
 00206                *    LOOK UP TABLES
 00207                *
 00208 012E 19        TAB     FCB
25,26,27,28,29,30,31,32,33,34,35,36,37,
       012F 1A
       0130 1B
       0131 1C
       0132 1D
       0133 1E
       0134 1F
       0135 20
       0136 21
       0137 22
       0138 23
       0139 24
       013A 25
       013B 26
       013C 27
       013D 28
       013E 29
       013F 2A
       0140 2B
 00209 0141 2C                FCB
44,45,46,47,48,49,50,51,52,53,54,55,56,
       0142 2D
```

```
       0143 2E
       0144 2F
       0145 30
       0146 31
       0147 32
       0148 33
       0149 34
       014A 35
       014B 36
       014C 37
       014D 38
       014E 39
       014F 3A
       0150 3B
       0151 3C
       0152 3D
 00210 0153 3F             FCB
63,64,65,66,67,68,69,70,71,72,73,74,75,
       0154 40
       0155 41
       0156 42
       0157 43
       0158 44
       0159 45
       015A 46
       015B 47
       015C 48
       015D 49
       015E 4A
       015F 4B
       0160 4C
       0161 4D
       0162 4E
       0163 4F
       0164 50
       0165 51
 00211 0166 52             FCB
82,83,84,85,86,87,88,89,90,91,92,93,94,
       0167 53
       0168 54
       0169 55
       016A 56
       016B 57
       016C 58
       016D 59
       016E 5A
       016F 5B
       0170 5C
       0171 5D
       0172 5E
       0173 5F
       0174 60
       0175 61
       0176 62
```

```
       0177 63
       0178 64
 00212 0179 65             FCB
101,102,103,104,105,106,107,108,109,110
       017A 66
       017B 67
       017C 68
       017D 69
       017E 6A
       017F 6B
       0180 6C
       0181 6D
       0182 6E
       0183 6F
       0184 70
       0185 71
       0186 72
 00213 0187 73             FCB
115,116,117,118,119,120,121,122,123,124
       0188 74
       0189 75
       018A 76
       018B 77
       018C 78
       018D 79
       018E 7A
       018F 7B
       0190 7C
       0191 7D
       0192 7E
       0193 7F
       0194 80
 00214 0195 81             FCB
129,130,131,132,133,134,135,136,137,138
       0196 82
       0197 83
       0198 84
       0199 85
       019A 86
       019B 87
       019C 88
       019D 89
       019E 8A
       019F 8B
       01A0 8C
       01A1 8D
       01A2 8E
 00215 01A3 8F             FCB
143,144,145,146,147,148,149,150,151,152
       01A4 90
       01A5 91
       01A6 92
       01A7 93
       01A8 94
```

```
       01A9 95
       01AA 96
       01AB 97
       01AC 98
       01AD 99
       01AE 9A
       01AF 9B
       01B0 9C
 00216 01B1 9D              FCB
157,158,159,160,161,162,163,164,165,166
       01B2 9E
       01B3 9F
       01B4 A0
       01B5 A1
       01B6 A2
       01B7 A3
       01B8 A4
       01B9 A5
       01BA A6
       01BB A7
       01BC A8
       01BD A9
       01BE AA
 00217 01BF AB              FCB
171,172,173,174,175,176,177,178,179,180
       01C0 AC
       01C1 AD
       01C2 AE
       01C3 AF
       01C4 B0
       01C5 B1
       01C6 B2
       01C7 B3
       01C8 B4
       01C9 B5
       01CA B6
       01CB B7
       01CC B8
 00218 01CD B9              FCB
185,186,187,188,189,190,191,192,193,194
       01CE BA
       01CF BB
       01D0 BC
       01D1 BD
       01D2 BE
       01D3 BF
       01D4 C0
       01D5 C1
       01D6 C2
       01D7 C3
       01D8 C4
       01D9 C5
       01DA C6
```

```
00219 01DB C7               FCB
199,200,201,202,203,204,205,206,207,208
      01DC C8
      01DD C9
      01DE CA
      01DF CB
      01E0 CC
      01E1 CD
      01E2 CE
      01E3 CF
      01E4 D0
      01E5 D1
      01E6 D2
      01E7 D3
      01E8 D4
00220 01E9 01        TVAL   FCB
1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,
      01EA 02
      01EB 03
      01EC 04
      01ED 05
      01EE 06
      01EF 07
      01F0 08
      01F1 09
      01F2 0A
      01F3 0B
      01F4 0C
      01F5 0D
      01F6 0E
      01F7 0F
      01F8 10
      01F9 11
      01FA 12
00221 01FB 13               FCB
19,20,21,22,23,24,25,26,27,28,29,30,31,
      01FC 14
      01FD 15
      01FE 16
      01FF 17
      0200 18
      0201 19
      0202 1A
      0203 1B
      0204 1C
      0205 1D
      0206 1E
      0207 1F
      0208 20
      0209 21
00222 020A 22               FCB
34,35,36,37,38,39,40,41,42,43,44,45,46
      020B 23
      020C 24
```

```
        020D 25
        020E 26
        020F 27
        0210 28
        0211 29
        0212 2A
        0213 2B
        0214 2C
        0215 2D
        0216 2E
 00223               *
 00224               *
 00225
**************************************************
 00226               *
 00227                          END
```

SYMBOL TABLE

```
 OFF     00F7  ON      0008  OUTBYT FE20  REDIS  FCBC  PIADR
8000
 PIBDR   8002  PIACR   8001  PIBCR  8003  LEVEL  0000  CO2HI
0001
 CO2LOW  0002  CO2TAB  0003  CO2    0005  TABTEM 0006  TEMPTB
0008
 BEGIN   0021  MSKIP   0047  COND   004C  THERM  0056  TRANS
0060
 TSKP1   0076  TRTEM   007A  TSKP2  0088  CONTRL 008D  LVCO2
009F
 CLOSE   00AD  NOCO2   00B2  CONRTN 00BF  DELAY  0100  DLP1
0104
 DLP2    0108  DLAST   011B  DLYFIN 0120  NIGHT  0121  NLOOP
0122
 TAB     012E  TVAL    01E9
```

Appendix B

TABLE B.1. GROWTH DATA FOR LETTUCE PLANT TOP GROWTH UNDER EIGHTEEN TREATMENT COMBINATIONS OF CO_2 AND PPFD FOR THREE EXPERIMENTS

OBS.	DAYS FROM SEEDING	DAYS FROM EMERGENCE	EXP.	CO_2 CONC.	PPFD	FRESH MASS	DRY MASS
1	6	2	1	14	175	0.0158	0.0013
2	6	2	1	14	175	0.0190	0.0015
3	6	2	1	14	175	0.0137	0.0011
4	6	2	1	14	175	0.0165	0.0014
5	6	2	1	14	175	0.0180	0.0015
6	6	2	1	14	275	0.0145	0.0015
7	6	2	1	14	275	0.0180	0.0019
8	6	2	1	14	275	0.0184	0.0017
9	6	2	1	14	275	0.0148	0.0014
10	6	2	1	14	275	0.0173	0.0015
11	6	2	1	33	175	0.0174	0.0009
12	6	2	1	33	175	0.0211	0.0013
13	6	2	1	33	175	0.0280	0.0021
14	6	2	1	33	175	0.0249	0.0016
15	6	2	1	33	175	0.0113	0.0009
16	6	2	1	33	275	0.0136	0.0006
17	6	2	1	33	275	0.0139	0.0008
18	6	2	1	33	275	0.0125	0.0007
19	6	2	1	33	275	0.0163	0.0005
20	6	2	1	33	275	0.0150	0.0010
21	6	2	1	42	175	0.0164	0.0013
22	6	2	1	42	175	0.0181	0.0014
23	6	2	1	42	175	0.0301	0.0021
24	6	2	1	42	175	0.0140	0.0010
25	6	2	1	42	175	0.0314	0.0024
26	6	2	1	42	275	0.0312	0.0026
27	6	2	1	42	275	0.0203	0.0019
28	6	2	1	42	275	0.0229	0.0022
29	6	2	1	42	275	0.0221	0.0022
30	6	2	1	42	275	0.0183	0.0017
31	13	9	1	14	175	0.1220	0.0083
32	13	9	1	14	175	0.1413	0.0109
33	13	9	1	14	175	0.1183	0.0081
34	13	9	1	14	175	0.0884	0.0071
35	13	9	1	14	175	0.1012	0.0074
36	13	9	1	14	275	0.1681	0.0140
37	13	9	1	14	275	0.1251	0.0114
38	13	9	1	14	275	0.0766	0.0071
39	13	9	1	14	275	0.0560	0.0061
40	13	9	1	14	275	0.0989	0.0086
41	13	9	1	33	175	0.1015	0.0085
42	13	9	1	33	175	0.1341	0.0112
43	13	9	1	33	175	0.1364	0.0113
44	13	9	1	33	175	0.1424	0.0127
45	13	9	1	33	175	0.0744	0.0077
46	13	9	1	33	275	0.1094	0.0105
47	13	9	1	33	275	0.0752	0.0083
48	13	9	1	33	275	0.1147	0.0113
49	13	9	1	33	275	0.0718	0.0075
50	13	9	1	33	275	0.0978	0.0098
51	13	9	1	42	175	0.1264	0.0076

OBS.	DAYS FROM SEEDING	DAYS FROM EMERGENCE	EXP.	CO_2 CONC.	PPFD	FRESH MASS	DRY MASS
52	13	9	1	42	175	0.1216	0.0073
53	13	9	1	42	175	0.1319	0.0079
54	13	9	1	42	175	0.1243	0.0076
55	13	9	1	42	175	0.1281	0.0074
56	13	9	1	42	275	0.1436	0.0125
57	13	9	1	42	275	0.1336	0.0054
58	13	9	1	42	275	0.1460	0.0096
59	13	9	1	42	275	0.1581	0.0105
60	13	9	1	42	275	0.1160	0.0081
61	19	15	1	14	175	0.7102	0.0495
62	19	15	1	14	175	1.0970	0.0736
63	19	15	1	14	175	0.9182	0.0585
64	19	15	1	14	175	1.0060	0.0716
65	19	15	1	14	175	0.6991	0.0507
66	19	15	1	14	275	1.3410	0.1024
67	19	15	1	14	275	1.1470	0.0952
68	19	15	1	14	275	1.0270	0.0803
69	19	15	1	14	275	1.2610	0.0977
70	19	15	1	14	275	0.9139	0.0723
71	19	15	1	33	175	1.3720	0.1014
72	19	15	1	33	175	1.0780	0.0765
73	19	15	1	33	175	2.1110	0.1513
74	19	15	1	33	175	1.0890	0.0757
75	19	15	1	33	175	0.8851	0.0666
76	19	15	1	33	275	1.8700	0.1503
77	19	15	1	33	275	0.8627	0.0744
78	19	15	1	33	275	1.9040	0.1594
79	19	15	1	33	275	1.3010	0.1100
80	19	15	1	33	275	0.9262	0.0796
81	19	15	1	42	175	1.2430	0.0918
82	19	15	1	42	175	0.8196	0.0639
83	19	15	1	42	175	1.4120	0.1076
84	19	15	1	42	175	1.1250	0.0835
85	19	15	1	42	175	0.8284	0.0636
86	19	15	1	42	275	0.7204	0.0599
87	19	15	1	42	275	0.8948	0.0765
88	19	15	1	42	275	0.8081	0.0655
89	19	15	1	42	275	0.8591	0.0699
90	19	15	1	42	275	1.4050	0.1103
91	25	21	1	14	175	6.5190	0.4488
92	25	21	1	14	175	5.5920	0.4009
93	25	21	1	14	175	3.8510	0.2394
94	25	21	1	14	175	5.6060	0.3873
95	25	21	1	14	175	4.8950	0.3309
96	25	21	1	14	275	8.0160	0.6943
97	25	21	1	14	275	6.2050	0.5201
98	25	21	1	14	275	6.5120	0.5304
99	25	21	1	14	275	7.7410	0.6334
100	25	21	1	14	275	8.2700	0.6675
101	25	21	1	33	175	8.8560	0.6794
102	25	21	1	33	175	12.1790	0.8317

OBS.	DAYS FROM SEEDING	DAYS FROM EMERGENCE	EXP.	CO_2 CONC.	PPFD	FRESH MASS	DRY MASS
103	25	21	1	33	175	12.3350	0.8237
104	25	21	1	33	175	11.0070	0.7342
105	25	21	1	33	175	12.2070	0.6718
106	25	21	1	33	275	8.9630	0.7083
107	25	21	1	33	275	9.6260	0.7503
108	25	21	1	33	275	11.6200	0.9276
109	25	21	1	33	275	10.3480	0.8091
110	25	21	1	33	275	8.6730	0.7062
111	25	21	1	42	175	6.8434	0.5205
112	25	21	1	42	175	5.8510	0.4328
113	25	21	1	42	175	8.757	0.6333
114	25	21	1	42	175	6.465	0.4634
115	25	21	1	42	175	7.308	0.5532
116	25	21	1	42	275	10.304	0.8456
117	25	21	1	42	275	7.744	0.6417
118	25	21	1	42	275	9.634	0.7746
119	25	21	1	42	275	9.726	0.7822
120	25	21	1	42	275	10.581	0.7939
121	31	27	1	14	175	16.230	1.1930
122	31	27	1	14	175	12.510	0.9767
123	31	27	1	14	175	17.370	1.3230
124	31	27	1	14	175	12.280	0.8317
125	31	27	1	14	175	13.050	0.9021
126	31	27	1	14	275	17.120	1.4770
127	31	27	1	14	275	18.610	1.4800
128	31	27	1	14	275	17.380	1.3860
129	31	27	1	14	275	13.540	1.1300
130	31	27	1	14	275	17.640	1.4460
131	31	27	1	33	175	25.110	1.5980
132	31	27	1	33	175	22.430	1.3750
133	31	27	1	33	175	25.800	1.8300
134	31	27	1	33	175	28.120	2.1260
135	31	27	1	33	175	32.470	2.3910
136	31	27	1	33	275	27.400	2.1650
137	31	27	1	33	275	24.820	1.8630
138	31	27	1	33	275	21.830	1.8380
139	31	27	1	33	275	26.630	1.8670
140	31	27	1	33	275	22.550	2.3660
141	31	27	1	42	175	17.790	1.3760
142	31	27	1	42	175	15.960	1.2630
143	31	27	1	42	175	13.220	1.1330
144	31	27	1	42	175	19.870	1.3560
145	31	27	1	42	175	17.780	1.3570
146	31	27	1	42	275	21.180	1.5950
147	31	27	1	42	275	17.880	1.4050
148	31	27	1	42	275	20.220	1.6540
149	31	27	1	42	275	23.030	1.8800
150	31	27	1	42	275	21.710	1.6230
151	37	33	1	14	175	38.100	2.7080
152	37	33	1	14	175	38.000	2.7820
153	37	33	1	14	175	38.860	3.1360

OBS.	DAYS FROM SEEDING	DAYS FROM EMERGENCE	EXP.	CO_2 CONC.	PPFD	FRESH MASS	DRY MASS
154	37	33	1	14	175	34.850	2.6090
155	37	33	1	14	175	30.950	2.4710
156	37	33	1	14	275	31.330	3.5090
157	37	33	1	14	275	35.240	2.8700
158	37	33	1	14	275	35.270	3.1170
159	37	33	1	14	275	31.140	2.9970
160	37	33	1	14	275	34.710	3.4540
161	37	33	1	33	175	50.520	3.9260
162	37	33	1	33	175	52.890	3.8950
163	37	33	1	33	175	55.890	4.2830
164	37	33	1	33	175	42.000	3.6740
165	37	33	1	33	175	43.790	3.5640
166	37	33	1	33	275	49.610	4.5210
167	37	33	1	33	275	53.150	4.6570
168	37	33	1	33	275	47.660	5.9180
169	37	33	1	33	275	47.7300	3.1620
170	37	33	1	33	275	35.4500	3.3910
171	37	33	1	42	175	38.4000	3.0790
172	37	33	1	42	175	43.5200	3.7190
173	37	33	1	42	175	46.6800	3.4290
174	37	33	1	42	175	44.2700	3.3910
175	37	33	1	42	175	40.1700	2.9060
176	37	33	1	42	275	41.3500	4.1040
177	37	33	1	42	275	43.2300	4.2910
178	37	33	1	42	275	38.1600	3.7300
179	37	33	1	42	275	41.7900	3.7000
180	37	33	1	42	275	40.0000	3.7570
181	43	39	1	14	175	63.0200	4.8950
182	43	39	1	14	175	67.0600	5.0340
183	43	39	1	14	175	44.3300	3.9750
184	43	39	1	14	175	47.8800	4.1400
185	43	39	1	14	175	60.5200	4.8660
186	43	39	1	14	275	52.3600	5.1760
187	43	39	1	14	275	51.5000	5.2010
188	43	39	1	14	275	43.4400	4.5150
189	43	39	1	14	275	56.3100	5.7190
190	43	39	1	14	275	43.6500	4.1810
191	43	39	1	33	175	55.5900	4.7180
192	43	39	1	33	175	76.3600	5.2920
193	43	39	1	33	175	66.6500	5.6930
194	43	39	1	33	175	57.3900	5.0180
195	43	39	1	33	175	55.9300	4.8920
196	43	39	1	33	275	43.4300	4.3360
197	43	39	1	33	275	45.6000	4.4820
198	43	39	1	33	275	61.1600	5.4160
199	43	39	1	33	275	66.4500	6.4830
200	43	39	1	33	275	67.3200	6.5420
201	43	39	1	42	175	76.2300	5.1440
202	43	39	1	42	175	66.5000	4.1910
203	43	39	1	42	175	59.1700	4.3170
204	43	39	1	42	175	68.4800	4.4710

OBS.	DAYS FROM SEEDING	DAYS FROM EMERGENCE	EXP.	CO_2 CONC.	PPFD	FRESH MASS	DRY MASS
205	43	39	1	42	175	71.3300	4.8070
206	43	39	1	42	275	61.5200	5.5420
207	43	39	1	42	275	72.9800	5.5370
208	43	39	1	42	275	63.4300	5.1310
209	43	39	1	42	275	54.2500	5.7400
210	43	39	1	42	275	68.3000	5.0890
211	7	4	2	14	150	0.0149	0.0015
212	7	4	2	14	150	0.0292	0.0026
213	7	4	2	14	150	0.0265	0.0024
214	7	4	2	14	150	0.0172	0.0015
215	7	4	2	14	150	0.0200	0.0019
216	7	4	2	14	325	0.0237	0.0025
217	7	4	2	14	325	0.0310	0.0029
218	7	4	2	14	325	0.0245	0.0022
219	7	4	2	14	325	0.0258	0.0023
220	7	4	2	14	325	0.0313	0.0034
221	7	4	2	25	150	0.0301	0.0025
222	7	4	2	25	150	0.0209	0.0017
223	7	4	2	25	150	0.0244	0.0020
224	7	4	2	25	150	0.0263	0.0023
225	7	4	2	25	150	0.0284	0.0024
226	7	4	2	25	325	0.0266	0.0029
227	7	4	2	25	325	0.0277	0.0031
228	7	4	2	25	325	0.0263	0.0031
229	7	4	2	25	325	0.0245	0.0027
230	7	4	2	25	325	0.0213	0.0023
231	7	4	2	37	150	0.0162	0.0010
232	7	4	2	37	150	0.0233	0.0015
233	7	4	2	37	150	0.0270	0.0018
234	7	4	2	37	150	0.0249	0.0017
235	7	4	2	37	150	0.0202	0.0019
236	7	4	2	37	325	0.0177	0.0019
237	7	4	2	37	325	0.0170	0.0018
238	7	4	2	37	325	0.0167	0.0015
239	7	4	2	37	325	0.0304	0.0030
240	7	4	2	37	325	0.0256	0.0035
241	14	11	2	14	150	0.2475	0.0185
242	14	11	2	14	150	0.1354	0.0105
243	14	11	2	14	150	0.1564	0.0123
244	14	11	2	14	150	0.1554	0.0113
245	14	11	2	14	150	0.1563	0.0111
246	14	11	2	14	325	0.3225	0.0285
247	14	11	2	14	325	0.2597	0.0232
248	14	11	2	14	325	0.2237	0.0214
249	14	11	2	14	325	0.2332	0.0206
250	14	11	2	14	325	0.2632	0.0231
251	14	11	2	25	150	0.2320	0.0157
252	14	11	2	25	150	0.2339	0.0158
253	14	11	2	25	150	0.1263	0.0091
254	14	11	2	25	150	0.2122	0.0147
255	14	11	2	25	150	0.2455	0.0181

OBS.	DAYS FROM SEEDING	DAYS FROM EMERGENCE	EXP.	CO_2 CONC.	PPFD	FRESH MASS	DRY MASS
256	14	11	2	25	325	0.1727	0.0156
257	14	11	2	25	325	0.2863	0.0241
258	14	11	2	25	325	0.3836	0.0317
259	14	11	2	25	325	0.1606	0.0132
260	14	11	2	25	325	0.1549	0.0143
261	14	11	2	37	150	0.2088	0.0146
262	14	11	2	37	150	0.1708	0.0114
263	14	11	2	37	150	0.1617	0.0116
264	14	11	2	37	150	0.1927	0.0149
265	14	11	2	37	150	0.1633	0.0118
266	14	11	2	37	325	0.1753	0.0169
267	14	11	2	37	325	0.2370	0.0221
268	14	11	2	37	325	0.3172	0.0290
269	14	11	2	37	325	0.2739	0.0248
270	14	11	2	37	325	0.3332	0.0310
271	21	18	2	14	150	1.4980	0.1188
272	21	18	2	14	150	1.5400	0.1028
273	21	18	2	14	150	1.3840	0.0983
274	21	18	2	14	150	1.7390	0.1197
275	21	18	2	14	150	1.3040	0.0926
276	21	18	2	14	325	2.5300	0.1981
277	21	18	2	14	325	3.4760	0.2854
278	21	18	2	14	325	1.8300	0.1414
279	21	18	2	14	325	2.1450	0.1791
280	21	18	2	14	325	3.3420	0.2584
281	21	18	2	25	150	2.174	0.1379
282	21	18	2	25	150	3.180	0.2198
283	21	18	2	25	150	2.419	0.1398
284	21	18	2	25	150	1.672	0.1146
285	21	18	2	25	150	2.455	0.1545
286	21	18	2	25	325	3.789	0.3234
287	21	18	2	25	325	3.600	0.3006
288	21	18	2	25	325	4.560	0.3846
289	21	18	2	25	325	3.428	0.2913
290	21	18	2	25	325	4.907	0.3977
291	21	18	2	37	150	2.004	0.1340
292	21	18	2	37	150	1.777	0.1227
293	21	18	2	37	150	1.955	0.1292
294	21	18	2	37	150	1.777	0.1269
295	21	18	2	37	150	1.698	0.1151
296	21	18	2	37	325	2.621	0.2323
297	21	18	2	37	325	4.845	0.4485
298	21	18	2	37	325	2.858	0.2423
299	21	18	2	37	325	4.659	0.4183
300	21	18	2	37	325	7.149	0.5854
301	28	25	2	14	150	11.740	0.8401
302	28	25	2	14	150	6.458	0.4628
303	28	25	2	14	150	9.591	0.7032
304	28	25	2	14	150	9.690	0.6867
305	28	25	2	14	150	5.657	0.4216
306	28	25	2	14	325	11.820	1.1030

OBS.	DAYS FROM SEEDING	DAYS FROM EMERGENCE	EXP.	CO_2 CONC.	PPFD	FRESH MASS	DRY MASS
307	28	25	2	14	325	15.630	1.3930
308	28	25	2	14	325	13.680	1.2230
309	28	25	2	14	325	16.000	1.2970
310	28	25	2	14	325	16.500	1.4480
311	28	25	2	25	150	16.990	1.1350
312	28	25	2	25	150	6.888	0.5054
313	28	25	2	25	150	12.610	0.8736
314	28	25	2	25	150	17.390	1.0590
315	28	25	2	25	150	17.050	1.1880
316	28	25	2	25	325	20.620	2.0530
317	28	25	2	25	325	20.010	1.8930
318	28	25	2	25	325	21.380	2.1320
319	28	25	2	25	325	27.600	2.3400
320	28	25	2	25	325	16.310	1.4530
321	28	25	2	37	150	15.710	1.0240
322	28	25	2	37	150	14.320	0.9672
323	28	25	2	37	150	9.892	0.6395
324	28	25	2	37	150	17.470	1.1939
325	28	25	2	37	150	8.070	0.5206
326	28	25	2	37	325	23.790	2.2450
327	28	25	2	37	325	23.100	2.3440
328	28	25	2	37	325	26.250	2.7920
329	28	25	2	37	325	25.200	2.4600
330	28	25	2	37	325	26.220	2.4080
331	35	32	2	14	150	30.620	2.0360
332	35	32	2	14	150	30.620	2.0360
333	35	32	2	14	150	35.190	2.0430
334	35	32	2	14	150	32.490	2.3390
335	35	32	2	14	150	34.620	1.9430
336	35	32	2	14	325	37.630	2.9010
337	35	32	2	14	325	37.63	2.901
338	35	32	2	14	325	36.40	3.404
339	35	32	2	14	325	37.86	3.328
340	35	32	2	14	325	41.37	3.390
341	35	32	2	25	150	55.94	4.045
342	35	32	2	25	150	55.94	4.045
343	35	32	2	25	150	50.59	3.197
344	35	32	2	25	150	46.43	2.893
345	35	32	2	25	150	55.57	3.561
346	35	32	2	25	325	44.79	5.509
347	35	32	2	25	325	44.79	5.509
348	35	32	2	25	325	44.89	5.329
349	35	32	2	25	325	36.91	5.493
350	35	32	2	25	325	47.37	5.234
351	35	32	2	37	150	53.04	2.946
352	35	32	2	37	150	53.04	2.946
353	35	32	2	37	150	48.48	2.675
354	35	32	2	37	150	35.24	2.498
355	35	32	2	37	150	54.44	2.666
356	35	32	2	37	325	53.31	6.287
357	35	32	2	37	325	53.31	6.287

OBS.	DAYS FROM SEEDING	DAYS FROM EMERGENCE	EXP.	CO_2 CONC.	PPFD	FRESH MASS	DRY MASS
358	35	32	2	37	325	53.71	5.926
359	35	32	2	37	325	56.23	7.015
360	35	32	2	37	325	57.82	6.133
361	42	39	2	14	150	50.93	3.944
362	42	39	2	14	150	49.05	3.895
363	42	39	2	14	150	54.89	4.253
364	42	39	2	14	150	49.60	3.808
365	42	39	2	14	150	36.17	3.343
366	42	39	2	14	325	53.07	5.659
367	42	39	2	14	325	50.71	6.056
368	42	39	2	14	325	47.72	4.993
369	42	39	2	14	325	52.54	5.582
370	42	39	2	14	325	53.68	6.203
371	42	39	2	25	150	68.87	6.119
372	42	39	2	25	150	68.74	7.050
373	42	39	2	25	150	79.19	7.463
374	42	39	2	25	150	78.72	7.231
375	42	39	2	25	150	81.96	7.772
376	42	39	2	25	325	62.60	8.351
377	42	39	2	25	325	64.11	8.088
378	42	39	2	25	325	59.56	8.705
379	42	39	2	25	325	59.55	7.806
380	42	39	2	25	325	71.05	8.576
381	42	39	2	37	150	79.16	6.984
382	42	39	2	37	150	79.66	7.775
383	42	39	2	37	150	84.56	7.888
384	42	39	2	37	150	84.28	7.753
385	42	39	2	37	150	76.33	6.719
386	42	39	2	37	325	73.77	9.780
387	42	39	2	37	325	71.60	10.210
388	42	39	2	37	325	62.44	8.496
389	42	39	2	37	325	81.14	11.900
390	42	39	2	37	325	71.17	9.866
391	49	46	2	14	150	79.53	6.931
392	49	46	2	14	150	67.49	5.894
393	49	46	2	14	150	78.46	8.503
394	49	46	2	14	150	53.21	5.346
395	49	46	2	14	150	75.32	7.203
396	49	46	2	14	325	93.54	13.670
397	49	46	2	14	325	95.03	13.550
398	49	46	2	14	325	85.59	13.950
399	49	46	2	14	325	91.55	15.350
400	49	46	2	14	325	85.54	11.950
401	49	46	2	25	150	106.40	13.650
402	49	46	2	25	150	101.20	11.520
403	49	46	2	25	150	104.90	14.250
404	49	46	2	25	150	105.70	9.429
405	49	46	2	25	150	99.34	10.240
406	49	46	2	25	325	72.66	8.838
407	49	46	2	25	325	74.40	10.590
408	49	46	2	25	325	85.41	11.790

OBS.	DAYS FROM SEEDING	DAYS FROM EMERGENCE	EXP.	CO_2 CONC.	PPFD	FRESH MASS	DRY MASS
409	49	46	2	25	325	65.71	7.653
410	49	46	2	25	325	67.05	8.524
411	49	46	2	37	150	111.20	12.160
412	49	46	2	37	150	108.10	10.660
413	49	46	2	37	150	100.80	10.060
414	49	46	2	37	150	103.60	10.550
415	49	46	2	37	150	79.79	7.931
416	49	46	2	37	325	102.22	15.420
417	49	46	2	37	325	91.65	12.650
418	49	46	2	37	325	106.10	18.130
419	49	46	2	37	325	100.00	15.570
420	49	46	2	37	325	108.50	17.020
421	56	53	2	14	150	84.59	9.108
422	56	53	2	14	150	97.70	9.430
423	56	53	2	14	150	94.43	9.468
424	56	53	2	14	150	88.91	8.993
425	56	53	2	14	150	84.51	8.779
426	56	53	2	14	325	88.02	11.570
427	56	53	2	14	325	84.86	11.530
428	56	53	2	14	325	86.32	11.000
429	56	53	2	14	325	87.86	11.240
430	56	53	2	14	325	90.03	11.740
431	56	53	2	25	150	111.33	12.480
432	56	53	2	25	150	116.42	13.830
433	56	53	2	25	150	113.14	12.620
434	56	53	2	25	150	114.16	13.420
435	56	53	2	25	150	123.70	16.110
436	56	53	2	25	325	111.92	17.840
437	56	53	2	25	325	88.58	14.240
438	56	53	2	25	325	95.29	14.790
439	56	53	2	25	325	93.52	16.130
440	56	53	2	25	325	102.66	15.550
441	56	53	2	37	150	100.54	10.600
442	56	53	2	37	150	111.82	11.510
443	56	53	2	37	150	119.40	13.070
444	56	53	2	37	150	119.30	12.230
445	56	53	2	37	150	122.40	12.450
446	56	53	2	37	325	102.65	16.780
447	56	53	2	37	325	113.95	18.680
448	56	53	2	37	325	106.74	16.650
449	56	53	2	37	325	103.180	15.0700
450	56	53	2	37	325	119.200	18.5500
451	8	4	3	14	225	0.022	0.0017
452	8	4	3	14	225	0.016	0.0014
453	8	4	3	14	225	0.025	0.0022
454	8	4	3	14	225	0.025	0.0023
455	8	4	3	14	225	0.021	0.0021
456	8	4	3	14	300	0.011	0.0006
457	8	4	3	14	300	0.028	0.0024
458	8	4	3	14	300	0.026	0.0025
459	8	4	3	14	300	0.019	0.0016

OBS.	DAYS FROM SEEDING	DAYS FROM EMERGENCE	EXP.	CO_2 CONC.	PPFD	FRESH MASS	DRY MASS
460	8	4	3	14	300	0.015	0.0013
461	8	4	3	33	225	0.028	0.0023
462	8	4	3	33	225	0.023	0.0019
463	8	4	3	33	225	0.024	0.0016
464	8	4	3	33	225	0.024	0.0021
465	8	4	3	33	225	0.026	0.0022
466	8	4	3	33	300	0.026	0.0025
467	8	4	3	33	300	0.016	0.0014
468	8	4	3	33	300	0.035	0.0033
469	8	4	3	33	300	0.030	0.0026
470	8	4	3	33	300	0.023	0.0022
471	8	4	3	42	225	0.032	0.0024
472	8	4	3	42	225	0.035	0.0028
473	8	4	3	42	225	0.022	0.0017
474	8	4	3	42	225	0.037	0.0031
475	8	4	3	42	225	0.025	0.0017
476	8	4	3	42	300	0.026	0.0021
477	8	4	3	42	300	0.019	0.0016
478	8	4	3	42	300	0.023	0.0015
479	8	4	3	42	300	0.025	0.0018
480	8	4	3	42	300	0.020	0.0015
481	15	11	3	14	225	0.186	0.0155
482	15	11	3	14	225	0.191	0.0143
483	15	11	3	14	225	0.319	0.0214
484	15	11	3	14	225	0.217	0.0151
485	15	11	3	14	225	0.122	0.0104
486	15	11	3	14	300	0.269	0.0209
487	15	11	3	14	300	0.177	0.0137
488	15	11	3	14	300	0.238	0.0192
489	15	11	3	14	300	0.048	0.0056
490	15	11	3	14	300	0.206	0.0174
491	15	11	3	33	225	0.249	0.0172
492	15	11	3	33	225	0.200	0.0152
493	15	11	3	33	225	0.220	0.0147
494	15	11	3	33	225	0.242	0.0178
495	15	11	3	33	225	0.318	0.0281
496	15	11	3	33	300	0.363	0.0291
497	15	11	3	33	300	0.261	0.0235
498	15	11	3	33	300	0.542	0.0433
499	15	11	3	33	300	0.203	0.0154
500	15	11	3	33	300	0.190	0.0170
501	15	11	3	42	225	0.361	0.0259
502	15	11	3	42	225	0.190	0.0137
503	15	11	3	42	225	0.332	0.0249
504	15	11	3	42	225	0.282	0.0214
505	15	11	3	42	225	0.2731	0.0203
506	15	11	3	42	300	0.3938	0.0345
507	15	11	3	42	300	0.3551	0.0311
508	15	11	3	42	300	0.2236	0.0193
509	15	11	3	42	300	0.2906	0.0238
510	15	11	3	42	300	0.3305	0.0288

OBS.	DAYS FROM SEEDING	DAYS FROM EMERGENCE	EXP.	CO_2 CONC.	PPFD	FRESH MASS	DRY MASS
511	22	18	3	14	225	2.9060	0.2147
512	22	18	3	14	225	1.5090	0.1184
513	22	18	3	14	225	2.8080	0.2115
514	22	18	3	14	225	2.2940	0.1831
515	22	18	3	14	225	3.1220	0.2091
516	22	18	3	14	300	2.7800	0.2049
517	22	18	3	14	300	2.2490	0.1649
518	22	18	3	14	300	1.3980	0.1152
519	22	18	3	14	300	3.0830	0.2283
520	22	18	3	14	300	3.9750	0.2835
521	22	18	3	33	225	3.6530	0.2443
522	22	18	3	33	225	2.6480	0.1937
523	22	18	3	33	225	3.8280	0.2569
524	22	18	3	33	225	2.8850	0.2018
525	22	18	3	33	225	3.9320	0.2440
526	22	18	3	33	300	4.3650	0.3312
527	22	18	3	33	300	4.6080	0.3732
528	22	18	3	33	300	5.3490	0.4030
529	22	18	3	33	300	4.5560	0.3836
530	22	18	3	33	300	4.5820	0.3591
531	22	18	3	42	225	5.2260	0.3570
532	22	18	3	42	225	2.5350	0.1778
533	22	18	3	42	225	4.7690	0.2592
534	22	18	3	42	225	5.7110	0.4357
535	22	18	3	42	225	6.1430	0.4273
536	22	18	3	42	300	3.7020	0.2936
537	22	18	3	42	300	4.7160	0.3613
538	22	18	3	42	300	5.8920	0.4257
539	22	18	3	42	300	5.4720	0.3866
540	22	18	3	42	300	5.6730	0.4017
541	29	25	3	14	225	15.5600	1.0050
542	29	25	3	14	225	13.9400	0.8854
543	29	25	3	14	225	17.8800	1.0430
544	29	25	3	14	225	19.1100	1.1220
545	29	25	3	14	225	23.9700	1.5020
546	29	25	3	14	300	29.1900	1.9580
547	29	25	3	14	300	23.7200	1.4400
548	29	25	3	14	300	19.5700	1.3890
549	29	25	3	14	300	13.5200	0.9533
550	29	25	3	14	300	22.6800	1.3950
551	29	25	3	33	225	20.3200	1.5880
552	29	25	3	33	225	19.8900	2.1760
553	29	25	3	33	225	17.7800	1.9690
554	29	25	3	33	225	22.8900	1.7990
555	29	25	3	33	225	18.0000	1.9540
556	29	25	3	33	300	26.9400	2.0350
557	29	25	3	33	300	35.2400	2.2510
558	29	25	3	33	300	30.5400	2.5320
559	29	25	3	33	300	31.0500	2.9350
560	29	25	3	33	300	31.0100	2.5950
561	29	25	3	42	225	27.15	1.302

OBS.	DAYS FROM SEEDING	DAYS FROM EMERGENCE	EXP.	CO_2 CONC.	PPFD	FRESH MASS	DRY MASS
562	29	25	3	42	225	37.52	1.297
563	29	25	3	42	225	34.23	1.148
564	29	25	3	42	225	28.17	1.431
565	29	25	3	42	225	32.96	1.138
566	29	25	3	42	300	34.20	2.157
567	29	25	3	42	300	35.79	2.686
568	29	25	3	42	300	44.37	2.456
569	29	25	3	42	300	46.02	1.834
570	29	25	3	42	300	43.32	1.969
571	36	32	3	14	225	37.25	3.339
572	36	32	3	14	225	39.40	3.600
573	36	32	3	14	225	46.24	4.132
574	36	32	3	14	225	40.55	3.525
575	36	32	3	14	225	36.68	3.087
576	36	32	3	14	300	40.49	3.670
577	36	32	3	14	300	35.66	3.513
578	36	32	3	14	300	43.11	4.214
579	36	32	3	14	300	31.72	2.967
580	36	32	3	14	300	40.08	3.640
581	36	32	3	33	225	85.82	4.864
582	36	32	3	33	225	70.90	4.563
583	36	32	3	33	225	73.91	3.535
584	36	32	3	33	225	78.14	4.575
585	36	32	3	33	225	74.57	4.132
586	36	32	3	33	300	54.50	5.765
587	36	32	3	33	300	61.50	6.175
588	36	32	3	33	300	76.63	6.367
589	36	32	3	33	300	88.85	5.687
590	36	32	3	33	300	77.97	5.328
591	36	32	3	42	225	53.36	7.232
592	36	32	3	42	225	51.76	5.914
593	36	32	3	42	225	40.98	6.226
594	36	32	3	42	225	51.76	5.968
595	36	32	3	42	225	55.10	5.827
596	36	32	3	42	300	52.77	6.139
597	36	32	3	42	300	57.11	6.612
598	36	32	3	42	300	58.69	8.690
599	36	32	3	42	300	62.45	9.312
600	36	32	3	42	300	55.24	8.306
601	43	39	3	14	225	64.34	6.423
602	43	39	3	14	225	56.83	5.610
603	43	39	3	14	225	72.18	6.760
604	43	39	3	14	225	74.05	6.607
605	43	39	3	14	225	62.44	5.706
606	43	39	3	14	300	67.49	7.019
607	43	39	3	14	300	51.23	5.038
608	43	39	3	14	300	57.89	5.899
609	43	39	3	14	300	57.97	5.809
610	43	39	3	14	300	58.34	5.373
611	43	39	3	33	225	99.94	8.404
612	43	39	3	33	225	70.27	9.076

OBS.	DAYS FROM SEEDING	DAYS FROM EMERGENCE	EXP.	CO_2 CONC.	PPFD	FRESH MASS	DRY MASS
613	43	39	3	33	225	109.56	7.721
614	43	39	3	33	225	108.22	8.246
615	43	39	3	33	225	116.40	8.699
616	43	39	3	33	300	99.53	10.680
617	43	39	3	33	300	97.56	11.150
618	43	39	3	33	300	98.46	11.560
619	43	39	3	33	300	71.15	9.433
620	43	39	3	33	300	105.01	13.320
621	43	39	3	42	225	74.76	11.040
622	43	39	3	42	225	78.93	8.437
623	43	39	3	42	225	85.22	10.570
624	43	39	3	42	225	88.41	11.220
625	43	39	3	42	225	84.15	12.930
626	43	39	3	42	300	82.59	12.910
627	43	39	3	42	300	85.23	12.850
628	43	39	3	42	300	85.17	13.570
629	43	39	3	42	300	74.56	9.234
630	43	39	3	42	300	103.60	14.480
631	50	46	3	14	225	99.89	11.290
632	50	46	3	14	225	101.37	9.472
633	50	46	3	14	225	95.14	9.024
634	50	46	3	14	225	93.50	10.210
635	50	46	3	14	225	98.94	10.300
636	50	46	3	14	300	62.23	7.304
637	50	46	3	14	300	73.77	7.739
638	50	46	3	14	300	74.47	9.034
639	50	46	3	14	300	83.88	10.310
640	50	46	3	14	300	61.10	6.285
641	50	46	3	33	225	90.82	15.890
642	50	46	3	33	225	111.80	15.370
643	50	46	3	33	225	96.57	16.700
644	50	46	3	33	225	101.10	15.910
645	50	46	3	33	225	102.20	18.190
646	50	46	3	33	300	117.50	12.740
647	50	46	3	33	300	109.50	11.160
648	50	46	3	33	300	113.50	11.120
649	50	46	3	33	300	104.90	14.870
650	50	46	3	33	300	111.60	11.610
651	50	46	3	42	225	125.90	16.820
652	50	46	3	42	225	132.00	17.560
653	50	46	3	42	225	112.30	14.340
654	50	46	3	42	225	127.90	16.400
655	50	46	3	42	225	129.80	15.410
656	50	46	3	42	300	142.40	20.750
657	50	46	3	42	300	140.20	21.370
658	50	46	3	42	300	139.10	21.230
659	50	46	3	42	300	111.20	15.500
660	50	46	3	42	300	100.20	14.120