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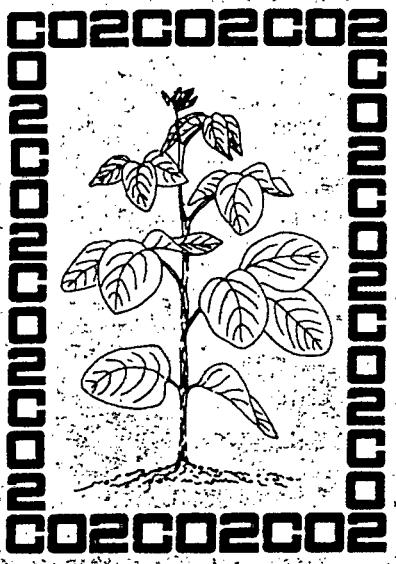

Response of Vegetation to Carbon Dioxide

030

Growth, Yield and Plant Water Relationships in Sweet Potatoes in Response to Carbon Dioxide Enrichment 1986

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Progress Report of Research: GROWTH, YIELD AND PLANT WATER RELATIONSHIPS IN SWEET POTATOES IN RESPONSE TO CARBON DIOXIDE ENRICHMENT

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EXECUTIVE SUMMARY

In the summer of 1985, under the joint program of U.S. Department of Energy, Carbon Dioxide Division, and Tuskegee University, experiments were conducted to study growth, yield, photosynthesis and plant water relationships in sweet potato plants grown in an enriched CO_2 environment.

The main experiment utilized open top chambers to study the effects of CO_2 and soil moisture on growth, yield and photosynthesis of field-grown plants. In addition, potted plants in open top chambers were utilized in a study of the effects of different CO_2 concentrations on growth pattern, relative growth rate, net assimilation rate and biomass increment at different stages of development. The interaction effects of enriched CO_2 and water stress on biomass production, yield, xylem potential, and stomatal conductance were also investigated. The overall results of the various studies are described in brief below.

Sweet potatoes grown in the field in open top chambers showed significant increases in tuber number, fresh weight, dry weight and total volume (per plant) with increasing CO_2. The effect of CO_2 on all of these variables (except tuber number) remained significant when soil moisture was used as a covariate in an analysis of covariance. Growth and yield of shoots were not affected by CO_2. When the open field plots were included in the analyses, there were significant effects of soil moisture on leaf area, stem length, shoot fresh and dry weight, tuber fresh and dry weight and total tuber volume. However, soil moisture had no significant effects on any of these variables when the open field plots were removed from the analyses. This was most likely due to the reduction of rainfall by the frustum in the open-top chambers.

Preliminary photosynthesis measurements on field-grown plants showed that elevated CO_2 was associated with increased photosynthesis at high light, but not at low light. Stomatal conductance and transpiration were not strongly affected by CO_2, but water use efficiency increased with increasing CO_2, due mainly to the increase in photosynthesis. Photosynthesis at high light was constant over the temperature range 25-35°C at all CO_2 levels.

The growth pattern of sweet potato plants grown in pots in open top chambers at different CO_2 concentrations showed a rapid production of the main stem, new branches and leaves at the highest CO_2 level (666 umol mol^{-1}) during the early stages of development. However, with the development of tuberous roots vegetative growth ceased at enriched CO_2 while it continued in ambient CO_2-grown plants at a slow rate.

Growth measurements on sweet potatoes grown in pots in open top chambers showed that shoots grew more rapidly early in the growing season in elevated CO_2. However, shoot growth also ceased earlier in elevated CO_2 than at ambient levels. Growth analysis indicated that the increase in ΔW and the decrease in relative growth rate (RGR) and net assimilation rate (NAR) with plant age occurred more rapidly in elevated CO_2 than at ambient CO_2.

Sweet potato plants subjected to water stress in pots in open top chambers showed stress earlier at ambient CO_2 than at elevated CO_2, as evidenced by decreasing stomatal conductance and decreasing (i.e. more negative) xylem pressure potential. Yield increased with increasing CO_2 in both well-watered and water-stressed plants.

ACKNOWLEDGEMENTS

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I. INTRODUCTION

A. Rationale

The mean global CO_2 concentrations is steadily increasing at the rate of 1.3 umol mol^{-1} annually, and forecasts suggest that the CO_2 concentrations will have reached double the pre-industrial concentration by late in the next century (Clark et al. 1982). This increase in CO_2 concentration will have two significant direct effects on plant growth. First, CO_2 enrichment will increase net CO_2 fixation, leading to increased plant dry weight and probably increased leaf area, at least in plants with C_3 photosynthesis (Kramer 1981). Secondly, high doses of CO_2 will reduce stomatal aperture, reducing transpiration and therefore increasing water use efficiency. In conditions of limited water supply, this could lead to increased plant dry weight in both C_3 and C_4 plants (Morison and Gifford 1983). However, the effect of CO_2 enrichment on water use per plant or per unit ground area cannot be immediately forecasted because of the antagonistic effects of CO_2 enrichment on leaf area per plant and on transpiration per unit leaf area. Studies have shown that elevated CO_2 results in the increases in dry matter accumulation in both vegetative and reproductive components of many plants (Wittwer 1980, 1983, Kimball 1983). But for the purposes of accurately modeling the carbon cycle and predicting future crop yields, more extensive data are required. This is especially true for tuber and root crops, which make up a substantial portion of the world's food supply. Root crops, including sweet potato, have simple source-sink relationships for the translocation of photoassimilates during

different stages of growth and development. Sweet potato roots provide a substantial sink for the photosynthate produced at elevated CO_2. Thus the responses of root crops to elevated CO_2 may differ from those of crops without tubers or tuberous roots. We investigated the growth, yield, photosynthesis, water relations, and responses to water stress of sweet potato plants grown under elevated CO_2.

B. Objectives

1. To determine the morphological, physiological, growth and yield responses of sweet potatoes to an enriched CO_2 environment.
2. To determine the effects of CO_2 enrichment on plant water relations in sweet potatoes.
3. To measure leaf photosynthesis and conductance, in relation to CO_2 enrichment and plant water status.
4. To provide data for a generalized crop growth model for predicting crop yield as a function of CO_2 enrichment.

C. Approach

This study focused on growth and development of sweet potatoes grown in the field and in pots, in open top chambers. Target CO_2 levels ranged from ambient to 300 umol mol^{-1} above ambient. The growth, yield, photosynthesis and water relations studies were carried out using field-grown plants. The water stress study was carried out using potted plants.

II. CO_2 EXPERIMENTAL SYSTEM

A. Carbon Dioxide Dispensing and Monitoring System

This section describes a brief overview of the equipment used in dispensing, and monitoring, and sampling carbon dioxide in the field at Tuskegee University during 1985 study. The system had three main components: a CO_2 dispensing unit, open top field chambers for plant exposure, and an automatic sampling system. The system has been described in detail in a previous report (Biswas et al. 1985).

Liquid CO_2 was stored in a 14-ton receiver adjacent to the field site. CO_2 was dispensed to the field plots through a custom made dispensing manifold which allowed the flow of CO_2 to each plot to be adjusted individually. Open top chambers were used to expose field grown plants to elevated CO_2. Each chamber consisted of a cylindrical aluminum framework 3 m in diameter and 2.4 m high, covered with clear plastic film. The area of the top opening was reduced by about 50% with a 45 degree frustum.

Air samples were drawn continuously from each field plot to a sampling manifold by a vacuum pump. A timer and separate sample pump were used to divert one sample at a time through two absolute CO_2 infrared gas analysers (Binos Type 4b.1T).

There were 15 plots in the row crop study (9 elevated CO_2 chambers, 3 ambient chambers and 3 open field plots) and 5 plots in the pot study (3 elevated CO_2 chambers, 1 ambient chamber and 1 open field plot). The sample manifold was designed to handle 16 samples. Fourteen of the sample

ports were used to monitor all 12 elevated CO_2 chambers plus one ambient chamber and one open field plot in the row crop study. The two remaining ports were each used to monitor two plots on alternate days. The four plots that were monitored on alternate days were the ambient chamber and the open field plot in the pot study, and one ambient chamber and one open field plot in the row crop study. The third ambient chamber and open field plot in the row crop study were not monitored.

Each plot was sampled every 32 minutes for 2 minutes. The gas analysers were calibrated against a series of tanks of known CO_2 concentrations, and the CO_2 concentrations in the chambers were readjusted at 0900 hrs and 1600 hrs CST daily.

B. Statistical Analysis of Carbon Dioxide Data

In order to determine the actual concentration of CO_2 inside the chambers, a sub-sample of the entire CO_2 data set was obtained and analyzed as follows. Beginning on 26 May (5 days after CO_2 dispensing began) hourly chart readings were taken every 8 days. This yielded CO_2 values for nine 24-hour periods. The data for two of the nine selected days could not be used. In one case a thunderstorm and high winds caused large fluctuations in the CO_2 concentrations. In the other case the chamber doors were open during parts of the day for sampling purposes. In those two cases, an adjacent day was substituted for the unacceptable day. Using these data, hourly means and standard deviations of CO_2 concentrations were calculated for each chamber. Daytime (0700 to 1700 hrs CST), nighttime (before 0700 and after 1700 hrs CST) and 24-hour treatment means are shown in Tables 1-3 for the field study, and in Tables 4-6 for the pot study.

Table 1. Daytime CO_2 concentrations in sweet potato row crop study plots. Values represent means (± S.E.) of readings taken every hour on nine selected days evenly spaced throughout the growth period.

CO_2 Values (umol mol^{-1})	Open Field Plots	Open Top Chambers			
		+0	+75	+150	+300
Target	---	360	435	510	660
Treatment Means					
Actual	360 ± 0.91	361 ± 1.03	438 ± 0.77	514 ± 0.81	665 ± 0.86
Actual-Target	---	+1	+3	+4	+5
Plots Means					
Plot Number	7	6	10	9	8
Actual	360 ± 1.29	360 ± 1.29	439 ± 1.42	515 ± 1.36	664 ± 1.36
Plot Number	14	12	13	15	11
Actual	*	*	439 ± 1.28	515 ± 1.46	666 ± 1.49
Plot Number	20	18	19	16	17
Actual	360 ± 1.27	363 ± 1.60	437 ± 1.33	514 ± 1.43	666 ± 1.63

*Plot not monitored.

Table 2. Nighttime CO_2 concentrations in sweet potato row crop study plots. Values represent means (± S.E.) of readings taken every hour on nine selected days evenly spaced throughout the growth period.

CO_2 Values (umol mol^{-1})	Open Field Plots	Open Top Chambers			
		+0	+75	+150	+300
Target	---	426	501	576	726
Treatment Means					
Actual	426 ± 2.91	418 ± 2.42	502 ± 2.50	578 ± 2.39	719 ± 2.10
Actual-Target	---	-8	+1	+2	-7
Plots Means					
Plot Number	7	6	10	9	8
Actual	421 ± 3.54	421 ± 3.45	509 ± 5.11	580 ± 4.46	722 ± 4.01
Plot Number	14	12	13	15	11
Actual	*	*	496 ± 3.66	582 ± 4.36	715 ± 3.33
Plot Number	20	18	19	16	17
Actual	430 ± 4.61	415 ± 3.38	502 ± 4.06	472 ± 3.54	720 ± 3.53

*Plot not monitored.

Table 3. Twenty-four hour CO_2 concentrations in sweet potato row crop study plots. Values represent means (± S.E.) of readings taken every hour on nine selected days evenly spaced throughout the growth period.

CO_2 Values (umol mol^{-1})	Open Field Plots	Open Top Chambers			
		+0	+75	+150	+300
Target	---	393	468	543	693
Treatment Means					
Actual	393 ± 2.09	390 ± 1.81	470 ± 1.74	546 ± 1.69	692 ± 1.48
Actual-Target	---	-3	+2	+3	-1
Plots Means					
Plot Number	7	6	10	9	8
Actual	391 ± 6.60	390 ± 2.63	474 ± 3.40	547 ± 3.07	693 ± 2.76
Plot Number	14	12	13	15	11
Actual	*	*	467 ± 2.62	548 ± 3.09	691 ± 2.37
Plot Number	20	18	19	16	17
Actual	395 ± 3.23	389 ± 2.48	469 ± 2.93	543 ± 2.62	693 ± 2.54

*Plot not monitored.

Table 4. Daytime CO_2 concentrations in sweet potato pot study plots. Values represent means (± S.E.) of readings taken every hour on nine selected days evenly spaced throughout the growth period.

CO_2 Values (umol mol^{-1})	Open Field Plot	Open Top Chambers			
		+0	+75	+150	+300
Target	---	361	436	511	661
Treatment/Plot Means					
Plot Number	4	3	1	2	5
Actual	361 ± 1.30	364 ± 1.53	438 ± 1.36	514 ± 1.49	666 ± 1.66
Actual-Target	---	+3	+2	+3	+5

Table 5. Nighttime CO_2 concentrations in sweet potato pot study plots. Values represent means (± S.E.) of readings taken every hour on nine selected days evenly spaced throughout the growth period.

CO_2 Values (umol mol^{-1})	Open Field Plot	Open Top Chambers			
		+0	+75	+150	+300
Target	---	431	506	581	731
Treatment/Plot Means					
Plot Number	4	3	1	2	5
Actual	431 ± 4.39	419 ± 3.61	500 ± 3.93	576 ± 3.85	737 ± 4.70
Actual-Target	---	-12	-6	-5	+6

Table 6. Twenty-four hour CO_2 concentrations in sweet potato pot study plots. Values represent means (± S.E.) of readings taken every hour on nine selected days evenly spaced throughout the growth period.

CO_2 Values (umol mol^{-1})	Open Field Plot	Open Top Chambers			
		+0	+75	+150	+300
Target	---	396	471	546	696
Treatment/Plot Means					
Plot Number	4	3	1	2	5
Actual	396 ± 3.14	392 ± 2.59	469 ± 2.82	545 ± 2.83	702 ± 3.32
Actual-Target	---	-4	-2	-1	+6

III. ROW CROP STUDY

B. Effect of CO_2 and Soil Moisture on Growth and Yield

1. Experimental Design and Methodology

Field site: The experiment was conducted in the summer of 1985 at the Tuskegee University's George Washington Carver Agricultural Experiment Station on Franklin Road Farm in Macon County, Alabama. The soil was a Norfolk sandy loam (Typic Paleudult), with a pH ranging from 6.2 to 6.9. The specific field used for the experiment was flat, but slightly sloped to the northeast. The field had been used in the previous year for studies of CO_2 enrichment on sweet potatoes and cowpeas. For the 1985 study chambers were placed in positions in between the positions that they had occupied for the 1984 study. In 1984 the cowpeas were planted only inside the chambers. Therefore, in 1985 no chamber occupied a site where cowpeas had been planted in 1984. The field was fumigated with methyl bromide, then planted with ryegrass after the harvest of the previous year's crop. The ryegrass was plowed under at the end of April, 1985. Soil analyses were done a month prior to planting to determine the nutrient status of the field.

Experimental design and field layout: Sweet potatoes were exposed to five treatments in a randomized complete block design with three replicate blocks for the row crop study and one block for the pot study (Fig. 1). The five treatments consisted of an open field plot with no chamber and four chambers with target CO_2 levels of 0, 75, 150 and 300 umol mol^{-1} above ambient. A randomized complete block design was used

Fertilizer was applied at the rate of 89 kg N ha^{-1}, 128 kg P ha^{-1} and 128 kg K ha^{-1}. Half of the N and all of the P and K were applied at the time of planting. The other half of the N was side dressed 55 days after planting. Weeding was done manually. Nematode counts were taken a month prior to planting; nematode counts were insignificant.

Temperature, Humidity and Light Measurements: A Taylor Weatherscope Thermivolt Thermometer with thermistor, barometric pressure indicator, anemometer and wind direction indicator was used to monitor weather conditions. Readings were taken twice a day, at the time of calibration of the infrared gas analyzers. The thermistor was shielded from direct sunlight. Temperature were also recorded using two max-min thermometers, placed in instrument shelters located at either end of the field. These were read at 0800 hrs CST. In addition, 24 hour records of temperature, humidity and light were obtained using a recording hygrometer-thermometer placed in one of the instrument shelters and a pyranograph placed on top of a table in an open area of the field beyond the study plots.

Precipitation Measurement: Rainfall was measured in each study plot using rainfall gauges located on poles so that the top of the gauge was level with the top of the frustum opening. An additional rainfall gauge was located in the open field. Rainfall gauges were checked each morning and read and emptied as necessary.

Soil moisture Determination: One 122 cm (48 inch) neutron probe PVC access tube was placed in the middle of one of the main rows of sweet potatoes in each plot. Neutron probe measurements were taken at depths of 15.2, 30.5, 45.7, 71.1, 96.5 cm (6, 12, 18, 28 and 38 inches) at 2 to 5 day intervals starting on 18 June. Calibration of the neutron probe was done by digging a 1.83 m (6 ft) hole in the center of the field with a soil

sampler. Fresh and dry weights were determined on samples taken at 30.5 cm (12 in) intervals, thus giving a range of soil moisture readings. Immediately after completion of the soil sampling, a PVC neutron probe access tube was inserted into the hole and triplicate neutron probe readings were taken at depths corresponding to the center of the soil samples. A linear regression based on this calibration data was used to convert neutron probe readings to percent soil moisture.

Growth Measurements : Measurements of shoot growth were taken at 30, 50 and 70 days after transplanting on 5 plants in each main row of each plot. The numbers of leaves and runners were determined, and the length of each runner was measured.

Harvest: The above-ground portions were harvested during 18-25 August. Five plants from both the left and right row of each plot were randomly harvested to give ten plants for each plot. The first and tenth plants of each row were never harvested due to their close proximity to the edge of the chamber. The stems were cut 1 cm above the ground. Green and dead leaves were separated from the runners; petioles remained with the leaves. Fresh weights of green and dead leaves were determined. Runner lengths were measured, and a total runner count was taken. The leaves were passed through a LI-COR area meter (LI-3100), and were counted as they passed out of the meter. At the end of each harvest day, individual leaf and runner sample bags were placed in ovens at $70 \pm 5\ ^{o}C$ in Auburn University's E. V. Smith Research Center. The leaf and runner samples were checked every other day and turned over to ensure uniform drying in each bag. All leaf and runner samples were removed from the ovens after 72 hours of drying. Dry weights were recorded for dead leaves, green leaves and runners separately.

The below-ground portions were harvested during 27-29 August. The tuberous roots along with an adhering fibrous roots were dug for the same ten plants in each plot for which the shoots had been harvested. The tuberous roots were rinsed lightly with water to remove clumps of soil adhering to the potatoes, and then air dried outdoors for 10-15 min. Fresh weight, diameter, length, and volume were taken for each individual tuber. Any tubers which were oddly shaped were noted. Diameter was taken with callipers at the greatest dimension measured at right angles to the longitudinal axis. The length was taken at the greatest dimension measured in a line between points at each end. Volumes were measured by water displacement. Individual tuber fresh weights and volumes were used to calculate the density of each tuber. Tubers were individually sliced to about 0.5 cm in width, placed in paper bags and dried at 70 $\pm$ 5 ^{o}C for 71-80 hrs.

Effect of Soil Moisture : An attempt was made to calculate season-long evapotranspiration separately for each plot based on the measured rainfall and irrigation inputs and the changes in soil moisture profile during the season. This was not successful due to the frequency of rainfall events and to penetration of soil water beyond the bottom of the neutron probe access tubes.

However, the soil moisture data did provide useful information. When it became clear that soil water was penetrating beyond the bottom of the access tubes, we installed 2.13 m (7 ft) tubes at each end of the open field, in an attempt to determine the depth of soil water penetration. (It would have been too disruptive to the plants to install new longer tubes in the chambers.)

Readings on these tubes indicated a marked difference between the two ends of the field. The tube located at the south east end of the field (between plots 6 and 11, Fig. 1) showed evidence of penetration of soil water to about 97 cm (38 inches), with relatively constant soil moisture readings below that depth. However, the tube located at the north west end of the field (between plots 10 and 15) showed evidence of soil water penetration beyond the deepest sampling point of 185 cm (73 inches). In addition, soil moisture readings at depths of less than 119 cm (47 inches) were significantly lower at the north west end of the field than at the south east end. Thus, the north west end of the field was much better drained and therefore drier in the surface layers than the south east end (Fig. 1).

Statistical Analyses : Because of the large differences in soil moisture, we incorporated soil moisture into the statistical analyses as follows. Pearson correlation coefficients were calculated for all yield variables against mean, maximum and minimum soil moisture readings at all depths. In general, shoot variables correlated most strongly with the maximum soil moisture at 15.2 cm (6 inches). Root and total yield variables correlated most strongly with the maximum soil moisture at 45.7 cm (18 inches). These two variables were then used as covariates in an analysis of covariance of the effect of elevated CO_2 on growth and yield. Analyses of covariance were performed using a model that included CO_2 and block effects with soil moisture as a covariate. Analysis were performed both with and without the open field plots included. For variables for which the overall analysis of covariance (without the open field plots) was significant ($P < 0.05$), linear regressions were performed using CO_2 and soil moisture as independent variables. Significance

levels from the analyses of covariance and coefficients for the linear regressions are shown in the data tables.

2. Results

Shoots: There were few significant differences in shoot growth during the growing season (Tables 11-13). The differences that were statistically significant seemed to be due mainly to differences between the three replicate blocks.

There was little effect of CO_2 on shoot yield, regardless of whether or not the open field plots were included in the analyses. While many variables showed increasing trends with increasing CO_2, only mean runner length was significantly affected by CO_2 (Tables 14-18).

When the open field plots were included in the analyses, there was a strong effect of soil moisture on shoot yield. Leaf area, the number and total length of runners, fresh weights of leaves, and fresh and dry weights of runners and total shoots all increased significantly with increasing soil moisture (Tables 14-16,18). However, when the open field plots were excluded, soil moisture had no significant effect on shoot yield (Tables 14-18). This indicates that the soil moisture effect was mainly a chamber effect, caused in all likelihood by the exclusion of about 50% of the rainfall by the frusta on the chambers.

Roots: There was a strong effect of CO_2 on root yield. This was true regardless of whether or not the open field plots were included in the analyses. The volume, fresh weight and dry weight of tuberous roots (on a per plant basis) increased significantly with increasing CO_2 (Tables 19-21). The number of tuberous roots per plant and the density of

tuberous roots also increased with increasing CO_2, but not significantly (Table 19).

Total plant fresh and dry weights increased significantly with increasing CO_2, due mainly to the increased root yield (Tables 20-21). The root/shoot ratio was much lower in the ambient chambers than at the 3 elevated CO_2 concentrations, but the trend was not significant (Table 21).

When the open field plots were included in the analyses, there was a significant effect of soil moisture on some root yield variables, always in the direction of decreasing yield with increasing soil moisture (Tables 19-21). However, when the open field plots were excluded, the soil moisture effect became much less significant, and the regression coefficients for soil moisture were not significant, indicating a weak effect of soil moisture on root yield.

3. Discussion

The results of the 1985 study parallel those of our 1984 study (Biswas et al. 1985). Both studies showed small, non-significant increases in shoot yield with increasing CO_2 concentration. Both studies also showed large increases in root yield. In the 1984 study, most of the increased root yield was due to increases in the number of tuberous roots per plant. In the 1985 study, more of the increase was due to increases in the sizes of individual tuberous roots. Overall yield was lower in 1985 than in 1984, probably due to low rainfall and high temperatures early in the growing season (Fig. 2). It is clear from these two studies that, in sweet potatoes, the majority of the increased photosynthate produced at

elevated CO_2 is partitioned to storage roots. Howvever, differences in soil moisture had a greater effect on shoot growth than on root yield.

In both years there was a large reduction in yield caused by the open top chambers. Much of this effect may be due to the exclusion of about 50% of the rainfall by the frustum. In future studies, supplemental irrigation should be employed to replace the rainfall excluded by the frustum.

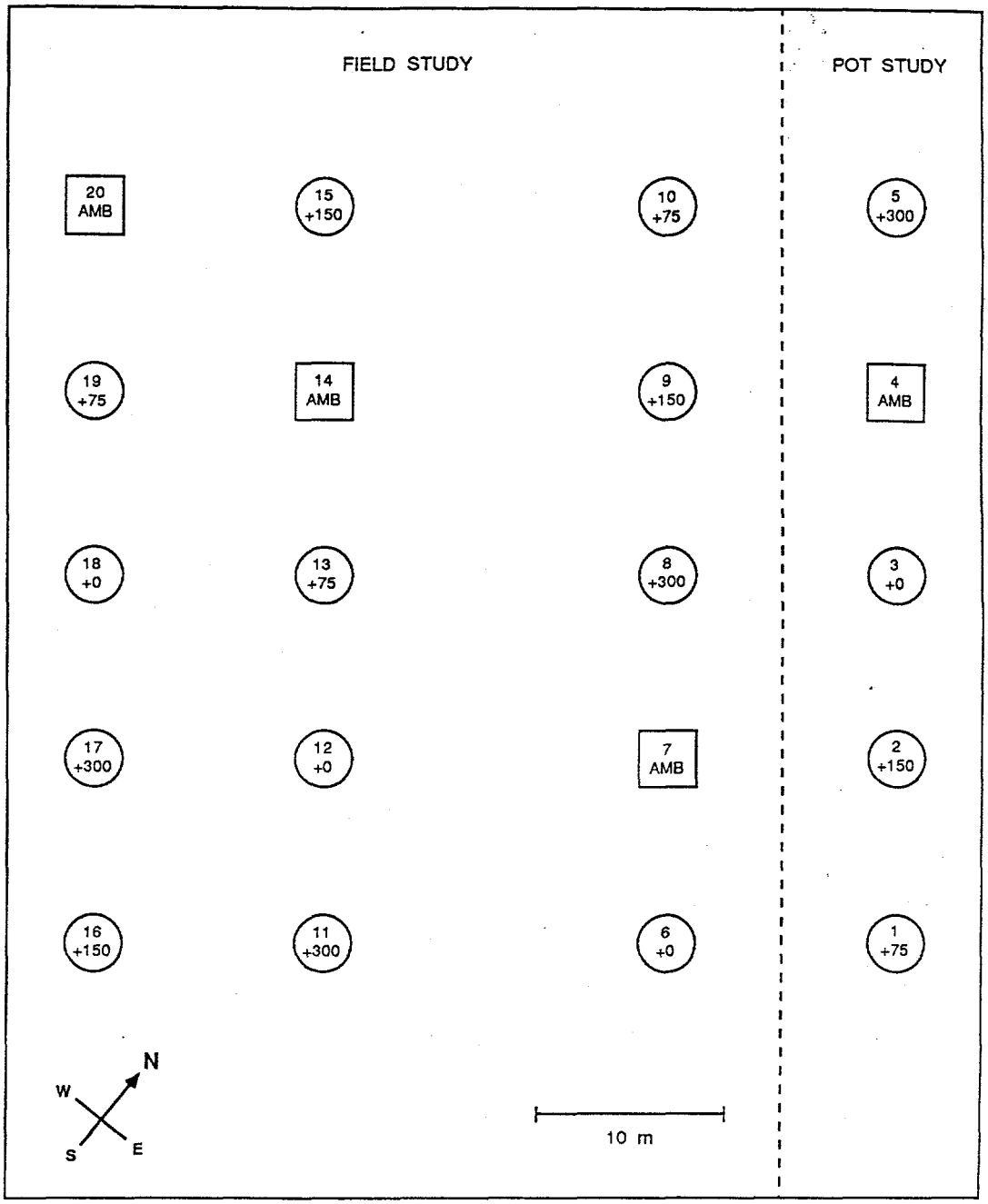

Figure 1. Layout of study plots for 1985 field season. Top number in each plot is plot number. Bottom number is treatment in umol mol^{-1} CO_2 above ambient. AMB = open field plot.

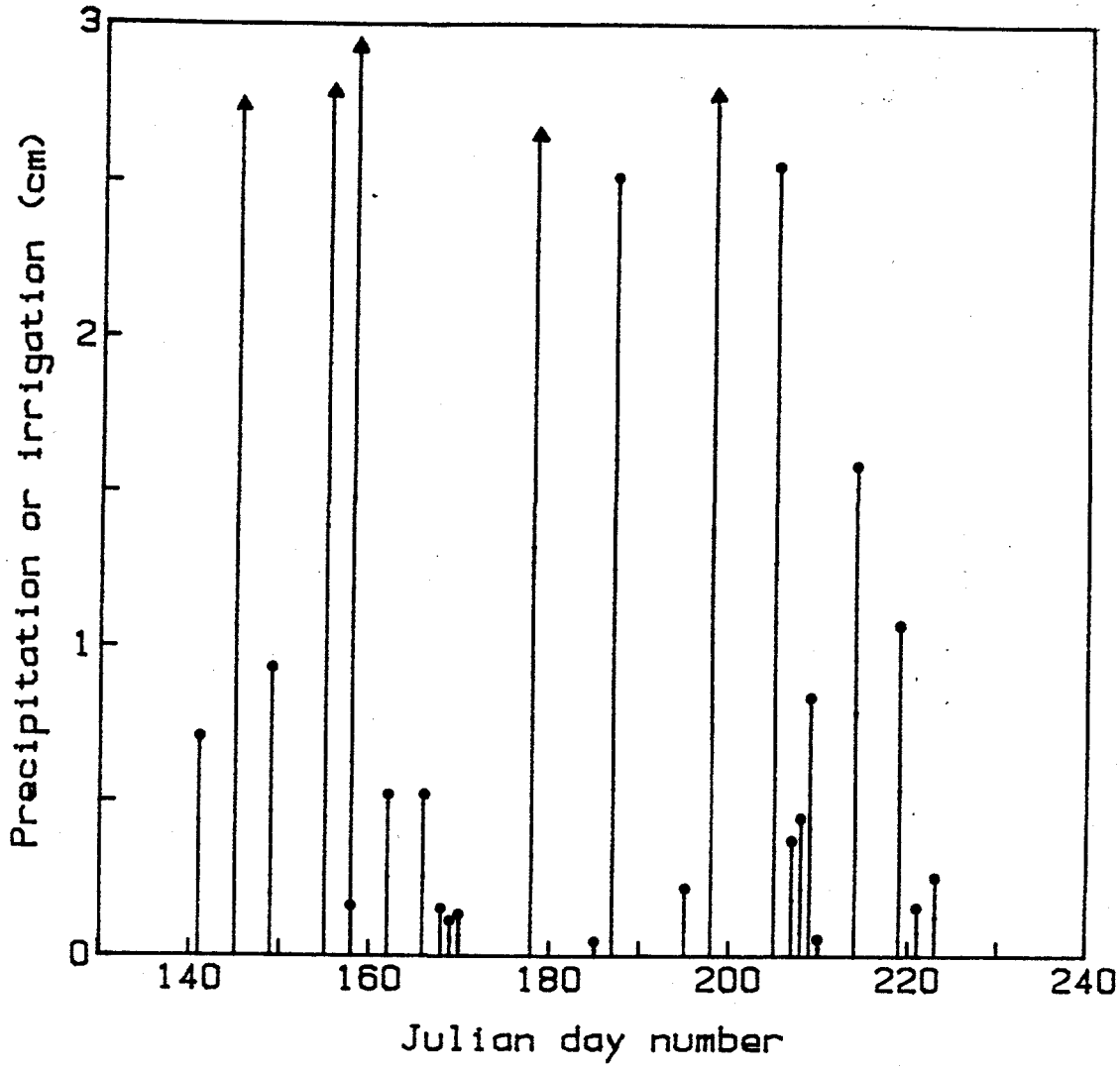

Figure 2. Precipitation (●) and irrigation (▲) soil moisture inputs to sweet potato plots during the growing season (Julian day numbers 141-230). Precipitation is for the open field; precipitation in open-top chambers was reduced approximately 58% by the frustum. Irrigation values are the means for all chambers.

Table 7. Total whole-season precipitation and irrigation for sweet potato plants grown in open top chambers and open field plots at elevated CO_2 concentrations.

Plot	CO_2 ($\mu mol\ mol^{-1}$)	Soil Moisture Inputs (cm H_2O)		
		Precipitation	Irrigation	Total
6	361	13.7	12.9	26.6
7	360+	33.8	12.8	46.6
8	665	14.2	13.3	27.5
9	514	14.3	15.8	30.1
10	438	14.6	15.4	30.0
11	665	13.6	12.6	26.2
12	361	14.4	13.1	27.5
13	438	13.8	14.0	27.8
14	360+	33.3	14.2	47.5
15	514	14.0	14.7	28.7
16	514	14.2	13.0	27.2
17	665	13.8	12.8	26.6
18	361	13.7	12.6	26.3
19	438	13.8	14.2	28.0
20	360+	34.5	14.6	49.1

+Open field plot. Other values are from within chambers. CO_2 values are daytime means.

Table 8. Whole-season mean soil moisture content in open top chambers and open field plots containing sweet potatoes grown at elevated CO_2 concentrations.

Plot	CO_2 ($\mu mol\ mol^{-1}$)	Mean Soil Moisture (% volume)				
		15 cm	31 cm	46 cm	71 cm	97 cm
6	361	4.88	7.66	8.31	8.77	9.61
7	360+	6.03	7.20	8.46	9.36	11.25
8	665	4.55	6.21	7.19	8.58	10.37
9	514	3.11	4.72	5.56	7.75	10.92
10	438	2.89	4.60	5.40	7.54	9.33
11	665	5.28	7.78	8.25	9.23	10.61
12	361	4.27	6.94	8.48	9.50	10.91
13	438	3.77	5.97	7.39	9.99	11.74
14	360+	4.31	5.88	6.47	8.58	11.18
15	514	3.43	5.19	5.66	6.40	9.47
16	514	4.68	6.83	7.91	9.51	11.21
17	665	4.63	6.90	8.12	9.42	11.03
18	361	4.83	6.99	8.93	10.69	12.41
19	438	4.49	6.21	7.43	9.35	11.66
20	360+	4.66	5.81	6.90	9.49	11.31

+Open field plot. Other values are from within chambers. CO_2 values are daytime means.

Table 9. Whole-season maximum soil moisture content in open top chambers and open field plots containing sweet potatoes grown at elevated CO_2 concentrations.

Plot	CO_2 ($\mu mol\ mol^{-1}$)	Maximum Soil Moisture (% volume)				
		15 cm	31 cm	46 cm	71 cm	97 cm
6	361	6.79	8.37	8.68	9.02	9.84
7	360+	7.46	7.77	9.02	9.68	11.49
8	665	6.36	7.17	7.64	8.77	10.71
9	514	4.57	5.96	6.43	8.05	11.18
10	438	4.17	5.91	6.20	7.81	9.57
11	665	7.05	8.50	8.75	9.60	10.85
12	361	5.87	7.93	8.81	9.72	11.25
13	438	5.24	6.78	7.80	10.28	11.97
14	360+	5.68	6.88	7.03	8.91	11.41
15	514	4.93	6.34	6.27	6.66	9.73
16	514	6.57	7.74	8.26	9.77	11.47
17	665	6.26	7.64	8.39	9.65	11.29
18	361	6.25	7.58	9.25	10.96	12.58
19	438	6.02	6.92	7.76	9.63	11.87
20	360+	6.08	6.49	7.41	9.83	11.77

+Open field plot. Other values are from within chambers. CO_2 values are daytime means.

Table 10. Whole-season minimum soil moisture content in open top chambers and open field plots containing sweet potatoes grown at elevated CO_2 concentrations.

Plot	CO_2 (umol mol^{-1})	Minimum Soil Moisture (% volume)				
		15 cm	31 cm	46 cm	71 cm	97 cm
6	361	3.57	6.86	7.41	8.39	9.31
7	360+	4.22	6.17	7.71	8.86	11.06
8	665	3.13	5.47	6.83	8.32	10.04
9	514	1.96	3.76	4.86	7.29	10.68
10	438	1.92	3.52	4.50	7.00	9.03
11	665	4.04	6.80	7.24	8.41	10.33
12	361	2.89	5.93	7.97	9.24	10.62
13	438	2.79	5.20	6.80	9.44	11.45
14	360+	3.02	4.60	5.75	8.22	10.95
15	514	2.53	4.40	5.14	5.98	9.21
16	514	3.57	6.13	7.36	9.18	10.94
17	665	3.67	6.36	7.76	9.13	10.72
18	361	3.59	6.17	8.34	10.41	12.26
19	438	3.46	5.48	6.84	8.92	11.33
20	360+	3.27	4.86	6.02	9.15	11.04

+Open field plot. Other values are from within chambers. CO_2 values are daytime means.

Table 11. Effect of different CO_2 concentrations on shoot growth (mean ± S.E.) of sweet potato plants grown in the field, in open top chambers and open field plots at 30 days of growth, n=3.

CO_2 (umol mol^{-1})	Number of Leaves	Number of Runners	Total Runner Length (cm)	Mean Runner Length (cm)
360+	30.23 ± 2.86	3.40 ± 0.30	56.70 ± 6.95	17.25 ± 1.76
361	30.57 ± 2.28	2.80 ± 0.21	62.82 ± 6.18	22.53 ± 1.58
438	35.30 ± 2.78	2.97 ± 0.19	68.83 ± 6.52	22.60 ± 1.61
514	31.57 ± 2.19	2.93 ± 0.22	62.42 ± 5.70	21.96 ± 1.59
665	40.20 ± 1.82	3.30 ± 0.18	89.18 ± 6.33	28.10 ± 1.68

Analysis of Covariance -- Significance Levels

Open field plots included:

ANCOVA	0.177	0.305	0.132	0.124
CO_2	0.218	0.356	0.183	0.185
Block	0.090	0.217	0.079	0.059
Soil H_2O	0.321	0.660	0.369	0.609

Open field plots not included:

ANCOVA	0.085	0.271	0.057	0.200
CO_2	0.147	0.302	0.145	0.503
Block	0.040	0.220	0.031	0.087
Soil H_2O	0.147	0.128	0.117	0.484

+The first CO_2 value is from open field plots (no chambers); the other values are from within chambers. Values are daytime means.

Table 12. Effect of different CO_2 concentrations on shoot growth (mean ± S.E.) of sweet potato plants grown in the field, in open top chambers and open field plots at 50 days of growth n=3.

CO_2 (umol mol^{-1})	Number of Leaves	Number of Runners	Total Runner Length (cm)	Mean Runner Length (cm)
360+	89.50 ± 8.77	5.50 ± 0.47	184.35 ± 17.55	34.30 ± 2.60
361	55.93 ± 4.67	4.10 ± 0.28	130.77 ± 13.68	30.89 ± 2.10
438	60.50 ± 5.37	3.67 ± 0.24	124.48 ± 13.67	31.80 ± 2.27
514	58.80 ± 4.05	3.53 ± 0.21	121.10 ± 10.35	34.41 ± 2.52
665	67.03 ± 4.15	3.80 ± 0.22	152.57 ± 10.52	40.72 ± 2.33

Analysis of Covariance -- Significance Levels

Open field plots included:

ANCOVA	0.004	0.097	0.001	0.229
CO_2	0.016	0.156	0.040	0.485
Block	0.002	0.072	0.003	0.066
Soil H_2O	0.225	0.589	0.082	0.968

Open field plots not included:

ANCOVA	0.088	0.364	0.008	0.035
CO_2	0.566	0.872	0.525	0.120
Block	0.021	0.113	0.002	0.016
Soil H_2O	0.296	0.347	0.047	0.360

Linear Regression Coefficients

Intercept	91.1	20.4
CO_2	0.0759	0.0345
Soil H_2O	0.614	-0.513

+The first CO_2 value is from open field plots (no chambers); the other values are from within chambers. Values are daytime means.

Table 13. Effect of different CO_2 concentrations on shoot growth (mean ± S.E.) of sweet potato plants grown in the field, in open top chambers and open field plots at 70 days of growth, n=3.

CO_2 (umol mol^{-1})	Number of Leaves	Number of Runners	Total Runner Length (cm)	Mean Runner Length (cm)
360+	161.83 ± 17.70	8.13 ± 0.80	364.28 ± 35.70	45.85 ± 2.80
361	123.80 ± 9.31	6.43 ± 0.43	300.93 ± 25.77	46.35 ± 2.31
438	107.45 ± 9.06	5.24 ± 0.45	254.22 ± 26.45	46.34 ± 2.20
514	108.80 ± 8.69	5.76 ± 0.39	257.38 ± 20.07	44.24 ± 2.05
665	137.67 ± 7.39	7.26 ± 0.54	377.33 ± 25.83	54.52 ± 3.11

Analysis of Covariance -- Significance levels

Open field plots included:

ANCOVA	0.105	0.675	0.028	0.193
CO_2	0.384	0.679	0.480	0.561
Block	0.055	0.789	0.023	0.067
Soil H_2O	0.370	0.786	0.046	0.262

Open field plots not included:

ANCOVA	0.159	0.405	0.041	0.255
CO_2	0.620	0.745	0.379	0.471
Block	0.098	0.565	0.039	0.157
Soil H_2O	0.499	0.431	0.057	0.463

Linear Regression Coefficients

Intercept	-42.7
CO_2	0.225
Soil H_2O	39.1

+The first CO_2 value is from open field plots (no chambers); the other values are from within chambers. Values are daytime means.

Table 14. Effect of different CO_2 concentrations on the number of leaves, total leaf area and harvested leaf area (mean ± S.E.) of sweet potato plants grown in the field, in open top chambers and open field plots at 90 day harvest, n=3.

CO_2 (umol mol^{-1})	Number of Leaves	Total Leaf Area (cm^2)	Mean Leaf Area (cm^2)
360+	169.70 ± 19.41	7711.41 ± 1056	42.89 ± 2.03
361	149.50 ± 14.11	8428.40 ± 989	55.56 ± 3.89
438	143.60 ± 17.98	6146.76 ± 661	44.61 ± 1.72
514	157.40 ± 13.86	7229.38 ± 791	45.08 ± 2.04
665	177.37 ± 14.00	9135.96 ± 746	60.00 ± 1.51

Analysis of Covariance -- Significance Levels

Open field plots included:

ANCOVA	0.344	0.131	0.025
CO_2	0.830	0.895	0.144
Block	0.130	0.067	0.023
Soil H_2O	0.071	0.031	0.030

Open field plots not included:

ANCOVA	0.821	0.410	0.100
CO_2	0.817	0.981	0.627
Block	0.619	0.258	0.062
Soil H_2O	0.388	0.170	0.109

+The first CO_2 value is from open field plot (no chambers); the other values are from within chambers. Values are daytime means.

Table 15. Effect of different CO_2 concentrations on the number of runners, total runner length and average runner length (mean ± S.E.) of field grown sweet potato plants, in open top chambers and open field plots, at 90 day harvest, n=3.

CO_2 (umol mol^{-1})	Numbers of Runners	Total Runner Length (cm)	Mean Runner Length (cm)
360+	15.30 ± 2.22	622.83 ± 75.85	43.84 ± 2.61
361	15.00 ± 1.51	589.83 ± 62.76	40.76 ± 1.98
438	12.37 ± 1.39	454.97 ± 51.96	37.80 ± 1.71
514	13.50 ± 1.50	534.77 ± 54.77	41.82 ± 2.16
665	18.47 ± 1.69	727.67 ± 55.55	43.34 ± 2.42

Analysis of Covariance -- Significance Levels

Open field plots included:			
ANCOVA	0.109	0.071	0.109
CO_2	0.870	0.927	0.354
Block	0.057	0.034	0.068
Soil H_2O	0.032	0.023	0.453
Open field plots not included:			
ANCOVA	0.321	0.261	0.036
CO_2	0.854	0.892	0.036
Block	0.265	0.169	0.026
Soil H_2O	0.161	0.122	0.213

Linear Regression Coefficients

Intercept	33.3
CO_2	0.00826
Soil H_2O	0.564

+The first CO_2 value is from open field plot (no chambers); the other values are from within chambers. Values are daytime means.

Table 16. Effect of different CO_2 concentrations on the fresh weights of green leaves, dead leaves and total leaves (mean ± S.E.) of sweet potato plants grown in the field in open top chambers and open field plots, at 90 day harvest, n=3.

CO_2 (umol mol^{-1})	Fresh Weight (g)		
	Green Leaves	Dead Leaves	Total Leaves
360+	310.77 ± 47.47	12.87 ± 1.95	323.63 ± 48.90
361	355.60 ± 44.67	15.20 ± 2.12	370.80 ± 46.30
438	246.30 ± 26.16	8.07 ± 1.31	254.37 ± 26.68
514	307.53 ± 34.88	8.77 ± 1.41	316.30 ± 35.66
665	430.80 ± 35.36	15.60 ± 2.17	446.40 ± 36.68

Analysis of Covariance -- Significance Levels

Open field plots included:

ANCOVA	0.045	0.072	0.045
CO_2	0.632	0.817	0.658
Block	0.027	0.061	0.027
Soil H_2O	0.014	0.094	0.014

Open field plots not included:

ANCOVA	0.209	0.217	0.206
CO_2	0.910	0.803	0.923
Block	0.147	0.179	0.146
Soil H_2O	0.103	0.305	0.105

+The first CO_2 value is from open field plots (no chambers); the other values are from within chambers. Values are daytime means.

Table 17. Effect of different CO_2 concentrations on dry weights of green leaves, dead leaves and total leaves (mean ± S.E.) of sweet potato plants grown in the field in open top chambers and open field plots, at 90 day harvest, n=3.

CO_2 ($umol\ mol^{-1}$)	Dry Weight (g)		
	Green Leaves	Dead Leaves	Total Leaves
360+	39.33 ± 5.32	4.48 ± 0.73	43.81 ± 5.91
361	37.37 ± 3.20	5.00 ± 0.61	42.37 ± 3.60
438	32.80 ± 3.61	2.92 ± 0.45	35.72 ± 3.84
514	39.77 ± 3.76	2.85 ± 0.37	42.62 ± 3.97
665	48.00 ± 4.29	3.97 ± 0.51	51.97 ± 4.49

Analysis of Covariance -- Significance Levels

Open field plots included:

ANCOVA	0.286	0.158	0.302
CO_2	0.714	0.596	0.857
Block	0.226	0.074	0.220
Soil H_2O	0.060	0.427	0.071

Open field plots not included:

ANCOVA	0.550	0.223	0.565
CO_2	0.682	0.336	0.806
Block	0.577	0.118	0.510
Soil H_2O	0.295	0.787	0.351

+The first CO_2 value is from open field plot (no chambers); the other values are from within chambers. Values are daytime means.

Table 18. Effect of different CO_2 concentrations on the fresh and dry weights of runners and shoots (mean ± S.E.) of sweet potato plants, grown in the field open top chambers and open field plots at 90 day harvest, n=3.

CO_2 (umol mol^{-1})	Fresh Weight (g)		Dry Weight (g)	
	Runner	Shoot	Runner	Shoot
360+	141.83 ± 20.06	465.47 ± 59.4	22.31 ± 2.71	66.12 ± 8.49
361	151.57 ± 18.3	522.37 ± 64.4	20.40 ± 2.21	62.77 ± 5.72
438	107.47 ± 11.83	361.83 ± 38.14	17.10 ± 2.19	52.83 ± 5.61
514	126.20 ± 14.21	442.50 ± 49.27	17.77 ± 1.61	60.38 ± 5.49
665	181.83 ± 15.16	628.23 ± 50.24	24.73 ± 2.04	76.70 ± 6.38

Analysis of Covariance -- Significance levels

Open field plots included:

ANCOVA	0.024	0.038	0.051	0.180
CO_2	0.853	0.711	0.917	0.890
Block	0.008	0.019	0.044	0.135
Soil H_2O	0.015	0.014	0.010	0.038

Open field plots not included:

ANCOVA	0.134	0.183	0.209	0.434
CO_2	0.950	0.931	0.905	0.861
Block	0.064	0.116	0.174	0.384
Soil H_2O	0.104	0.103	0.063	0.209

+The first CO_2 value is from open field plots (no chambers); the other values are from within chambers. Values are daytime means.

Table 19. Effect of different CO_2 concentrations on tuberous root number, volume, and density (mean ± S.E.) of sweet potato plants, grown in the field in open top chambers and open field plots at 90 day harvest, n=3.

CO_2 (umol mol^{-1})	Number of Tuberous Roots	Tuberous Root Volume (cm^3)	Tuberous Root Density (g/cm^3)
360+	5.87 ± 0.452	664 ± 77	1.08 ± 0.02
361	5.37 ± 0.405	435 ± 43	1.01 ± 0.02
438	6.43 ± 0.538	535 ± 50	1.03 ± 0.02
514	6.53 ± 0.469	595 ± 58	1.06 ± 0.03
665	7.04 ± 0.567	718 ± 49	1.06 ± 0.02

Analysis of Covariance — Significance Levels

Open field plots included:

ANCOVA	0.052	0.002	0.306
CO_2	0.129	0.002	0.252
Block	0.030	0.001	0.304
Soil H_2O	0.636	0.010	0.840

Open field plots not included:

ANCOVA	0.041	0.030	0.034
CO_2	0.078	0.017	0.059
Block	0.071	0.060	0.014
Soil H_2O	0.859	0.200	0.023

Linear Regression Coefficients

Intercept	7.78	328	0.985
CO_2	0.00442	0.887	0.000159
Soil H_2O	-0.461	-24.9	-0.00319

+The first CO_2 value is from open field plots (no chambers); the other values are from within chambers. Values are daytime means.

Table 20. Effect of different CO_2 concentrations on tuberous roots and total plant fresh weights (mean ± S.E.) of sweet potato plants grown in the field, in open top chambers and open field plots at 90 day harvest, n=3.

CO_2 (umol mol^{-1})	Fresh Weight (g)	
	Tuberous Roots	Total Plant
360+	706.30 ± 81.49	1172.00 ± 146.79
361	435.40 ± 42.35	957.00 ± 96.00
438	549.40 ± 54.36	911.00 ± 90.29
514	611.50 ± 56.89	1054.00 ± 99.87
665	759.20 ± 53.25	1358.00 ± 97.62

Analysis of Covariance -- Significance Levels

Open field plots included:		
ANCOVA	0.003	0.003
CO_2	0.002	0.014
Block	0.002	0.001
Soil H_2O	0.010	0.002
Open field plots not included:		
ANCOVA	0.032	0.050
CO_2	0.015	0.042
Block	0.011	0.033
Soil H_2O	0.029	0.052

Linear Regression Coefficients

Intercept	262
CO_2	1.01
Soil H_2O	-22.3

+The first CO_2 value is from open field plots (no chambers); the other values are from within chambers. Values are daytime means.

Table 21. Effect of different CO_2 concentrations on tuberous roots and total plant dry weights and tuberous root:shoot ratio (mean ± S.E.) of sweet potato plants grown in the field, in open top chambers and open field plots at 90 day harvest, n=3.

CO_2 (umol mol^{-1})	Dry Weight (g)		Tuberous Root:Shoot Ratio
	Tuberous Roots	Total Plant	
360+	125.55 ± 11.74	191.67 ± 19.52	2.21 ± 0.14
361	80.40 ± 7.73	143.17 ± 12.04	1.38 ± 0.12
438	104.30 ± 10.52	157.13 ± 15.60	2.07 ± 0.10
514	115.96 ± 10.70	176.34 ± 15.48	2.05 ± 0.15
665	135.64 ± 9.38	209.14 ± 15.10	1.99 ± 0.11

Analysis of Covariance -- Significance Levels

Open field plots included:

ANCOVA	0.003	0.010	0.151
CO_2	0.002	0.011	0.447
Block	0.006	0.007	0.562
Soil H_2O	0.028	0.008	0.047

Open field plots not included:

ANCOVA	0.029	0.076	0.055
CO_2	0.013	0.036	0.271
Block	0.089	0.080	0.252
Soil H_2O	0.167	0.082	0.056

Linear Regression Coefficients

Intercept	62.8
CO_2	0.169
Soil H_2O	- 4.73

+The first CO_2 value is from open field plots (no chambers); the other values are from within chambers. Values are daytime means.

C. Effect of CO_2 on Photosynthesis

1. Experimental Design and Methodology

Photosynthesis was measured in leaves of field grown plants at different temperatures and light levels using a controlled-climate cuvette and a differential infrared gas analyzer. The photosynthesis apparatus was designed so as to be able to measure steady state exchange of both CO_2 and water under controlled conditions of light, temperature, humidity and CO_2 concentration.

Leaf cuvette: The leaf cuvette was constructed of clear, acrylic plastic lined on the internal surfaces with clear Teflon film. The top could be removed for leaf insertion. The leaf was held horizontally inside the cuvette between two networks of nylon threads. After insertion of the leaf, the slot for the petiole was plugged with an acrylic plastic insert and sealed with Apiezon sealing compound.

Temperature was controlled by Peltier cooling. The heat exchanger formed the bottom of the cuvette. A fan mounted in the heat exchanger mixed the cuvette air and forced air upwards toward the bottom of the leaf. Light was provided by indirect natural skylight supplemented with 4 slide projector bulbs (type EYF) mounted approximately 33 cm above the leaf. Direct sunlight was blocked from hitting the cuvette by a beach umbrella, so that fluctuations in light level caused by clouds did not prevent the attainment of steady state.

Gas control system: The infrared gas analyzer (IRGA) and the gas control system (Fig. 3) were mounted on a garden cart for transportation to the field. The gas cylinders were transported to the field in a separate

garden cart. CO_2 concentrations were measured with a differential infrared gas analyzer (Binos Type 4b.1). The IRGA was calibrated using pairs of standard gases that were calibrated against a series of reference standards using an absolute IRGA (Binos Type 4b.1T). The zero-point standard was approximately equal to the daytime CO_2 concentration in the open top chamber. The span standard was about 40 umol mol^{-1} below the zero-point standard.

Gas supplied to the leaf was mixed from two cylinders: one containing about 3000 umol mol^{-1} CO_2 in 20% oxygen and 80% nitrogen, and one containing only 20% oxygen and 80% nitrogen. Gases from the cylinders passed through two mass flow controllers (Tylan Model FC-260) which were used to set the CO_2 concentration in the gas supplied to the cuvette equal to the concentration of the zero-point standard.

Air supplied to the cuvette was humidified by passing a portion of the incoming gas stream through a gas washing bottle containing water. Humidity in the cuvette was monitored by passing the air leaving the cuvette through a dew point hygrometer. The gas was dried with magnesium perchlorate before entering the IRGA. Relative humidity in the cuvette was maintained at about 60% (approximate normal daytime level in Alabama in the summer) by altering the fraction of the incoming air that passed through the gas washing bottle.

After the gas was humidified, the gas stream was divided. Part of the gas passed into the leaf chamber; the rest bypassed the chamber and was vented. For each measurement, after steady state was attained, the gas flow was switched to that the gas bypassing the chamber was diverted to the IRGA and the gas leaving the chamber was vented. This provided

measurements of the CO_2 concentration and dew point of the gas stream supplied to the chamber.

Measurement procedures: After the leaf was inserted in the cuvette it was allowed to equilibrate for about one hour at a leaf temperature of 30 ^{o}C and maximum light (> 1500 uEinsteins m^{-2} s^{-1}). Steady-state measurements were then taken at 30^{o}C at progressively lower light levels by placing blackened screens on top of the cuvette until the light level reached about 25 uEinsteins m^{-2} s^{-1}. The light level was then raised to the maximum (> 1500 uEinsteins m^{-2} s^{-1}) and measurements were taken at 30, 35 and 25^{o}C.

Because of time constraints, one open top chamber from each treatment was randomly selected for photosynthesis measurements. The measurement order of the treatments was randomized, except for the open field treatment which was measured last. The five measurements were conducted between 10-14 August when the plants were 81-85 days old. The weather during the measurement days was mostly sunny with scattered clouds, air temperatures of about 28 to 32^{o} C, and relative humidities of 50 to 65%. The soil was moderately moist, but not well-watered. Rainfall amounts of 2.41, 0.39 and 0.61 cm fell in the evenings of 7, 9 and 11 August, respectively. Only leaves that were from the top of the canopy and that were 4 to 6 nodes down from a growing shoot tip were used. Otherwise, plant and leaf selection within each chamber were largely determined by the size of the cuvette and by the desire to minimize the disturbance to the plants.

2. Results and Discussion

Because of the lack of replication, the data can only be considered preliminary. However, the data do show some interesting trends. At low

levels of light, there was no difference in photosynthesis between the CO_2 treatments, but at light levels above 400 uEinsteins m^{-2} s^{-1} leaves grown and measured at 500 and 650 umol mol^{-1} CO_2 showed greater rates of net photosynthesis (on a leaf area basis) than leaves grown and measured at 350 and 420 umol mol^{-1} CO_2 (Fig. 4). This was due mainly to a higher light saturation point, indicating that under ambient conditions CO_2 is limiting to photosynthesis when the light level exceeds 400 uEinsteins m^{-2} s^{-1}. Photosynthesis did not show as great an increase with CO_2 when expressed on a dry weight basis, and specific leaf weight increased with increasing CO_2 (Table 22), indicating that some of the increase in photosynthesis at elevated CO_2 levels was due to increased leaf thickness.

There was no effect of temperatures between 25 and 35 ^{o}C on photosynthesis (Fig. 5). Transpiration increased with increasing temperature and showed a tendency to decrease with increasing CO_2 (Fig. 6, Table 22). Stomatal conductance did not seem to be affected by CO_2 (Table 22). This is similar to our previously reported work on stomatal conductance on sweet potatoes grown in the field under elevated CO_2 (Biswas et al. 1985).

Water use efficiency (expressed as moles H_2O/moles CO_2) increased (i.e. lower values), with increasing CO_2, mainly due to increased photosynthesis (Table 22). Thus, it appears that under conditions of elevated CO_2 and moderate soil moisture, sweet potatoes do not exhibit stomatal closure to the degree shown by other agricultural plants. However, sweet potatoes grow well under moderately dry conditions, and stomatal conductance may respond differently to CO_2 under water stress conditions (see the water stress study in this report).

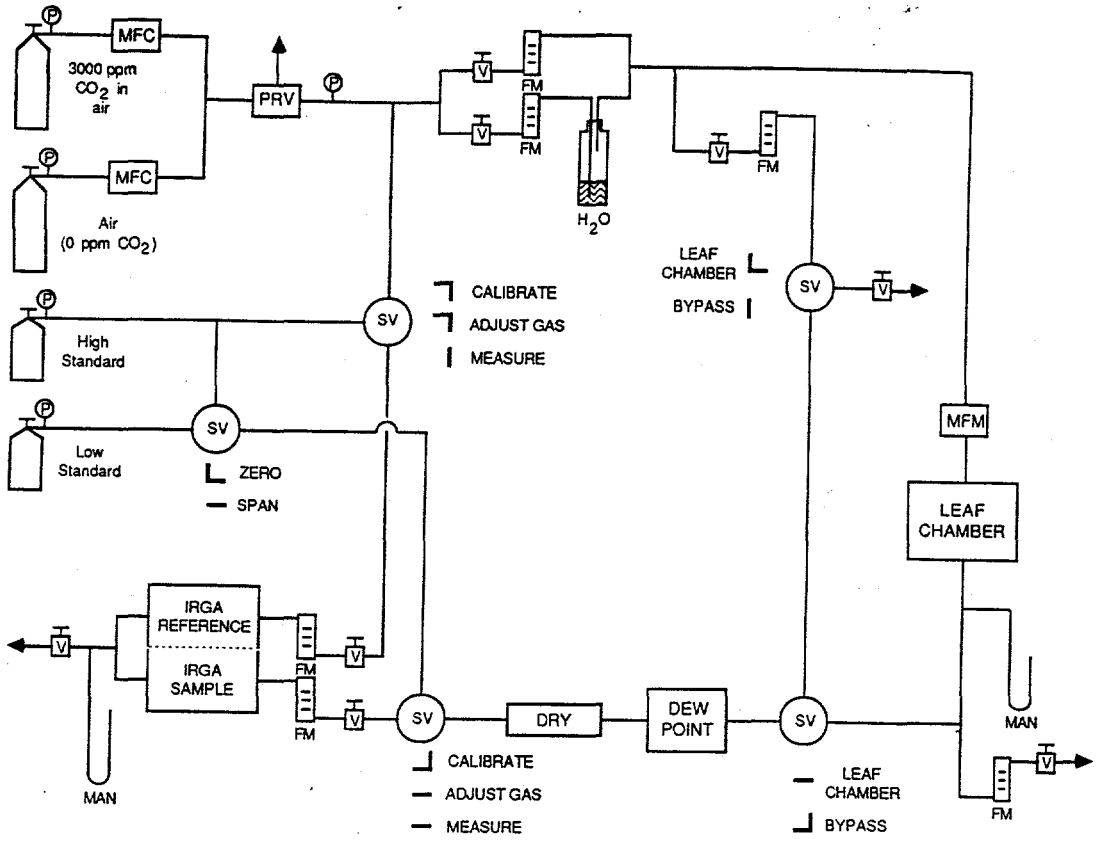

Figure 3. Open flow system used for measuring photosynthesis in the field. DEW POINT = dew point hygrometer; DRY = drying tube filled with magnesium perchlorate; FC = mass flow controller; IRGA = infrared gas analyzer; MFM = mass flow meter; PRV = pressure release valve; SV = solenoid valve; small round circle = pressure gauge; small square box with "T" on top = needle valve; rectangular box with lines = flow meter; "U" shaped branch off of gas line = water manometer; arrow = gas release point. Letters next to solenoid valves identify the valve ports. Lines next to solenoid valves indicate direction of gas flow in the different modes of operation.

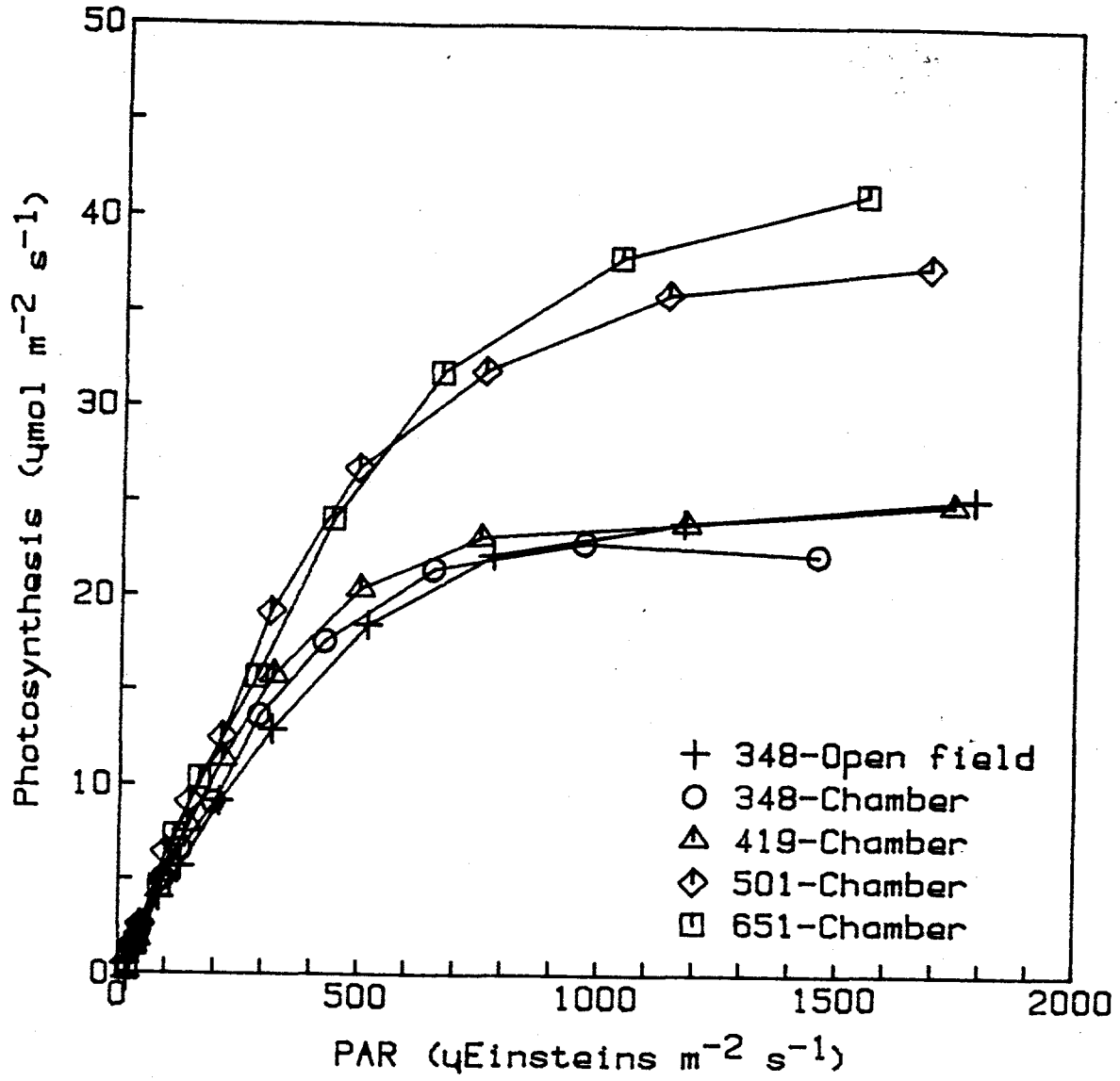

Figure 4. Effect of photosynthetically active radiation (PAR) on net photosynthesis of sweet potatoes grown in the open field and in open top chambers at different levels of CO_2. The CO_2 values refer to the levels in the leaf cuvette, which were approximately the same as the levels in the open top chambers. Measurements were made from proceeding from the highest light level to the lowest. Measurements were made at a leaf temperature of 30° C. Each curve represents a single curve from a single leaf.

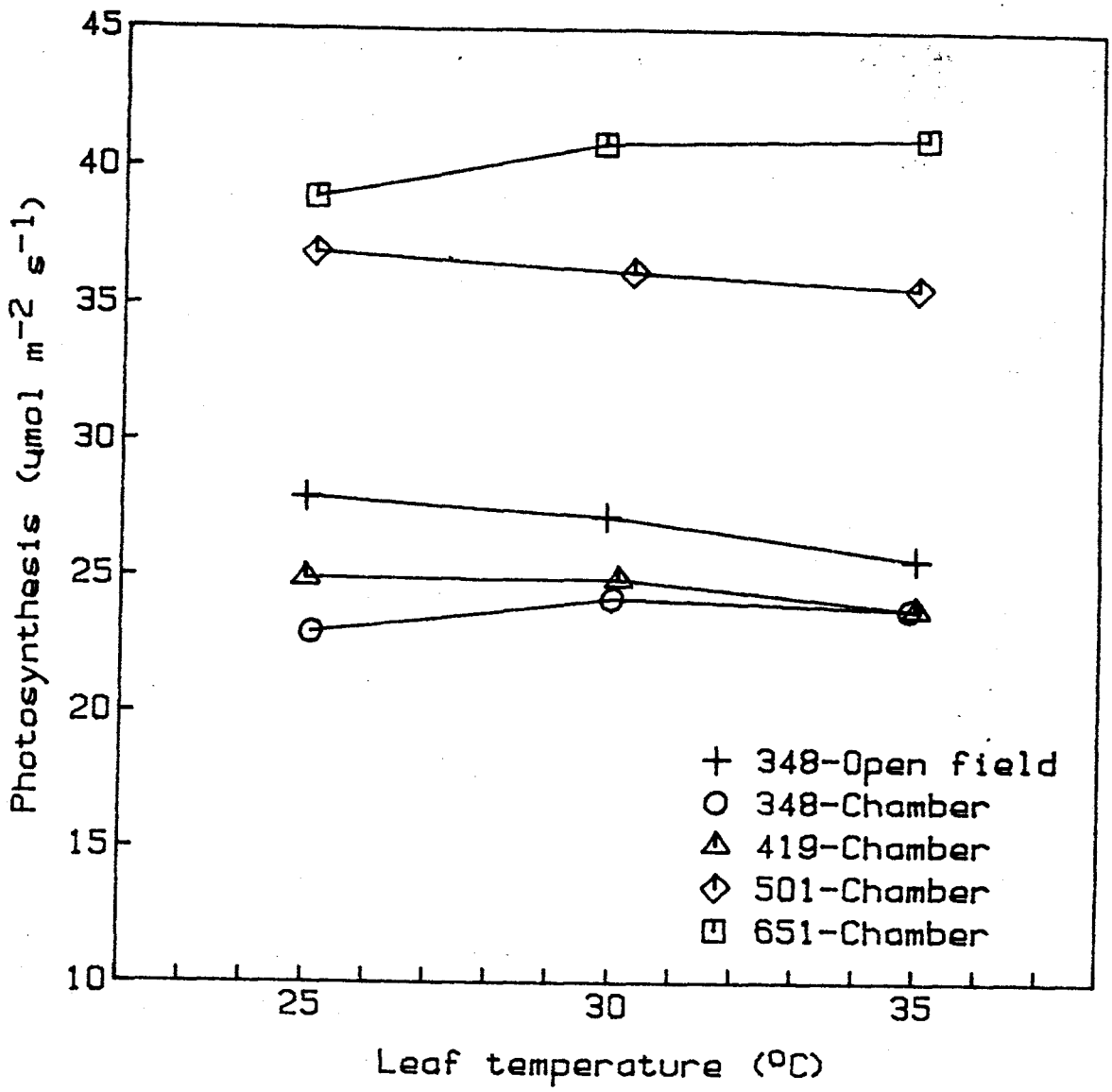

Figure 5. Effect of leaf temperature on net photosynthesis of sweet potatoes grown in the open field and in open top chambers at different levels of CO_2. The CO_2 values refer to the levels in the leaf cuvette, which were approximately the same as the levels in the open top chambers. Measurements were made in the order: 30, 35, 25° C. Measurements are interpolated to a light level of 1500 uEinsteins m^{-1} s^{-1} using the light curves shown in Figure 4. Each curve represents a single curve from a single leaf.

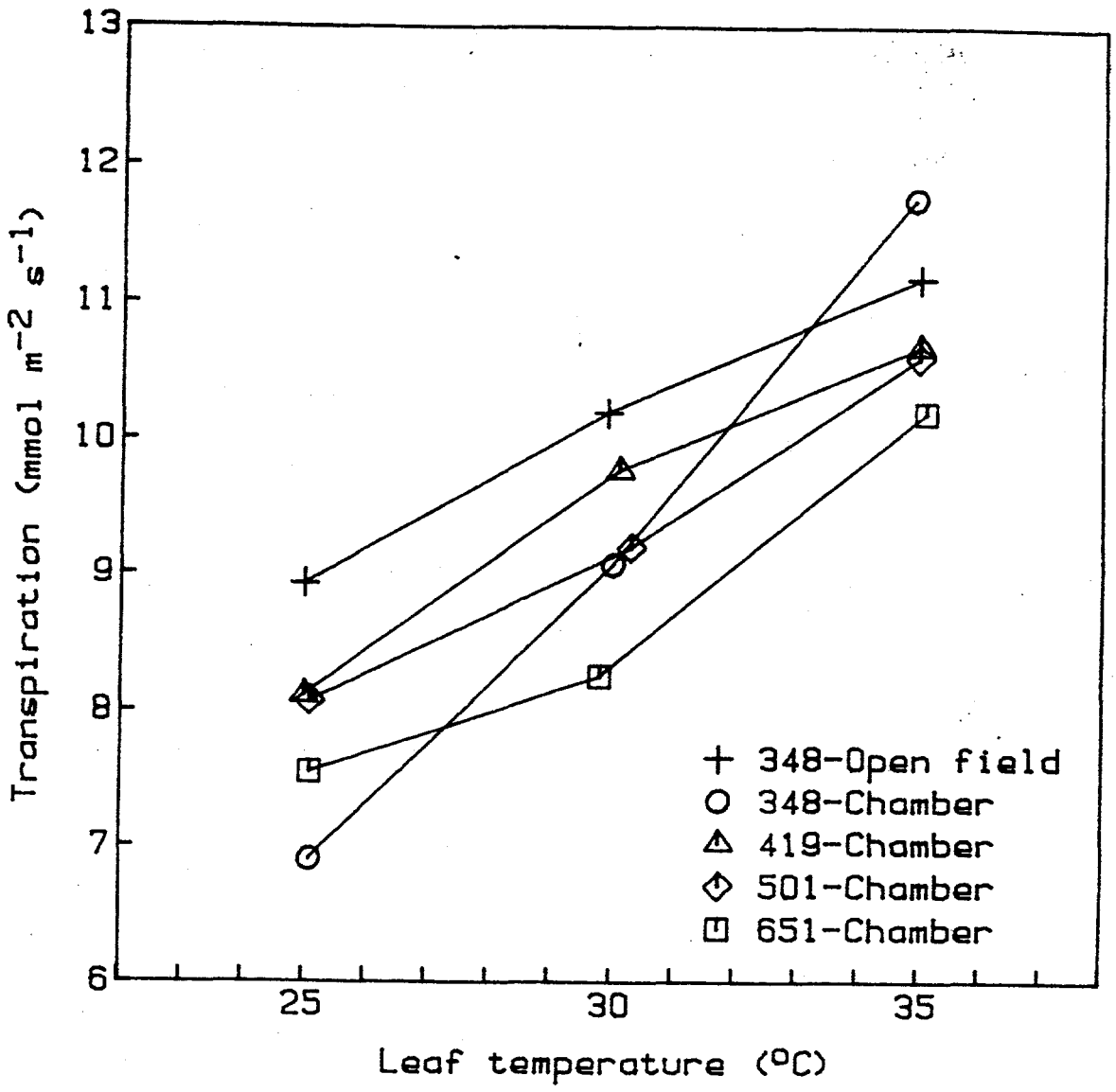

Figure 6. Effect of leaf temperature on transpiration of sweet potatoes grown in the open field and in open top chambers at different levels of CO_2. The CO_2 values refer to the levels in the leaf cuvette, which were approximately the same as the levels in the open top chambers. Measurements were made in the order: 30, 35, 25° C. Measurements are interpolated to a light level of 1500 uEinsteins m^{-1} s^{-1} using the light curves shown in Figure 4. Each curve represents a single curve from a single leaf.

Table 22. Effect of CO_2 concentration on photosynthesis, leaf density, conductance, transpiration and water use efficiency of sweet potatoes grown in open top chambers and in an open field plot. Values represent the means of 2 determinations on a single leaf at 30°C interpolated to a light level of 1500 uEinsteins m^{-1} s^{-1}.

CO_2 (umol mol-1)		Photosynthesis		Specific Leaf Weight	Stomatal Conductance	Transpiration	Water Use Efficiency
Growth	Cuvette	(umol m^{-2} s^{-1})	(umol g^{-1} s^{-1})	(g m^{-2})	(cm s^{-1})	(mmol m^{-2} s^{-1})	(mol mol^{-1})
360+	348+	25.6	0.562	45.6	1.39	8.89	345
363	348	23.2	0.668	34.7	1.34	8.99	388
439	419	24.4	0.610	39.9	1.21	8.73	358
515	501	36.3	0.710	51.0	1.32	8.69	240
666	651	40.9	0.773	52.9	1.37	8.35	204

+The first pair CO_2 values (360/348) is from the open field plot (no chamber); the other values are from within chambers. [2]Growth values are daytime means. Cuvette values represent concentrations in the gas supplied to the leaf cuvette during measurement.

IV. POT STUDIES

A. Growth Measurements and Growth Analysis

1. Experimental design and methodology

Sweet potato (Ipomoea batatas 'Georgia Jet') plants, which were 20-25 cm long and which had 4-5 leaves, were planted on 17 May in two different sizes (30 x 25 x 28 cm and 15 x 10 x 15 cm) of plastic pots containing 18.5 kg and 10.5 kg of Norfolk sandy loam soil (Typic Paleudult), plus a bottom layer of 4.5 kg and 2.0 kg of gravel respectively. There were 24 pots for each treatment: 8 pots each for the first and second harvests, and 8 pots for growth measurements and the third harvest.

The pots were maintained in the field in one open field plot and in four open top chambers with target CO_2 levels of 0, 75, 150 and 300 umol mol^{-1} above ambient. Actual season-long daytime mean CO_2 levels were 361 (open field plot), 364 (ambient chamber), 438, 514 and 666 umol mol^{-1} (Table 4).

Fertilizer was applied at a rate of 0.94 g of ammonium nitrate and 1.35 g of a mixture of muriate of potash and superphosphate per pot at the time of planting, plus an additional 0.47 g of ammonium nitrate per pot at 55 days of growth. Plants were watered by hand to the drip point whenever soil tensiometers read -30 to -35 centibars, as a supplement to natural rainfall. The plants were moved within the chambers periodically, to overcome position effects.

The number of leaves and the number and length of runners were recorded at 4 day intervals on the growth measurement plants. A group of 8 plants from each treatment were harvested at 30 and 45 days after planting. The plants used for the growth measurements were harvested 90 days after planting. Dry weights of leaves, runners, and roots were determined after drying at 70 ^{o}C for 48 hrs. Leaf area was determined using a LI-COR LI-3100 area meter.

2. Growth analysis calculations

The following growth characteristics were calculated using growth analysis techniques described by Kvet et al. (1971): (1) net assimilation rate (NAR), the amount of dry matter produced per unit leaf area per unit time (kg m^2 day^{-1}); (2) relative growth rate (RGR), the increase in dry matter per kg dry weight per day (kg kg^{-1} day^{-1}); (3) biomass increment (ΔW), the amount of dry matter produced each interval; and (4) specific leaf weight (SLW), the amount of leaf dry weight per unit of leaf area (kg m^2). The area and dry weight of abscised leaves (collected on alternate days) were added to the area and dry weight of green leaves in the last two harvests (45 and 90 days).

3. Results

Growth measurements: The length of the main stem increased more rapidly in 666 umol mol^{-1} CO_2 than in any other CO_2 treatment during 25 to 75 days (Fig. 7); thereafter the growth of the main stem ceased, regardless of the CO_2 concentration. The production of new branches occurred one week earlier in 514 umol mol^{-1} CO_2 than 361, 364, 438, and 666 umol mol^{-1} CO_2 (Fig. 8) while at later stages of growth (25 to 62 days) production of new branches increased rapidly at 666

umol mol^{-1} CO_2 as compared to the other CO_2 treatments. The number of branches did not show any significant increase at 438, 514, 361, or 364 umol mol^{-1} CO_2 during 25 to 62 days, however it increased rapidly in these treatments during 62 to 77 days.

The total branch length showed the greatest initial increase at 666 umol mol^{-1} CO_2 (7 to 18 days), but it increased more rapidly at 514 and 438 umol mol^{-1} CO_2 during 20 to 25 days (Fig. 9). The total branch length continued to increase at 361 (open field) and 364 umol mol^{-1} CO_2 at 65 to 90 days; however, it did not increase much in 666 umol mol^{-1} CO_2 environment.

The number of leaves at elevated CO_2 levels increased significantly during middle of the growth period (32 to 50 days), but at earlier or later stages of growth, the number of leaves did not differ among the CO_2 treatments (Fig. 10). Throughout the growing period, leaf area did not differ significantly among the treatments, but there was a tendency towards increased leaf area at elevated CO_2 levels at the 90 day harvest (Tables 23, 26, 29).

Growth analysis: The specific leaf weight (SLW) was highest in 666 umol mol^{-1} CO_2 grown plants at 30 days and remained unchanged between 30 to 45 days (Table 34). The SLW increased slightly at 45 days in the 361 (open field), 364, 438 and 514 umol mol^{-1} CO_2 treatments, but subsequently decreased in 361 (open field) and 364 umol mol^{-1} CO_2 at 90 days of growth. It is interesting to note that SLW increased again in 514 and 666 umol mol^{-1} CO_2 at 90 days (Table 34).

The ΔW increased in 514 and 666 umol mol^{-1} CO_2 in comparison to 361 and 364 umol mol^{-1} CO_2 during 30 to 45 days (Table 35).

Between 45 and 90 days of growth ΔW was higher in all three elevated CO_2 treatments.

The relative growth rate (RGR) of all plants decreased with age of plants (Table 35). Between 30 and 45 days there was no clear correlation between RGR and CO_2. However, between 45 and 90 days, RGR was increased in the elevated CO_2 treatments.

The net assimilation rate (NAR) was increased by CO_2 enrichment during both the 30-45 day and the 45-90 day growth periods, as compared to the 361 (open field) and 364 umol mol^{-1} CO_2 environments (Table 35). However, it may be noted that increase in NAR at enriched CO_2 was greater during early than later stages of growth.

4. Discussion

The rapid growth of the main stem in response to high CO_2 may be associated with rapid utilization of additional photosynthate that might have been produced at elevated CO_2. An increased rate of photosynthesis in response to CO_2 enrichment has been documented in literature (Akita and Tanaka 1973, Cooper and Brun 1967, Ford and Thorne 1967, Hurd 1968, Sionit et al. 1984; see also Chapter III-B of this report).

Similarly, increases in total branch length occurred more rapidly in elevated CO_2 during the early period of growth. However, branch growth slowed earlier in elevated CO_2, and the differences in total branch length between treatments decreased towards the end of the growth period. It may be inferred from these observations that effect of enriched CO_2 on shoot growth was more pronounced during the early stages of growth. The increase in number of branches in response to CO_2 enrichment has been

reported in other plants as well. (Cooper and Brun 1967, Krizek et al. 1968, 1971, 1974, Bhattacharya et al. 1985a, 1985b). The significant increase of tiller production by CO_2 enrichment and high nutrients has been reported for rice (Imai and Murata 1976) and wheat (Sionit et al. 1981a).

The increase in the number of leaves as well as leaf area at enriched CO_2 after 90 days of growth may be associated with increased interception of light intensity for photosynthesis resulting in the production of additional photosynthate. According to Sinclair et al. (1981) growth of leaves is of great importance in determining light interception and hence crop yield.

The specific leaf weight (SLW) did not change during 30-45 days at 666 umol mol^{-1} CO_2 while it increased in this environment during 45-90 days but decreased at 361, 364, 438 umol mol^{-1} CO_2 during the same period. The decrease in SLW during 30-45 days may be associated with rapid growth of tubers causing thereby a strong sink demand for photo-assimilates. In fact, Bhattacharya et al. (1985a) reported that tuber growth of sweet potato (Ipomoea batatas cv. Georgia Jet) is source limited under present ambient CO_2 conditions and sink capacity modified the production of tubers in response to elevated CO_2 concentrations. The increase of SLW at elevated CO_2 has been reported in faba bean [Vicia faba (L.)], poplar [Populus euramexicana (Dode) 'Robusta'] (Goudriaan and de Ruiter 1983) and in soybean (Sionit 1983).

The ΔW increased in enriched CO_2 with ageing of plants in contrast to gradual decrease in relative growth rate (RGR) and net assimilation rate (NAR) during the same time interval resulting in the more rapid accumulation of biomass at high CO_2 than at low CO_2. The greater

NAR during the early growth stages may be attributed to active vegetative growth as well as to accumulation of photoassimilates, while at the later growth stages, growth appeared to be associated with translocation of reserved carbohydrates for the development of tubers. Our present findings are in agreement with earlier reports on source-sink relationships in sweet potato (Hahn 1977, Kato et al. 1979, Bhattacharya et al. 1985a).

Table 23. Effect of different CO_2 concentrations on the leaf area, of leaves and main runner length of sweet potato plants grown in pots in open top chambers and an open field plot at 30 day harvest, n=8.

CO_2 (umol mol^{-1})	Leaf Area (cm^2)	Main Runner Length (cm)	Number of Leaves
361+	598.48[a]	20.88[a]	25.25[ab]
364	656.45[a]	18.00[a]	25.14[ab]
438	564.52[a]	19.79[a]	26.86[a]
514	514.78[a]	21.38[a]	20.00[ab]
666	623.32[a]	22.25[a]	18.88[b]
$\bar{Sx}$*	25	1.07	1.11
CV(%)*	26	32.3	30

+The first CO_2 value (361) is from the open field plot (no chamber); the other values are from within chambers. Values for CO_2 are daytime means.

*$\bar{Sx}$ and CV(%) are from ANOVA

[a]Within each column, values sharing the same letter are not significantly different at the 0.05 level, according to Duncan's Multiple Range Test.

Table 24. Effect of different CO_2 concentrations on the dry weights of leaves, runners and roots of sweet potato plants grown in pots in open top chambers and an open field plot at 30 day harvest, n=8.

CO_2 (umol mol^{-1})	Dry Weight (g)		
	Leaf	Runner	Root
361+	3.32[b]	0.90[a]	5.66[a]
364	3.64[ab]	1.13[a]	4.54[a]
438	3.32[b]	0.97[a]	4.82[a]
514	2.93[b]	0.84[a]	4.44[a]
666	4.62[a]	1.24[a]	5.48[a]
$S\bar{x}$*	0.2	0.07	0.29
CV(%)*	34.1	42	35

+The first CO_2 value (361) is from the open field plot (no chamber); the other values are from within chambers. Values for CO_2 are daytime means.

*$S\bar{x}$ and CV(%) are from ANOVA.

[a]Within each column, values sharing the same letter are not significantly different at the 0.05 level, according to Duncan's Multiple Range Test.

Table 25. Effect of different CO_2 concentrations on shoot dry weight and the root:shoot ratio of sweet potato plants grown in pots in open top chambers and an open field plot at 30 day harvest, n=8.

CO_2 (umol mol^{-1})	Shoot Dry Weight (g)	Root:Shoot Ratio
361+	4.21[ab]	1.36[a]
364	4.77[ab]	0.96[b]
438	4.29[ab]	1.12[ab]
514	3.77[b]	1.18[ab]
666	5.87[a]	0.95[b]
$\bar{Sx}$*	0.26	0.05
CV(%)*	34.7	26.1

+The first CO_2 value (361) is from the open field plot (no chamber); the other values are from within chambers. Values for CO_2 are daytime means.

*$\bar{Sx}$ and CV(%) are from ANOVA

[a]Within each column, values sharing the same letter are not significantly different at the 0.05 level, according to Duncan's Multiple Range Test.

Table 26. Effect of different CO_2 concentrations on the leaf area, number of leaves and main runner length of sweet potato plants grown in pots in open top chambers and an open field plot at 45 day harvest, n=8.

CO_2 (umol mol^{-1})	Leaf Area (cm^2)	Number of Leaves	Main Runner Length (cm)
361+	774.1[a]	39.38[a]	33.8[ab]
364	1161.5[a]	42.38[a]	26.6[b]
438	747.8[a]	34.63[a]	34.6[ab]
514	1019.1[a]	39.00[a]	41.6[a]
666	1076.9[a]	40.88[a]	41.5[a]
$\overline{Sx}$*	77.5	2.48	1.58
CV(%)*	51.3	40.0	28.0

+The first CO_2 value (361) is from the open field plot (no chamber); the other values are from within chambers. Values for CO_2 are daytime means.

*$\overline{Sx}$ and CV(%) are from ANOVA.

[a]Within each column, values sharing the same letter are not significantly different at the 0.05 level, according to Duncan's Multiple Range Test.

Table 27. Effect of different CO_2 concentrations on the dry weights of leaves, runners, and fibrous and tuberous roots of sweet potato plants grown in pots in open top chambers and an open field plot at 45 day harvest, n=8.

CO_2 (umol mol^{-1})	Dry Weight (g)			
	Leaf	Runner	Fibrous Roots	Tuberous Roots
361+	4.84[a]	4.47[b]	10.81[a]	8.86[a]
364	6.85[a]	4.14[b]	8.54[a]	12.60[a]
438	4.39[a]	7.50[a]	7.50[a]	11.50[a]
514	6.61[a]	4.13[b]	8.28[a]	15.68[a]
666	8.20[a]	4.88[b]	10.46[a]	13.54[a]
$\bar{Sx}$*	0.58	0.41	0.67	1.52
CV(%)*	59	51.6	47	77

+The first CO_2 value (361) is from the open field plot (no chamber); the other values are from within chambers. Values for CO_2 are daytime means.

*$\bar{Sx}$ and CV(%) are from ANOVA

[a]Within each column, values sharing the same letter are not significantly different at the 0.05 level, according to Duncan's Multiple Range Test.

Table 28. Effect of different CO_2 concentrations on the dry weights of shoots and roots (fibrous + tuberous) and on the root:shoot ratio of sweet potato plants grown in pots in open top chambers and an open field plot at 45 day harvest, n=8.

CO_2 (umol mol^{-1})	Dry Weight (g)		Root:Shoot Ratio
	Shoot	Fibrous + Tuberous Roots	
361+	9.31[a]	19.67[a]	2.07[ab]
364	10.99[a]	21.14[a]	1.90[ab]
438	11.89[a]	19.00[a]	1.63[b]
514	10.74[a]	23.96[a]	2.24[a]
666	13.08[a]	23.99[a]	1.97[ab]
$\bar{Sx}$*	0.88	1.77	0.08
CV(%)*	49.7	51.8	25.2

+The first CO_2 value (361) is from the open field plot (no chamber); the other values are from within chambers. Values for CO_2 are daytime means.

*$\bar{Sx}$ and CV(%) are from ANOVA

[a]Within each column, values sharing the same letter are not significantly different at the 0.05 level, according to Duncan's Multiple Range Test.

Table 29. Effect of different CO_2 concentrations on the leaf area, number of leaves and main runner length of sweet potato plants grown in pots in open top chambers and an open field plot at 90 day harvest, n=8.

CO_2 (umol mol^{-1})	Leaf Area (cm^2)	Number of Leaves	Main Runner Length (cm)
361+	1910.2[b]	90.25[a]	36.4[b]
364	2105.0[ab]	89.13[a]	41.88[ab]
438	2242.2[a]	91.88[a]	40.38[ab]
514	2123.9[ab]	98.50[a]	43.88[ab]
666	2012.3[ab]	93.50[a]	52.00[a]
$\bar{Sx}$*	46.28	2.70	2.00
CV(%)*	14	18.3	30

+The first CO_2 value (361) is from the open field plot (no chamber); the other values are from within chambers. Values for CO_2 are daytime means

*$\bar{Sx}$ and CV(%) are from ANOVA.

[a]Within each column, values sharing the same letter are not significantly different at the 0.05 level, according to Duncan's Multiple Range Test.

Table 30. Effect of different CO_2 concentrations on the dry weights of leaves, runners and fibrous and tuberous roots of sweet potato plants grown in pots in open top chambers and an open field plot at 90 day harvest, n=8.

CO_2 ($umol\ mol^{-1}$)	Dry Weight (g)			
	Leaf	Runner	Fibrous Roots	Tuberous Roots
361+	11.87[bc]	8.30[bc]	8.30[a]	52.00[a]
364	10.69[c]	7.51[c]	8.34[a]	60.59[a]
438	13.08[ab]	10.41[ab]	6.12[a]	70.15[a]
514	15.06[a]	11.00[a]	9.00[a]	70.51[a]
666	14.97[a]	11.00[a]	6.77[a]	71.43[a]
$\overline{Sx}$*	0.42	2.00	0.59	2.93
CV(%)*	20	30	48.1	29

+The first CO_2 value (361) is from the open field plot (no chamber); the other values are from within chambers. Values for CO_2 are daytime means.

*$\overline{Sx}$ and CV(%) are from Anova.

[a]Within each column, values sharing the same letter are not significantly different at the 0.05 level, according to Duncan's Multiple Range Test.

Table 31. Effect of different CO_2 concentrations on the fresh weights of fibrous and tuberous roots of sweet potato plants grown in pots in open top chambers and an open field plot at 90 day harvest, n=8.

CO_2 (umol mol^{-1})	Fresh Weight (g)	
	Fibrous Roots	Tuberous Roots
361+	51.06[a]	328.85[a]
364	51.41[a]	364.87[a]
438	42.00[a]	400.75[a]
514	57.31[a]	388.19[a]
666	38.35[a]	395.89[a]
$\bar{Sx}$*	4.19	18
CV(%)*	31	13

+The first CO_2 value (361) is from the open field plot (no chamber); the other values are from within chambers. Values for CO_2 are daytime means.

*$\bar{Sx}$ and CV(%) are from ANOVA

[a]Within each column, values sharing the same letter are not significantly different at the 0.05 level, according to Duncan's Multiple range test.

Table 32. Effect of different CO_2 concentrations on the dry weights of shoots and roots (fibrous + tuberous) and on the root:shoot ratio of sweet potato plants grown in pots in open top chambers and an open field plot at 90 day harvest, n=8.

CO_2 ($umol\ mol^{-1}$)	Dry Weight (g)		Root:Shoot Ratio
	Shoot	Fibrous + Tuberous Roots	
361+	20.17[bc]	60.31[b]	3.03[a]
364	18.20[c]	68.93[ab]	3.89[a]
438	23.49[ab]	76.28[ab]	3.3[a]
514	26.07[a]	79.51[a]	3.15[a]
666	25.93[a]	78.21[ab]	3.04[a]
$\bar{Sx}$*	0.78	2.76	0.13
CV(%)*	21.6	24.1	25.7

+The first CO_2 value (361) is from the open field plot (no chamber); the other values are from within chambers. Values for CO_2 are daytime means.

*$\bar{Sx}$ and CV(%) are from ANOVA

[a]Within each column, values sharing the same letter are not significantly different at the 0.05 level, according to Duncan's Multiple Range test.

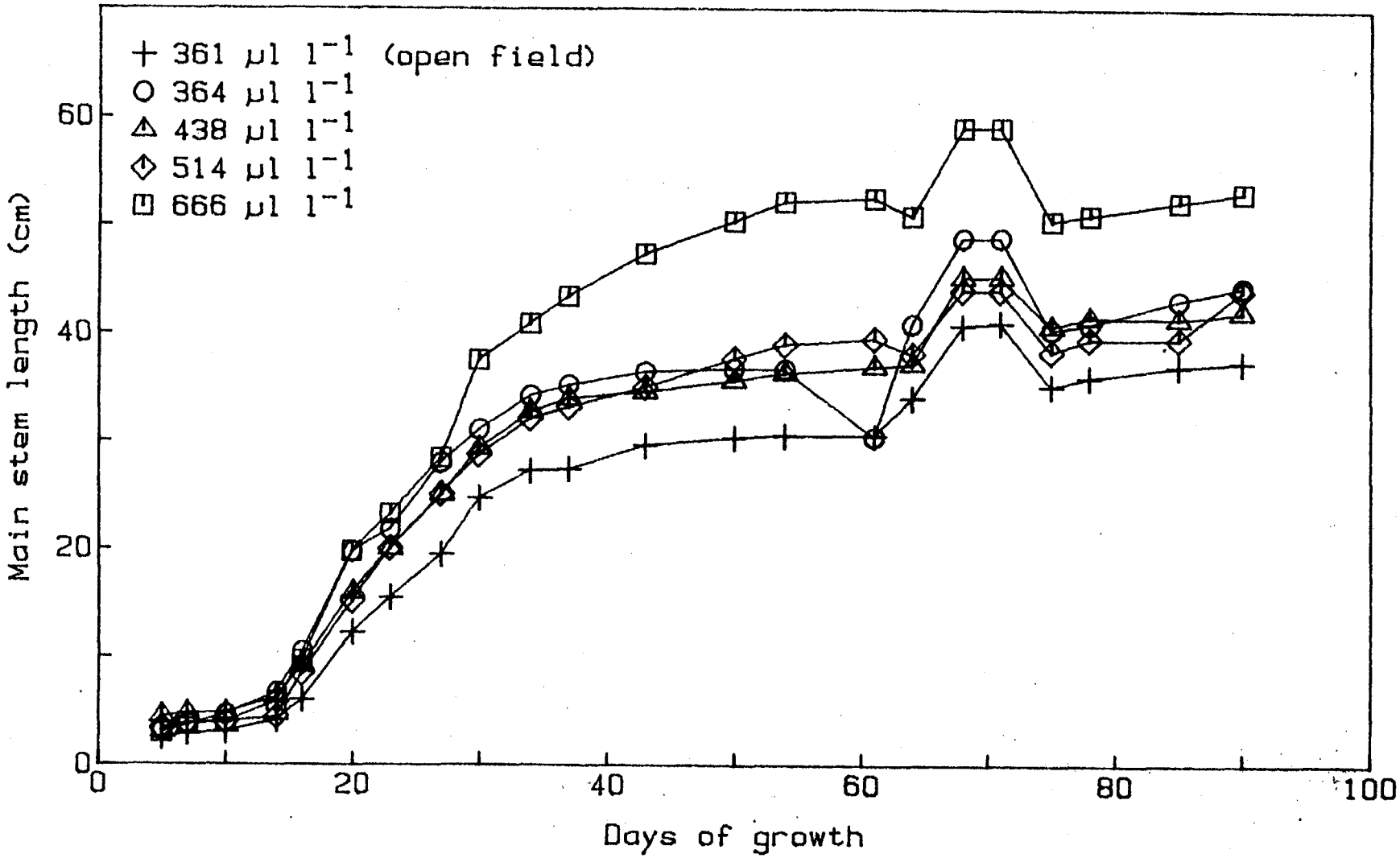

Figure 7. Effects of CO_2 concentration on the main stem length of sweet potato at different days after planting.

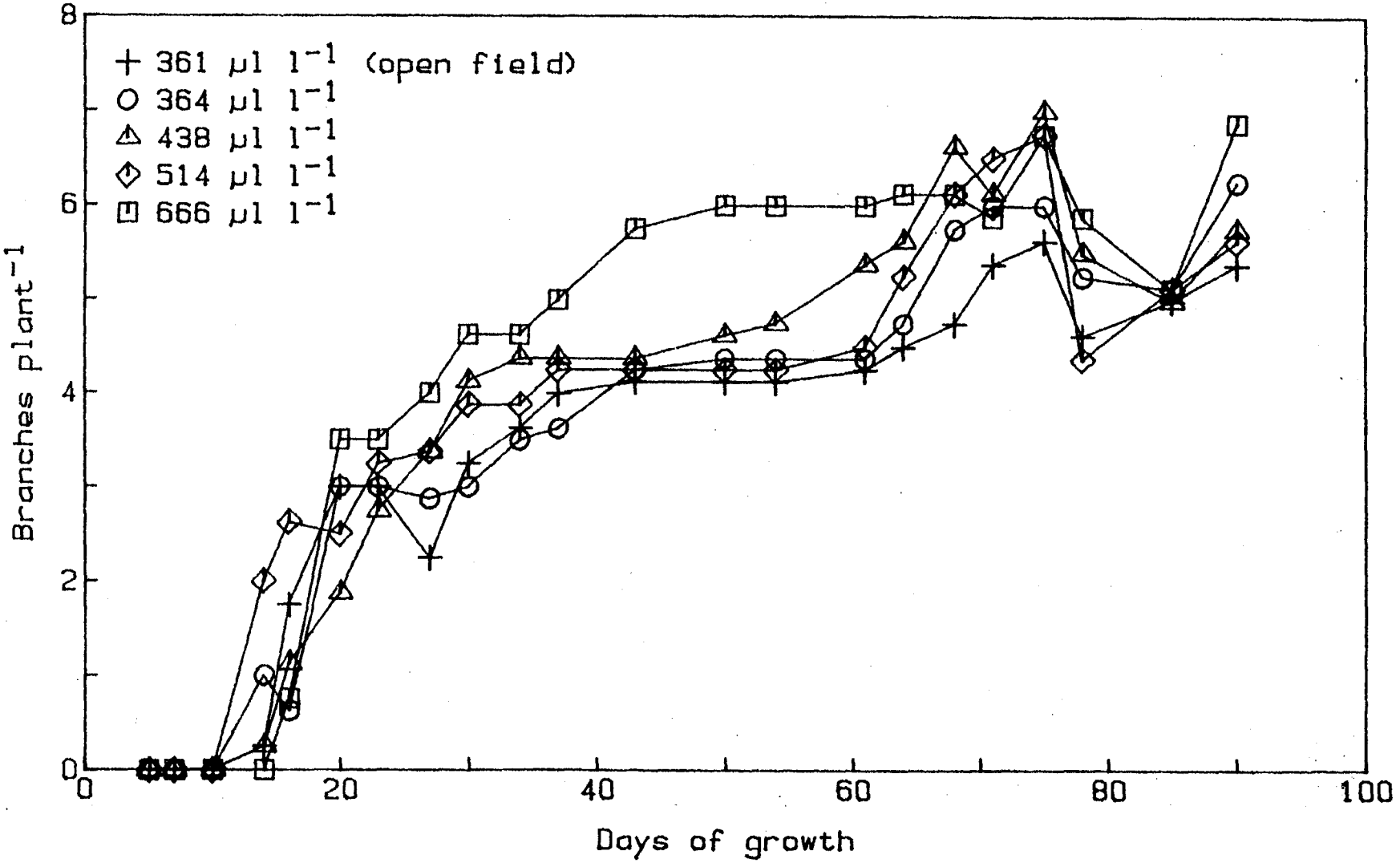

Figure 8. Effects of CO_2 concentration on the number of branches of sweet potato at different days after planting.

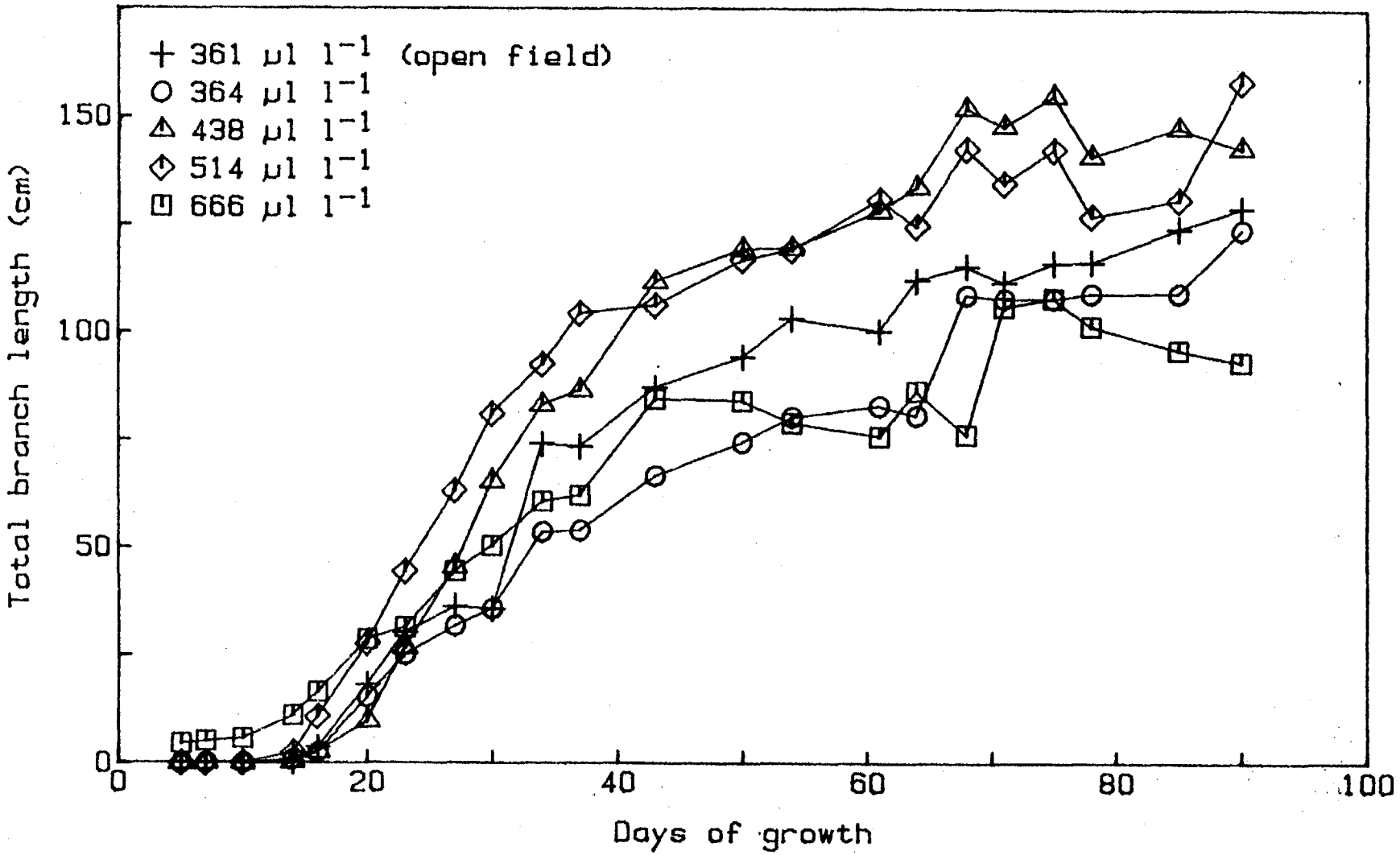

Figure 9. Effect of CO_2 concentration on the total branch length of sweet potato at different days after planting.

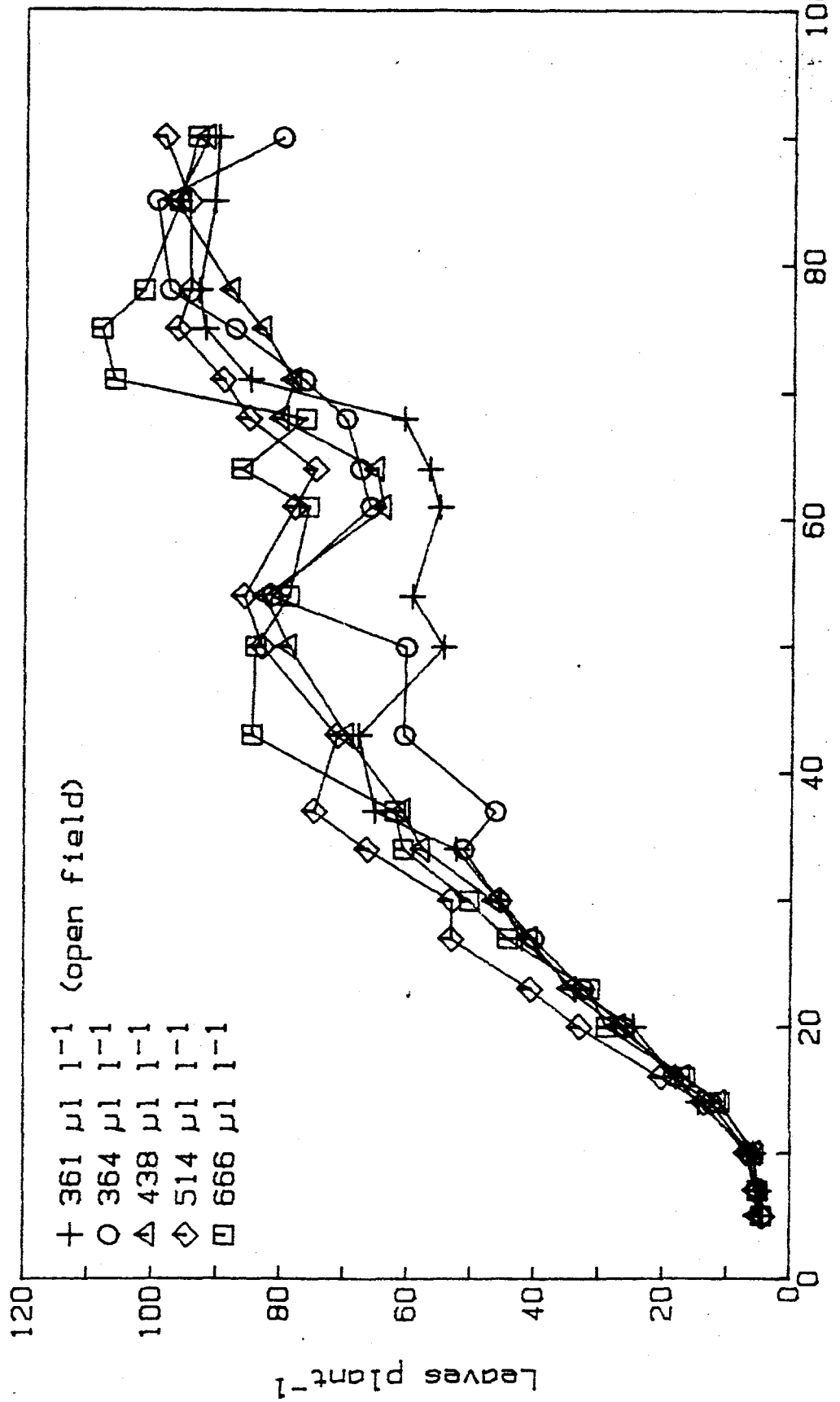

Figure 10. Effect of CO_2 concentration on the number of leaves of sweet potato at different days after planting.

Table 33. Effect of different CO_2 concentrations on leaf area, specific leaf area and leaf area ratio (mean ± S.E.) of sweet potato plants grown in pots, in open top chambers and an open field plot at different stages of growth, n=8.

CO_2 ($umol\ mol^{-1}$)	Leaf Area (cm^2)	Specific Leaf Area (cm^2)	Leaf Area Ratio
	30 days after planting		
361+	598 ± 53	186.0 ± 6.7	64.13 ± 4.7
364	634 ± 49	182.0 ± 5.4	71.29 ± 2.3
438	587 ± 61	176.0 ± 7.2	62.81 ± 1.6
514	514 ± 27	180.0 ± 8.5	63.98 ± 3.2
666	623 ± 60	137.0 ± 5.6	55.99 ± 3.1
	45 days after planting		
361+	774 ± 124	156.7 ± 9.0	26.35 ± 1.0
364	1193 ± 134	177.3 ± 8.4	38.54 ± 2.0
438	747 ± 117	173.3 ± 6.6	24.66 ± 2.6
514	1019 ± 165	156.0 ± 3.4	30.11 ± 1.8
666	1076 ± 229	138.4 ± 5.9	28.84 ± 1.1
	90 days after planting		
361+	1910 ± 35	161.1 ± 2.8	23.89 ± 0.8
364	2104 ± 62	198.4 ± 6.3	24.25 ± 0.8
438	2242 ± 119	172.9 ± 5.4	22.41 ± 0.7
514	2124 ± 86	142.3 ± 6.3	20.62 ± 1.5
666	2012 ± 134	135.6 ± 6.0	21.01 ± 2.5

+The first CO_2 value (361) is from the open field plot (no chamber); the other values are from within chambers. Values for CO_2 are daytime means.

Table 34. Effect of different CO_2 concentrations on total dry weight, specific leaf weight and leaf weight (mean ± S.E.) ratio of sweet potato plants grown in pots, in open top chambers and an open field plot at different stages of growth, n=8.

CO_2 ($\mu mol\ mol^{-1}$)	Total Weight (g)	Specific Leaf Weight ($g\ cm^{-2}$)	Leaf Weight Ratio
	30 days after planting		
361+	9.87 ± 1.20	0.0054 ± 0.0002	0.344 ± 0.020
364	8.99 ± 0.77	0.0055 ± 0.0002	0.392 ± 0.011
438	9.46 ± 1.04	0.0057 ± 0.0002	0.359 ± 0.008
514	8.21 ± 0.64	0.0057 ± 0.0003	0.356 ± 0.008
666	11.35 ± 1.30	0.0074 ± 0.0003	0.408 ± 0.009
	45 days after planting		
361+	28.98 ± 4.02	0.0065 ± 0.0003	0.170 ± 0.007
364	32.13 ± 4.89	0.0057 ± 0.0002	0.219 ± 0.013
438	30.89 ± 3.93	0.0058 ± 0.0002	0.143 ± 0.016
514	34.70 ± 6.09	0.0064 ± 0.0001	0.170 ± 0.014
666	37.07 ± 7.67	0.0073 ± 0.0003	0.213 ± 0.015
	90 days after planting		
361+	80.5 ± 2.26	0.006 ± 0.00008	0.149 ± 0.006
364	87.1 ± 2.33	0.005 ± 0.0002	0.123 ± 0.006
438	99.7 ± 3.16	0.006 ± 0.0002	0.130 ± 0.006
514	106.0 ± 5.76	0.007 ± 0.0003	0.147 ± 0.010
666	104.0 ± 10.77	0.008 ± 0.0004	0.153 ± 0.020

+The first CO_2 value (361) is from the open field plot (no chamber); the other values are from within chambers. Values for CO_2 are daytime means.

Table 35. Effect of different CO_2 concentrations on biomass increment (ΔW), net assimilation rate (NAR) and relative growth rate (RGR) (mean ± S.E.) on a dry weight basis, of sweet potato plants grown in pots in open top chambers and an open field plot during two harvest intervals, n=8.

CO_2 ($umol\ mol^{-1}$)	ΔW (g)	NAR $Kg\ m^{-2}\ day^{-1}$	RGR $Kg\ Kg^{-1}\ day^{-1}$
	30–45 days		
361+	19.107 ± 2.948	1.84 ± 0.1	0.07169 ± 0.004
364	23.135 ± 4.273	1.68 ± 0.1	0.08218 ± 0.005
438	21.430 ± 3.067	2.14 ± 0.1	0.07843 ± 0.004
514	26.488 ± 5.502	2.26 ± 0.2	0.09042 ± 0.006
666	25.721 ± 6.585	1.93 ± 0.2	0.07336 ± 0.006
	45–90 days		
361+	51.503 ± 2.458	0.975 ± 0.09	0.02415 ± 0.002
364	55.002 ± 2.948	0.796 ± 0.07	0.02365 ± 0.002
438	68.827 ± 2.266	1.209 ± 0.01	0.02729 ± 0.002
514	70.873 ± 3.667	1.132 ± 0.01	0.02681 ± 0.002
666	67.109 ± 5.233	1.053 ± 0.07	0.02508 ± 0.002

+The first CO_2 value (361) is from the open field plot (no chamber); the other values are from within chambers. Values for CO_2 are daytime means.

Table 36. Effect of different CO_2 concentrations on biomass increment (ΔW), leaf area duration (LAD) and relative growth rate (RGR-A) (mean ± S.E.) on a leaf area basis, of sweet potato plants grown in pots in open top chambers and an open field plot during two harvest intervals, n=8.

CO_2 ($\mu mol\ mol^{-1}$)	ΔW (g)	LAD $g\ m^{-2}\ day^{-1}$	RGR-A $g\ g^{-1}\ day^{-1}$
		30-45 days	
361+	176 ± 94	10158 ± 1173	0.01357 ± 0.006
364	559 ± 102	13225 ± 1200	0.04073 ± 0.004
438	160 ± 97	9854 ± 1152	0.01358 ± 0.008
514	505 ± 145	10967 ± 1204	0.03993 ± 0.008
666	454 ± 189	12278 ± 1855	0.02958 ± 0.008
		45-90 days	
361+	1136 ± 109	55841 ± 4017	0.02197 ± 0.003
364	911 ± 125	71792 ± 4140	0.01349 ± 0.002
438	1494 ± 87	60687 ± 5384	0.02598 ± 0.002
514	1105 ± 135	66871 ± 5728	0.01832 ± 0.003
666	935 ± 296	65057 ± 5703	0.01689 ± 0.005

+The first CO_2 value (361) is from the open field plot (no chamber); the other values are from within chambers. Values for CO_2 are daytime means.

the normal watering schedule, while water-stressed plants were not watered. During the first stress cycle the pots were covered with polyethylene sheeting stretched over the soil surface. In the second stress cycle temporary rain shelters were constructed with polyethylene sheeting 30 cm above the plant height within chambers as well as in open field plots to protect the water-stressed plants from rain. Throughout the drying and recovery periods, weather conditions were generally warm and sunny.

During water stress cycles, pre-dawn and mid-afternoon xylem pressure potential measurements were made with a pressure bomb, using the third, fourth or fifth leaf from the end of a growing shoot. Leaves removed for xylem water potential measurements were dried in the ovens at 70 ^{o}C for 48 hr. The dry weights of these leaves were used in the calculations of final biomass production. Stomatal conductance was measured on each plant between 1100 hrs and 1350 hrs CST with a LI-COR LI-700 transient porometer.

After 90 days, all plants were harvested and different component parts were separated for various measurements. Leaf area was determined using a LI-COR LI-3100 area meter. The main runner length and runner and the numbers of leaves and runners were also recorded. Fibrous and tuberous root fresh weights were determined after washing and air drying for 10-15 minutes. Leaves, runners and fibrous roots were dried at 70 ^{o}C for 48 hr. Individual tuber volumes were obtained by water displacement. The tuberous roots were individually sliced and dried at 75 ^{o}C for 120 hr.

2. Results

First water stress cycle: The xylem pressure of well-watered plants grown at different concentrations of CO_2 did not show any variation among the CO_2 treatments during the first stress cycle (Fig. 11).

However, under water stress conditions, plants grown at 364 and 438 umol mol^{-1} CO_2 showed low (i.e. more negative) xylem pressure within four days after water stress was imposed, decreasing further by the 7th day (Fig. 12). In plants grown at 514 umol mol^{-1} CO_2 the xylem pressure decreased significantly at day 7 but it remained high (i.e. less negative) at 666 umol mol^{-1} CO_2 even after 8 days of water stress.

In well-watered plants stomatal conductance was generally greatest in plants grown in 364 umol mol^{-1} CO_2 and generally lowest in plants grown in 666 umol mol^{-1} CO_2 (Fig. 13). In water-stressed plants, stomatal conductance decreased in all treatments during the water stress cycle (Fig. 14). However, the decrease in stomatal conductance was the least in plants grown at 666 umol mol^{-1} CO_2. Rewatering of stressed plants at day 47 led to a rapid recovery of stomatal conductance within 48 hours at all CO_2 concentrations.

Second water stress cycle: In well-watered plants the xylem pressure did not differ among CO_2 treatments (Fig. 15). In water-stressed plants, xylem pressure decreased considerably (i.e. became more negative) with the passage of time (Fig. 16). After 14 days of water stress, xylem pressure was lowest (i.e. most negative) at 364 umol mol^{-1} CO_2 and greatest at 666 umol mol^{-1} CO_2.

In well-watered plants, stomatal conductance differed from day to day, depending upon ambient conditions (Fig. 17). In general plants grown at 514 and 666 umol mol^{-1} CO_2 had lower stomatal conductances than plants grown at lower CO_2 concentrations. In water-stressed plants, stomatal conductance decreased most rapidly at 361 (open field), 364 and 438 umol mol^{-1} CO_2, becoming completely closed after 7 days of

water stress (Fig. 18). Stomates of plant grown at 514 and 666 umol mol^{-1} CO_2 remained open longer under water stress conditions.

Harvest : In well-watered plants the number of leaves was greatest at 438 umol mol^{-1} CO_2, while in water-stressed plants it was greatest in the open field plot (Table 37). In general, CO_2 enrichment reduced the number of abscised leaves per plant in both well-watered and water-stressed plants (Table 37). In both well-watered and water-stressed plants total leaf area increased under moderate CO_2 enrichment, but decreased at the highest CO_2 levels (Table 37). It is interesting to note that by increasing CO_2 concentration from 361 to 666 umol mol^{-1} the yield of tuberous roots increased significantly with increasing CO_2 both in well-watered and water-stressed plants. However, the increase was greater in well-watered plants (Table 39). The fresh weight of fibrous roots also increased with increasing CO_2 concentration, both in well-watered and water-stressed plants (Table 39). The greatest yield of fibrous roots occurred at 666 umol mol^{-1} CO_2 in well-watered plants. Total dry matter production was greater in well-watered plants than in water-stressed plants at each CO_2 concentration (Table 40). Dry matter production of tuberous roots increased in both well-watered and water-stressed plants in response to enriched CO_2, with the most significant increases occurring at 438 and 514 umol mol^{-1} CO_2 in well-watered and water-stressed plants respectively (Table 40). The tuberous root:shoot ratio increased significantly at 438 umol mol^{-1} CO_2 in both well-watered and water-stressed plants (Table 40). The number of tuberous roots, tuberous root density and total tuber volume did not show any significant variation

in water-stressed plants but increased in well-watered plants considerably in response to elevated CO_2 (Table 41).

3. Discussion

The xylem pressure did not change as much during the first stress cycle as during the second stress cycle at each CO_2 concentration. However, in both stress cycles, xylem pressure decreased (i.e. became more negative) more rapidly in low CO_2-grown plants than high CO_2-grown plants.

Stomatal conductance during the first stress cycle decreased more rapidly in high CO_2 than in ambient CO_2. In the second stress cycle, stomates remained open at 514 and 666 umol mol^{-1} CO_2 even after 6 days of water stress as compared to significantly lower conductances in low CO_2 grown plants during the same period. It is discernible from the above observations that during the first stress cycle, CO_2 enrichment resulted in the conservation of water which led to increased vegetative growth. During the second stress cycle, CO_2 enrichment resulted in increased leaf senescence and ultimately decreased vegetative growth in stressed plants. Significant decreases in yield have been reported in some of the cultivars of sweet potato (Jewel, Centennial, Carver, Rose Centennial and Travis) in field experiments under water stress conditions (Jones et al. 1985). The reduction in yield was greater during the later stages of plant maturity than during the initial period of growth. In general, plants grown under enriched CO_2 and subjected to water stress, exhibit decreased stomatal conductance and transpiration per leaf area surface (Dahlman et al. 1986). Furthermore, water conservation is greater and tissue water potentials remain higher in plants

grown in enriched CO_2 than in ambient controls. Huber et al. (1984) reported that soybean plants grown in CO_2 enriched atmospheres (300 umol mol^{-1} above ambient) had higher carbon exchange rates but similar rates of export and similar activities of sucrose-P-synthetase as compared to plants grown at ambient CO_2. In fact, export of assimilates was less affected by water stress than were carbon exchange rates.

In the present study, dry matter in different component plant parts of sweet potato increased at elevated CO_2, but plants subjected to water stress decreased accumulation of dry matter in leaves, stems, roots and tuberous roots. At enriched CO_2 under water stress, dry matter production decreased as compared to non-stress plants at the same CO_2 levels. However, under water stress conditions, the production of dry matter and the tuberous root:shoot ratio increased as compared with the ambient CO_2 stressed plants. The yield of tuberous roots followed a similar trend in both stress and non-stress plants. However, total production was greater in non-stress plants.

Reports on non tuberous crops (wheat, sugarbeet, okra and soybean) in response to enriched CO_2 and water stress reveal that osmotic pressures were higher in plant leaves grown in high CO_2 than in ambient controls. Perhaps this may also explain the greater increase in dry matter accumulation during water stress periods in wheat, sugarbeet, okra and soybean in high CO_2-grown plants than those plants grown in an ambient CO_2 environment (Sionit et al. 1982).

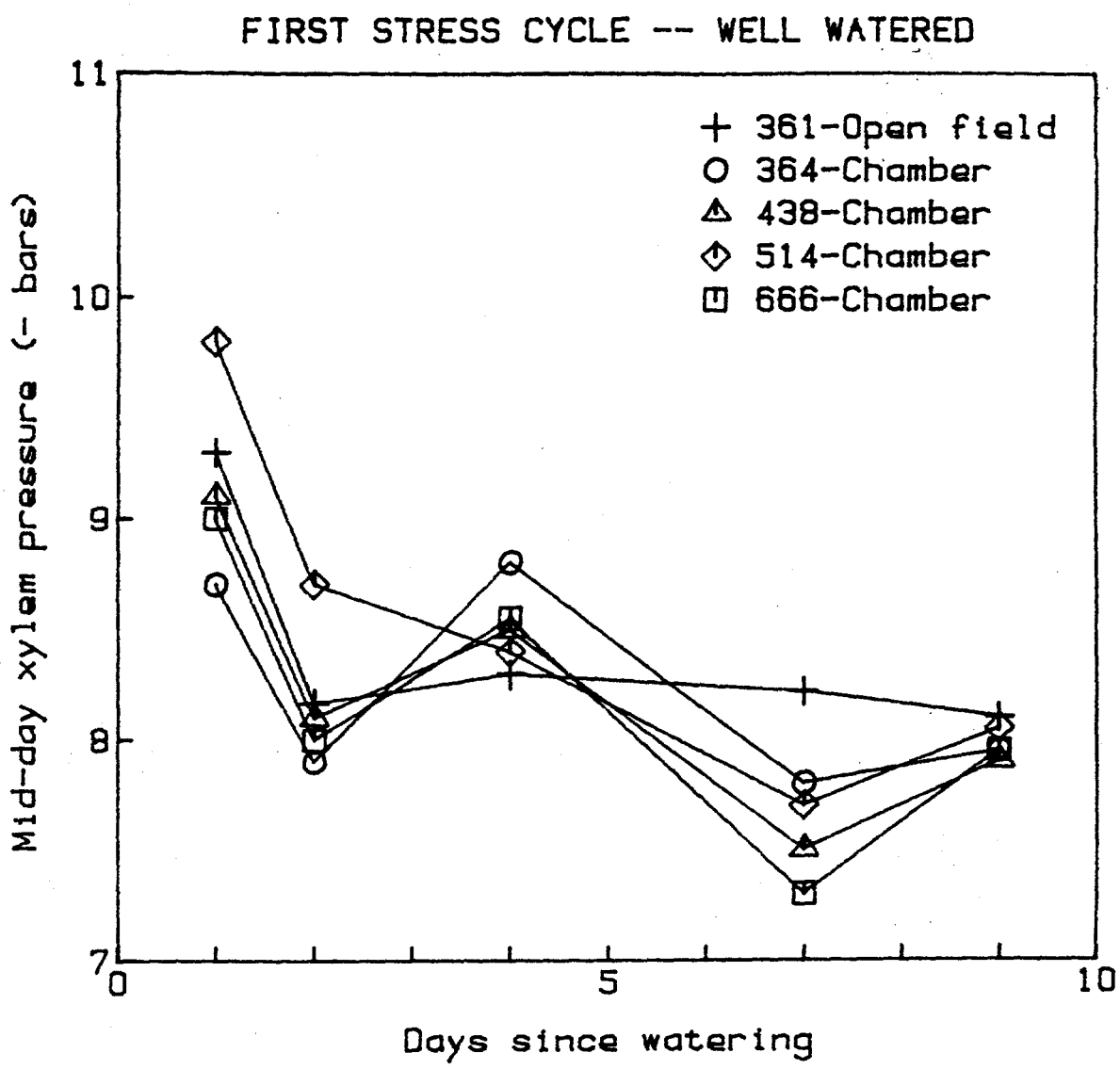

Figure 11. Effect of CO_2 concentration on mid-day xylem pressure of well-watered sweet potato plants at different days during the first stress cycle.

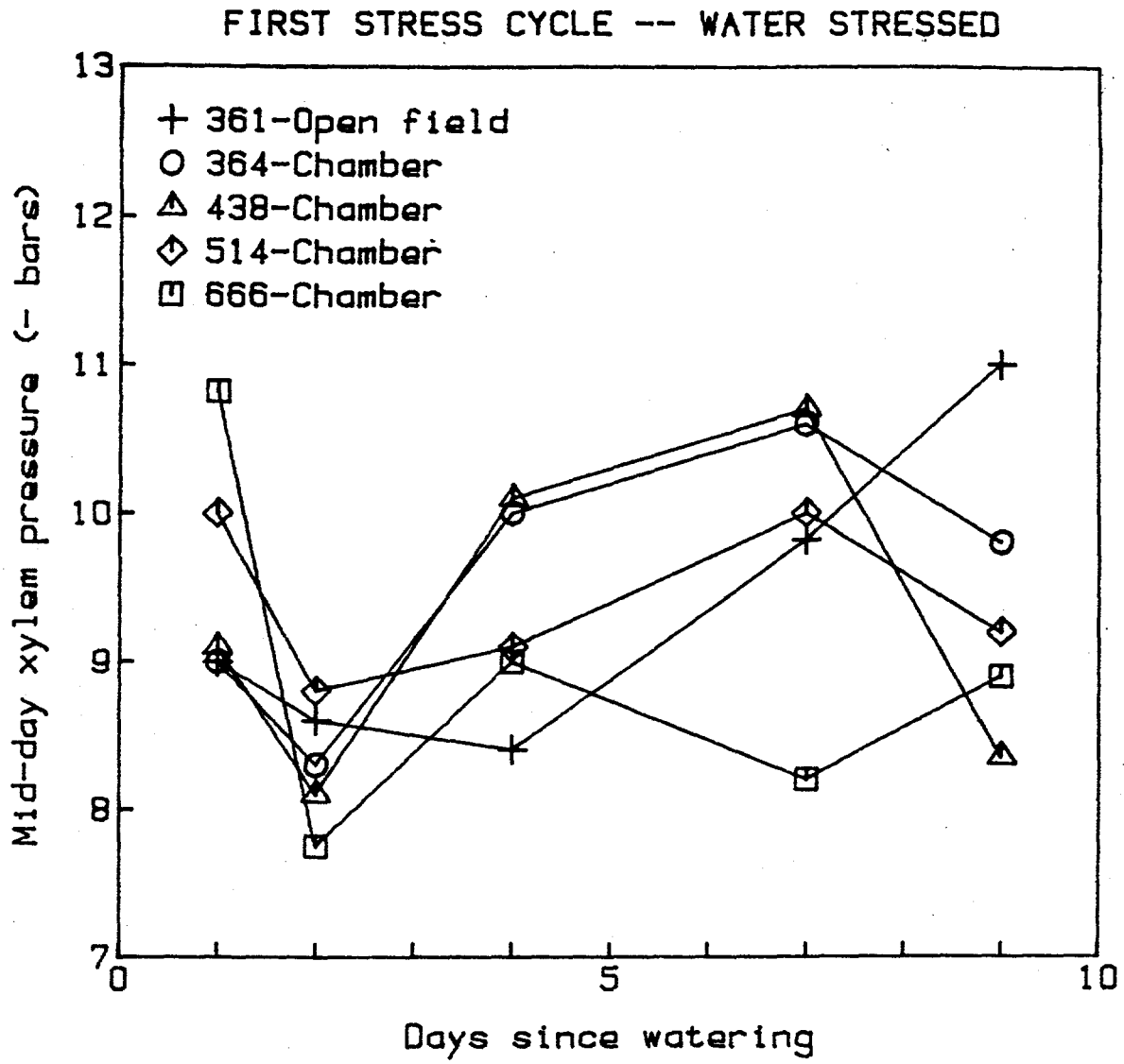

Figure 12. Effect of CO_2 concentration on mid-day xylem pressure of water-stressed sweet potato plants at different days during first stress cycle.

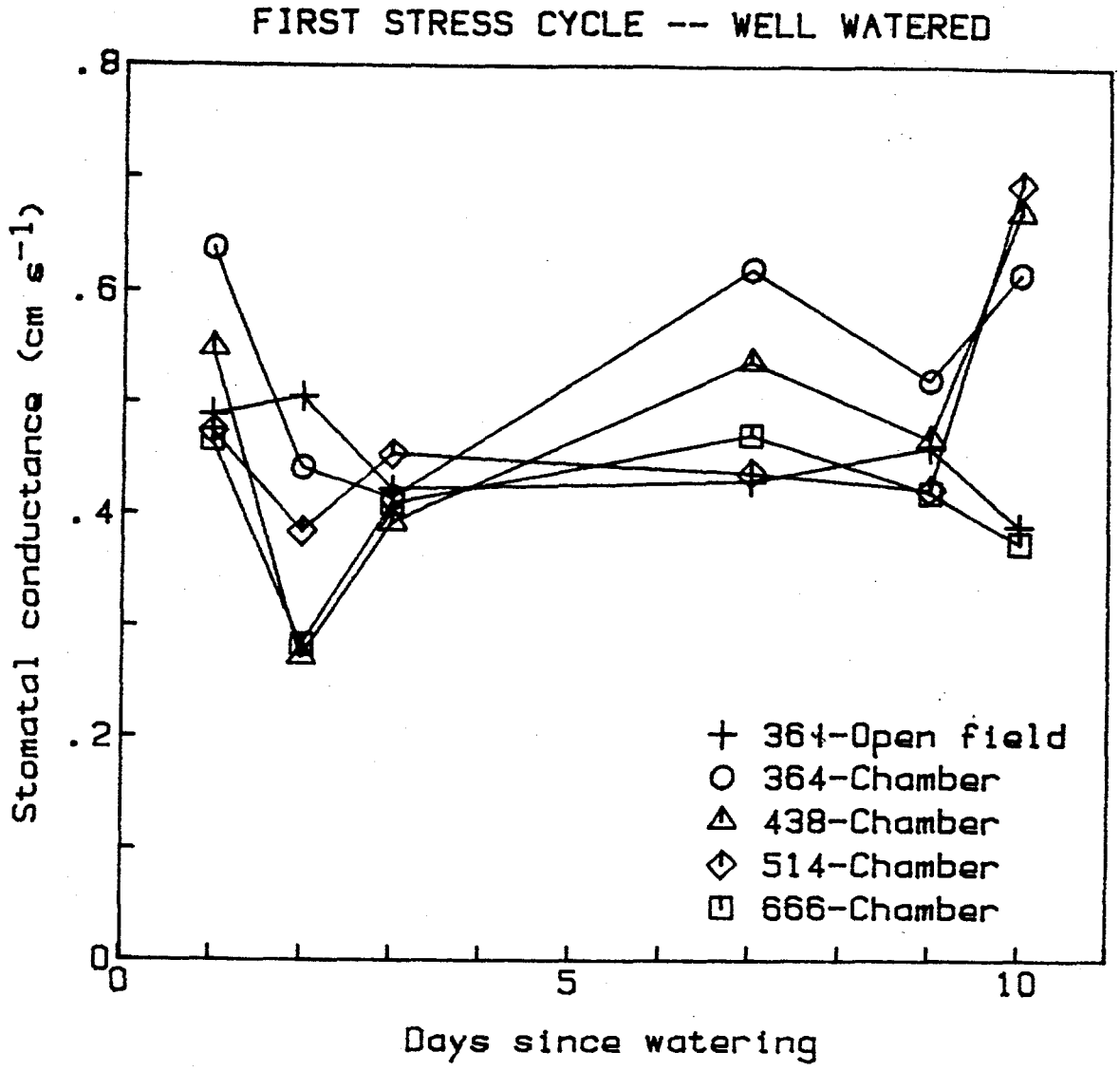

Figure 13. Effect of CO_2 concentration on mid-day stomatal conductance of well-watered sweet potato plants at different days during the first stress cycle.

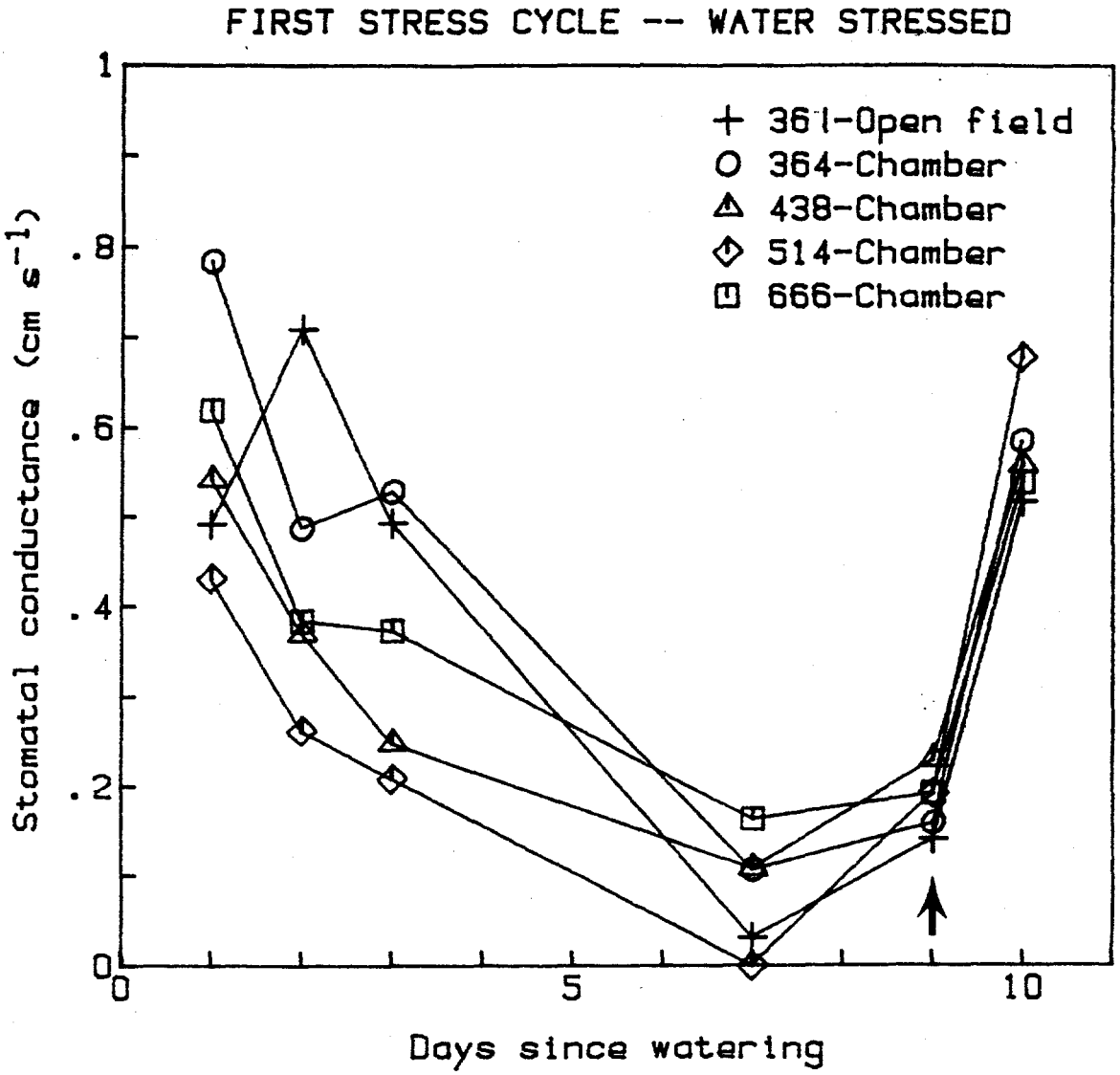

Figure 14. Effect of CO_2 concentration on mid-day stomatal conductance of water-stressed sweet potato plants at different days during first stress cycle. Arrow indicates the rewatering (after measurement) on day 9.

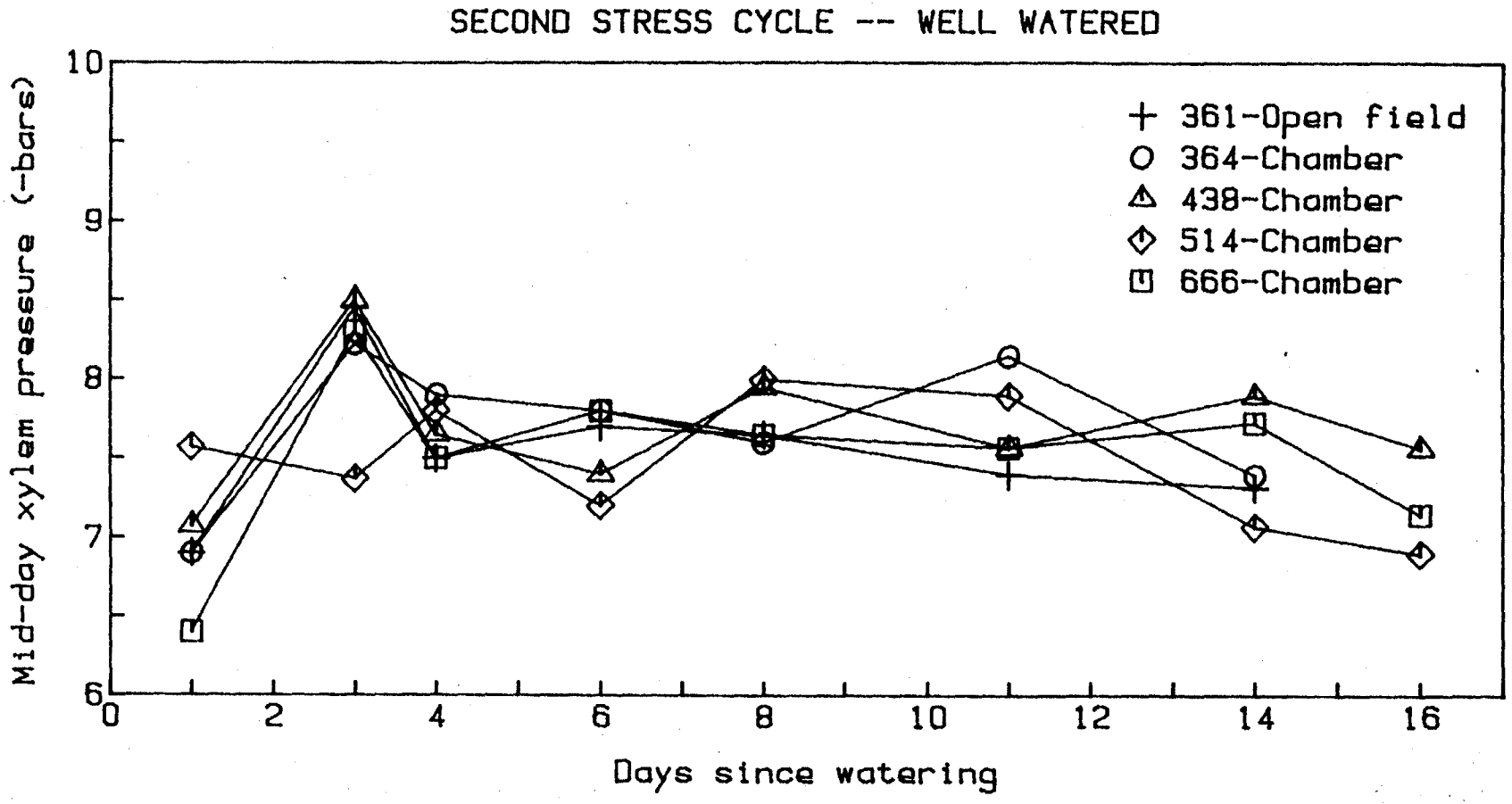

Figure 15. Effect of CO_2 concentration on the mid-day xylem pressure of well-watered sweet potato plants at different days during the second stress cycle.

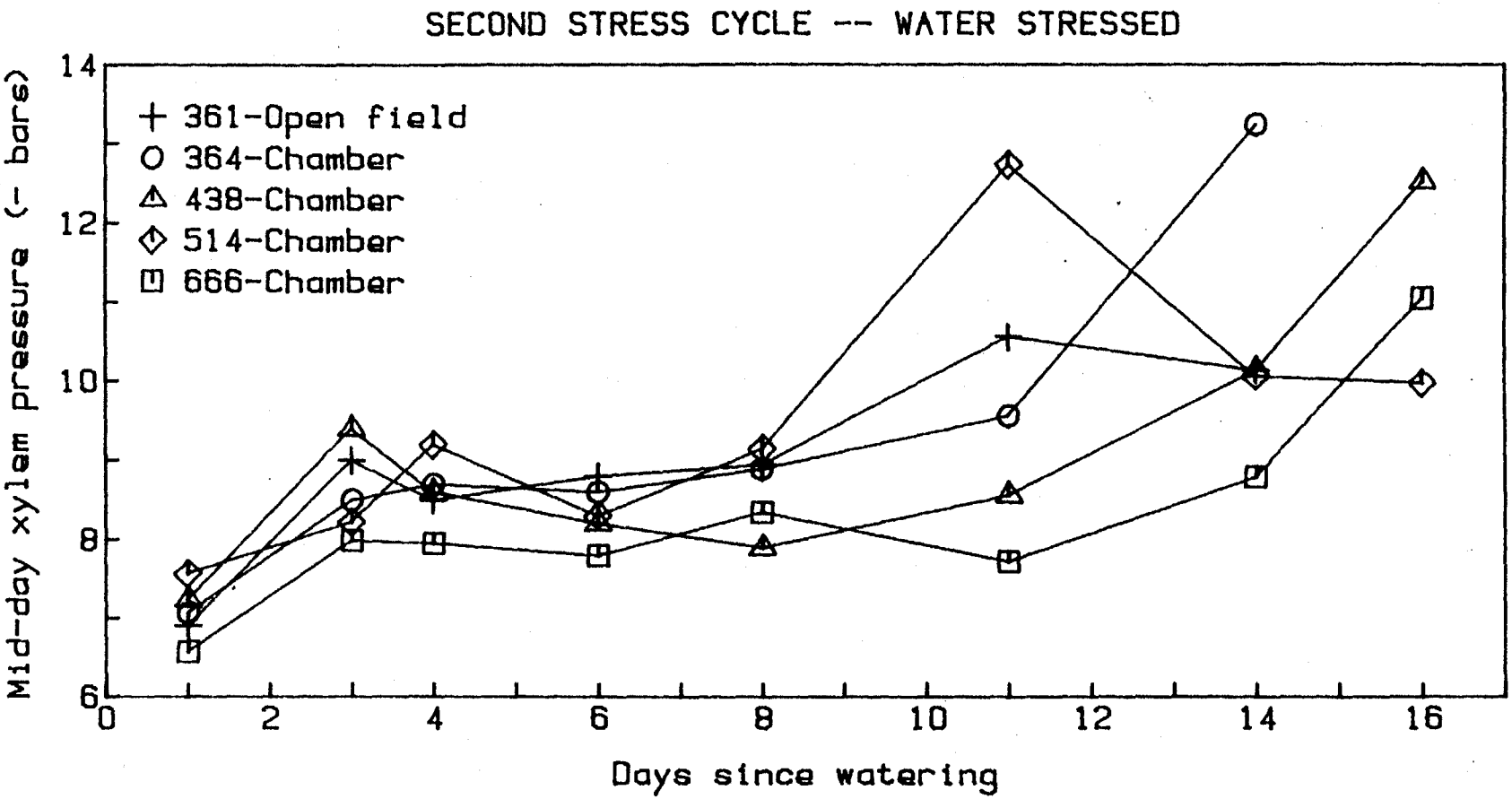

Figure 16. Effect of CO_2 concentration on the mid-day xylem pressure of water-stressed sweet potato plants at different days during second stress cycle.

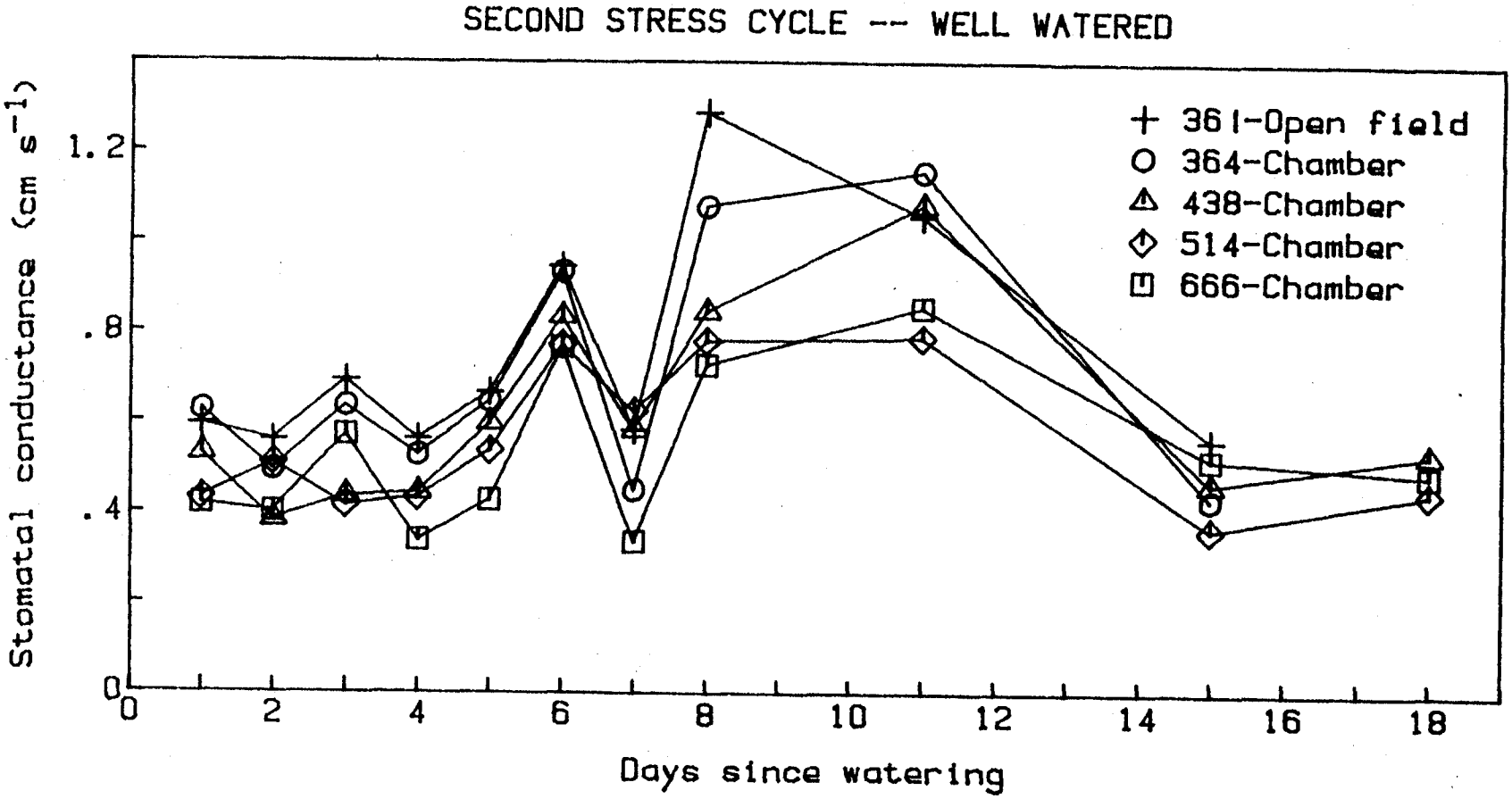

Figure 17. Effect of CO_2 concentration on the mid-day stomatal conductance of well-watered sweet potato plants at different days during the second stress cycle.

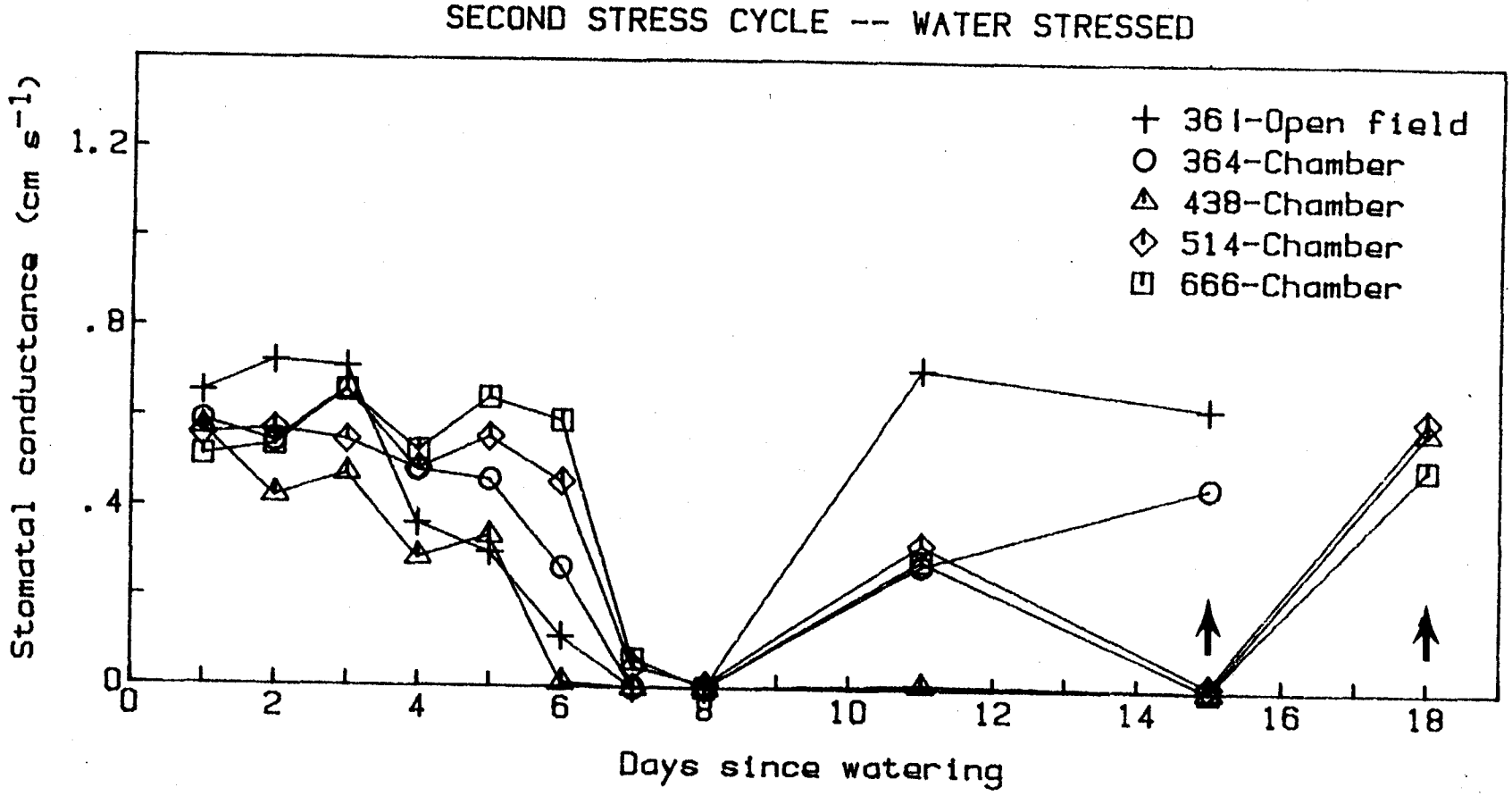

Figure 18. Effect of CO_2 concentration on the mid-day stomatal conductance of water-stressed sweet potato plants at different days during second stress cycle. Arrows indicate rewatering (after measurement) on day 15 (361 and 364 treatments) and day 18 (438, 514 and 666 treatments).

Table 37. Effects of different CO_2 concentrations and water stress on the number of leaves, the number leaves abscised, leaf area harvested and total leaf area of sweet potato plants grown in pots in open top chambers and an open field plot at 90 day harvest, n=8.

CO_2 (umol mol^{-1})	Number of Leaves (Abscised)	Number of Leaves (Total)	Leaf Area (Harvest) (cm^2)	Leaf Area (Total) (cm^2)
		Water-Stressed		
361+	60.8^{ab}	133.80^{ab}	888.9^{c}	2276.2^{bc}
364	47.4^{bc}	119.80^{bc}	958.8^{c}	2277.7^{bc}
438	70.6^{a}	130.80^{ab}	617.5^{c}	2433.6^{bc}
514	68.8^{a}	131.00^{ab}	805.6^{c}	2624.2^{b}
666	51.8^{bc}	105.00^{c}	621.0^{c}	2089.3^{c}
		Well-Watered		
361+	43.6^{cd}	149.00^{a}	1420.00^{ab}	2506.5^{bc}
364	39.6^{cd}	134.40^{ab}	1597.0^{ab}	3075.0^{a}
438	46.8^{bc}	152.00^{a}	1778.2^{a}	3205.8^{a}
514	43.4^{cd}	140.20^{ab}	1630.8^{ab}	3034.8^{a}
666	29.8^{d}	132.00^{ab}	1363.9^{b}	2273.1^{bc}

+The first CO_2 value (361) is from the open field plot (no chamber); the other values are from within chambers. Values for CO_2 are daytime means.

[a]Within each column values sharing the same letter are not significantly different at the 0.05 level according to Duncan's Multiple Range Test.

Table 38. Effects of different CO_2 concentrations and water stress on the dry weights of total leaves, runners, harvested shoot and total shoot of sweet potato plants grown in pots in open top chambers and an open field plot at 90 day harvest, n=8.

CO_2 ($\mu mol\ mol^{-1}$)	Dry Weight (g)			
	Leaves (Total)	Runners	Shoot (Harvested)	Shoot (Total)
		Water-Stressed		
361+	16.14^{bcd}	7.22^{cd}	12.31^{c}	23.36^{cde}
364	15.70^{bcd}	6.78^{d}	12.22^{c}	22.47^{de}
438	13.71^{d}	6.60^{d}	9.19^{c}	20.31^{e}
514	15.24^{cd}	7.51^{cd}	11.50^{c}	22.75^{cde}
666	13.63^{d}	6.91^{d}	9.70^{c}	20.54^{e}
		Well-Watered		
361+	18.90^{ab}	9.63^{ab}	19.79^{ab}	28.53^{ab}
364	16.91^{bdc}	8.40^{bcd}	16.90^{b}	25.31^{bcd}
438	17.80^{abc}	9.02^{abc}	19.40^{ab}	26.82^{abc}
514	20.26^{a}	10.68^{a}	21.44^{a}	30.94^{a}
666	18.01^{abc}	9.68^{ab}	19.55^{ab}	27.69^{ab}

+The first CO_2 value (361) is from the open field plot (no chamber); the other values are from within chambers. Values for CO_2 are daytime means.

[a]Within each column, values sharing the same letter are not significantly different at the 0.05 level according to Duncan's Multiple Range Test.

Table 39. Effects of different CO_2 concentrations and water stress on the fresh weights of fibrous and tuberous roots of sweet potato plants grown in pots in open top chambers and an open field plot at 90 day harvest, n=8.

CO_2 ($umol\ mol^{-1}$)	Fresh Weights (g)	
	Fibrous Roots	Tuberous Roots
	Water-Stressed	
361+	47.74^{abc}	241.34^{ef}
364	26.17^{bc}	222.22^{f}
438	38.04^{abc}	309.70^{cde}
514	23.63^{c}	312.24^{cd}
666	36.18^{abc}	263.23^{def}
	Well-Watered	
361+	53.91^{ab}	314.90^{cd}
364	22.71^{c}	322.87^{cd}
438	24.60^{c}	459.54^{a}
514	49.64^{abc}	380.21^{bc}
666	59.06^{a}	401.54^{ab}

+The first CO_2 value (361) is from the open field plot (no chamber); the other values are from within chambers. Values for CO_2 are daytime means.

[a]Within each column, values sharing the same letter are not significantly different at 0.05 level according to Duncan's Multiple Range Test.

Table 40. Effects of different CO_2 concentrations and water stress on the total plant dry weight, total biomass and tuberous root:shoot ratios of sweet potato plants grown in pots in open top chambers and an open field plot at 90 day harvest, n=8.

CO_2 ($umol\ mol^{-1}$)	Dry Weight (g) Tuberous Roots	Whole Plant (Harvested)	Whole Plant (Total)	Tuberous Root:Shoot Ratio (Harvested)	Tuberous Root:Shoot Ratio (Total)
		Water-Stressed			
361+	36.52^{d}	56.30^{d}	67.34^{d}	3.81^{cd}	1.93^{d}
364	46.98^{cd}	63.53^{cd}	73.79^{cd}	4.04^{cd}	2.21^{cd}
438	50.30^{bcd}	64.97^{cd}	76.10^{cd}	6.22^{a}	2.75^{abc}
514	54.03^{bcd}	70.60^{cd}	81.81^{cd}	5.21^{abc}	2.60^{abcd}
666	47.17^{cd}	63.61^{cd}	74.50^{cd}	5.68^{ab}	2.63^{abcd}
		Well-Watered			
361+	53.24^{bcd}	81.47^{bc}	90.21^{bc}	3.18^{d}	2.18^{cd}
364	54.46^{bcd}	76.17^{cd}	84.60^{cd}	3.53^{d}	2.35^{bcd}
438	83.12^{a}	106.31^{a}	113.73^{a}	4.48^{bcd}	3.25^{a}
514	67.02^{abc}	97.26^{ab}	106.76^{ab}	3.59^{d}	2.47^{bcd}
666	70.13^{ab}	102.74^{a}	110.87^{ab}	4.29^{bcd}	3.01^{ab}

+The first CO_2 value (361) is from open field plot (no chamber); the other values are from within chambers. Values for CO_2 are daytime means.

[a]Within each column, values sharing the same letter are not significantly different at the 0.05 level according to Duncan's Multiple Range Test.

Table 41. Effects of different CO_2 concentrations and water stress on tuberous root density, the number of tuberous roots, total tuberous root volume and percent dry matter of sweet potato plants grown in pots in an open top chambers and open field plot at 90 day harvest, n=8.

CO_2 ($umol\ mol^{-1}$)	Tuberous Root Density (g/cm^3)	Number of Tuberous Roots	Total Tuberous Root Volume (cm^3)	Percent Dry Matter
		Water-Stressed		
361+	1.48[a]	7.6[bcd]	199.60[c]	15.73[a]
364	0.996[b]	4.6[d]	266.00[bc]	20.08[a]
438	1.156[ab]	5.8[cd]	269.80[bc]	16.38[a]
514	1.095[ab]	7.4[bcd]	288.80[bc]	17.35[a]
666	1.156[ab]	6.6[cd]	228.20[bc]	18.00[a]
		Well-Watered		
361+	1.034[ab]	9.6[abc]	304.40[ab]	16.95[a]
364	1.1011[ab]	8.8[abc]	296.00[b]	16.96[a]
438	1.2008[ab]	11.4[ab]	388.20[a]	18.10[a]
514	1.3196[ab]	10.8[ab]	306.20[ab]	17.74[a]
666	1.4147[ab]	12.6[a]	287.20[bc]	17.50[a]

+The first CO_2 value (361) is from the open field plot (no chamber); the other values are from within chambers, values for CO_2 are daytime means.

[a]Within each column, values sharing the same letter are not significantly different at the 0.05 level according to Duncan's Multiple Range Test.

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