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Response of Vegetation to Carbon Dioxide

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Sorghum at Elevated Levels of CO₂

1985

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Progress Report of Research: SORGHUM AT ELEVATED LEVELS OF CO₂

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EXECUTIVE SUMMARY

The increase of concentration of carbon dioxide (CO_2) in the atmosphere is well-documented. The positive effects of enriched CO_2 levels on plant growth encouraged optimism among scientists for future agriculture production. Such optimism primarily resulted from the experiments conducted on C_3 crops.

Particularly vulnerable areas of the world are semi-arid regions where drought tolerant C_4 crops, such as sorghum (Sorghum bicolor (L.)), are grown. Effects of enriched CO_2 , especially on water use, one of the most important limiting factors of agricultural production, has not been well studied. Crop water-use efficiency can have a major impact during the growing season, particularly in arid regions where water is limited.

An experiment was conducted at Evapotranspiration Laboratory's research site, Kansas State University, Manhattan, Kansas, to study the effect of elevated CO_2 levels on sorghum. The experiment was set up in underground rhizotron boxes ($311,000 \text{ cm}^3$), 180 cm deep to observe periodic root and shoot growth of sorghum in chambers enriched with CO_2 . This report deals with the preliminary findings of the 1984 growing season. The experiment was an initial study which tested both the rhizotron and enriched system. Further statistical analysis still has to be completed.

Sorghum hybrid ('Asgrow Correl') was grown inside the rhizotron under enclosed plexiglass chambers (121 cm by 92 cm by 168 cm) at enriched levels of CO_2 (330, 485, 660, and $795 \mu\text{L}$).

L⁻¹). Throughout the entire growing season, the rhizotron facilitated nondestructive observation of root growth and also continuous and accurate measurements of evapotranspiration (ET) by direct weighing. Both shoot and root growth of sorghum at elevated CO₂ levels for the entire season was recorded. Physiological factors, which affect crop water use, namely stomatal resistance, canopy resistance, and leaf temperature, were also measured.

Enriched CO₂ delayed development of the boot (2 days), half bloom (6 days), and soft dough stages (7 days), as compared with plants grown under ambient conditions. The CO₂-enrichment treatments did not show any measureable effects on canopy height and leaf number. The rate of leaf area increase was rapid (in the early stages of growth soon after CO₂ was injected), but the rate gradually leveled off after the boot stage. At harvest, the dry weight of all the plant components (leaf, stem, root, grain and chaff) of sorghum was increased with enhanced CO₂ treatments. The increases were 58%, 48% and 62% for grain, above ground vegetative dry matter, and root by weight, respectively, at 795 μ LL⁻¹ of CO₂ compared to the ambient treatments. The root:shoot ratio and the harvest indices were similar irrespective of the CO₂ treatments. The root length per unit area at different depths indicated that enriched CO₂ treatments increased the root length compared to the ambient treatment at all growth stages.

Total evapotranspiration from the rhizotron at different treatments ranged from 163 L (330 μ LL⁻¹ CO₂) to 182 L (795 μ LL⁻¹ CO₂) from emergence to maturity. However, the results indicated

that less water was required to produce a unit of any yield component at the enriched CO_2 as compared to the ambient treatments. The sorghum enriched with $795 \mu\text{LL}^{-1}$ CO_2 used 27% less water to produce a gram of phytomass compared to the ambient treatment.

Although elevated CO_2 levels increased the stomatal resistance and canopy temperature, an increase in leaf area indices resulted in a lower canopy resistance. This nullifying effect caused similar water-use at different CO_2 levels.

Areas of Responsibility and Scientists Primarily Responsible

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INTRODUCTION

Enhancement of plant growth is an important effect of the rising concentration of atmospheric CO_2 (Dahlman, 1984). Crops vary in response to elevated CO_2 . Growth often appears greater in C_3 plants than in C_4 plants (Kramer, 1981; Lemon, 1983; Waggoner, 1984). But relatively little work has been done with C_4 plants, and most of it has been with corn (Zea mays L.) (Allen, 1979; Acock et al., 1984). The few existing C_4 data conflict. Some studies indicate that the yield of C_4 plants at elevated CO_2 is about one-fourth that of C_3 crops, but other studies show that C_4 plants with increased CO_2 yield at a rate double the average for all crops (Kimball, 1983).

Sorghum (Sorghum bicolor L. Moench.), a C_4 plant, is a staple food in many of the semi-arid regions of the world. It is the leading cereal grain in Africa, and is important also in India, Pakistan, China, the U.S.S.R., the Arabian Peninsula, Argentina, Australia, southern Europe, and the U.S.A. It is best adapted to warm conditions and is resistant to drought and heat (Martin, 1971). In many parts of the Great Plains of the U.S.A., irrigated corn is being replaced by dryland sorghum because farmers can no longer afford to pump irrigation water from the Ogallala aquifer. In Kansas, for example, the number of harvested hectares with sorghum increased 38% between 1983 and 1984 (1,340,000 ha in 1983; 1,844,000 ha in 1984), but, for corn, the number of hectares decreased 6% (441,600 ha in 1983; 414,000 ha in 1984) (Kansas Crop and Livestock Reporting Service, 1985).

Despite the importance of sorghum, few studies report its

response to high levels of CO_2 , even though several document photosynthesis at ambient CO_2 (Kanemasu and Hiebsch, 1975; Sumayao et al., 1977). Unpublished work by Riley and Hodges (1969) showed that sorghum at 300 and 1000 $\mu\text{L L}^{-1}$ CO_2 yielded 220 and 390 g grain m^{-2} , respectively. Mauney et al. (1978) exposed sorghum to an atmosphere enriched with CO_2 to 630 $\mu\text{L L}^{-1}$ during the entire growing season. Average CO_2 exchange rate (CER) increased a nonsignificant 2% for sorghum at 630 $\mu\text{L L}^{-1}$ CO_2 compared to the CER of sorghum at 300 $\mu\text{L L}^{-1}$ CO_2 . Relative growth rate and net assimilation rate were increased only during the juvenile stage (10-30 days) in the enriched atmosphere. Leaf area and dry weight of sorghum with the high CO_2 level were not significantly larger than that with the low CO_2 level.

Other work shows that growth of C_4 plants is not changed, or reduced, when exposed to higher-than-ambient levels of CO_2 (Acock et al., 1984). In addition, C_4 plants do not appear to compete well with C_3 plants, when C_3 and C_4 plants are grown together, according to studies by Bazzaz and colleagues (Bazzaz and Carlson, 1984; Zangerl and Bazzaz, 1984). In one study (Bazzaz and Carlson, 1984), four coexisting annual plant species were grown together at three levels of CO_2 (300, 600, and 1,200 $\mu\text{L L}^{-1}$) for 35 days. Plant height was higher at high CO_2 concentrations for the three C_3 species (Polygonum pensylvanicum L., Ambrosia artemisiifolia L., Abutilon theophrasti Medic.), but not for the C_4 species (Amaranthus retroflexus L.). The contribution of each species to total community biomass was influenced by CO_2 concentration. The effects were especially

pronounced for Polygonum pensylvanicum, which contributed more to community production as CO_2 increased. Amaranthus behaved in exactly the reverse way; it did best under ambient CO_2 . In another study of six co-occurring annuals (four C_3 plants; two C_4 plants), Zangerl and Bazzaz (1984) found that the proportion of total community production contributed by the C_3 species increased as a result of CO_2 enrichment during the entire growth cycle. The results of the two studies suggest that changes in competitive interactions and community structure will occur with the rise in global CO_2 concentration.

Carbon Dioxide has been shown to affect the time of flowering in sorghum. Floral initiation was delayed at $1000 \mu\text{L L}^{-1} \text{CO}_2$ in four cultivars of sorghum (Hesketh and Hellmers, 1973). In order to identify the process affected, Marc and Gifford (1984) found that air enriched with CO_2 (atmospheric + $500 \mu\text{L L}^{-1}$) significantly reduced the rate of differentiation of the primordial inflorescence compared to plants grown at normal atmospheric concentration of CO_2 (350 to $390 \mu\text{L L}^{-1}$). The sensitive period for retardation of inflorescence differentiation was six days before floral initiation. These results suggest that the steadily rising level of atmospheric CO_2 may alter the balance between vegetative growth and reproductive development.

None of the four studies that have been done with sorghum at elevated CO_2 (Riley and Hodges, 1969; Hesketh and Hellmers, 1973; Mauney et al., 1978; Marc and Gifford, 1984) reports the stomatal resistance of sorghum. The models of streamflow developed by Aston (1984) and Idso and Brazel (1984) depend upon the fact that CO_2 is an anti-transpirant (closes stomata). The

models do not consider differences between C_3 and C_4 plants. It is a widely held view that stomata of C_4 species are more CO_2 -sensitive than are those of C_3 species. [Stomata insensitive to CO_2 open widely (Dubbe et al., 1978).] Akita and Moss (1972) found that stomata of C_3 species were less prone to close than were stomata of C_4 species, as CO_2 concentration was increased from 0 to $8,000 \mu L L^{-1} CO_2$. Dubbe et al. (1978) reported that C_4 species exhibited higher sensitivity of leaf conductance to intercellular CO_2 concentration than did C_3 species. But Morison and Gifford (1983) saw no evidence that stomata of C_4 species were more sensitive to CO_2 than stomata of C_3 species. None of these studies documents sorghum.

The effect of elevated atmospheric levels of CO_2 on roots is poorly understood. Studies show that root: shoot ratios can be increased (Imai and Murata, 1976, Patterson and Flint, 1980), decreased (Wulff and Strain, 1982; Tolley and Strain, 1984a, 1984b), or not changed (Hurd, 1968; Sionit et al., 1980) under CO_2 enrichment. Most of the work has been done with roots of C_3 plants, and roots of C_4 plants rarely have been examined. No study reports root growth of sorghum grown in enriched CO_2 atmospheres.

Effect of enriched CO_2 , especially on water use of sorghum, an important crop in semi-arid regions of the world, has not been well studied. Important physiological measurements related to water use efficiency of sorghum, namely stomatal resistance, canopy temperature, and root growth are needed along with agronomic factors for the development and testing of yield models.

Therefore, this study was needed to understand fundamental effects of CO_2 on sorghum and to determine response functions that can be used to develop and test predictive models.

The objectives of the work were to determine the effects of enriched CO_2 on:

1. Agronomic factors of sorghum (growth stage, height, leaves per plant, leaf area per plant, vegetative yield, and reproductive yield);
2. Evapotranspiration (ET) rate and water use efficiency of sorghum;
3. Stomatal resistance and canopy temperature of sorghum; and
4. Root growth, root distribution, and root:shoot ratios of sorghum.

MATERIALS AND METHODS

The Evapotranspiration Research field near Manhattan, Kansas, was used to study performance of sorghum (Sorghum bicolor L. Moench.) at different carbon dioxide (CO_2) levels. The experiment was conducted in underground rhizotron boxes (Fig. 1 and 2). The boxes were 30 cm apart, were in a single row, and were housed in plywood frames. The internal volume of each box was $311,000 \text{ cm}^3$. The boxes were filled with Muir silt loam (fine silty, mixed mesic, Cumulic Haphistoll) soil taken from the experimental site (Table 1). At field capacity (38% moisture by volume), each box weighed approximately 564 kg. At the wilting point (14% moisture by volume), each box weighed approximately 488 kg. One side of each box had a grided glass for monitoring root growth nondestructively throughout the growing season. The boxes were raised above ground by an electrical hoist and weighed on a load cell balance.

Sorghum hybrid 'Asgro Correl', a correl hybrid from Asgrow Seed Company (7000 Portage Road; Kalamazoo, MI 49001), was hand-planted on 19 June 1984, in east-west row orientation in a single row in the center of the boxes. Rows were also planted between the boxes. The plant density both inside and outside the boxes was maintained at approximately 12 plants/m after 30 days from planting by hand thinning. For comparison and to avoid border effects, approximately 0.1 hectare area was seeded around the boxes under ambient atmospheric conditions. The entire experimental area including the boxes received 68 kg of N per hectare.

Figure 1. Research facility at Manhattan.

Figure 2. Schematic diagram of the rhizotron box - front, side and plan view.

Table 1. Physical and chemical properties of soil in the rhizotron.

Physical

Sand (%)	32
Silt (%)	52
Clay (%)	16

Chemical

pH	7.7
Avl. P (kg ha ⁻¹)	48.0
Exch. K (kg ha ⁻¹)	420.0
Avl. N. (μL L ⁻¹)	
NH ₄ - N	2.7
NO ₃ - N	2.7
Organic Matter (%)	1.0
DTPA Zinc (μL L ⁻¹)	0.5
DTPA Iron (μL L ⁻¹)	9.0
Exch. Ca (μL L ⁻¹)	2218.0
Exch. Mg (μL L ⁻¹)	149.0
Exch. Na (μL L ⁻¹)	5.0
Avl. MN (μL L ⁻¹)	7.0

Canopy height was recorded until physiological maturity, 6 times after CO₂ was initialized into the chamber. Similarly, leaf numbers and leaf areas were recorded (7/18; 7/28; 8/3; 8/12), starting from 25 days after emergence (DAE). The length (L) and width (W) of all the leaves of three plants from each box were recorded 3 times, starting from 35 DAE. The leaf area was calculated by (L x W x 0.78).

Stomatal resistance and leaf temperature of adaxial and abaxial surfaces of fully expanded top leaves were measured with a steady state porometer (Model LI 1600, LICOR Ltd., Lincoln, Nebraska 68504)^{*1}. Five expanded leaves were measured at each observation. The canopy resistance (Singh and Szricz, 1980) was calculated by the equation:

$$r_c = r_l / LAI$$

where r_c is an effective canopy resistance, r_l is stomatal resistance of the leaf, and LAI is the leaf area index.

The rhizotrons were weighed 9 times (0, 27, 32, 40, 46, 55, 61, 76 and physiological maturity) starting from emergence (0 DAE) to physiological maturity. Between the second measurement (27 DAE) and 8th measurements (76 DAE), 15 L (4.8 cm) of water was applied to each rhizotron after weighing.

Shoots of the sorghum plants were harvested on 24 September and separated into leaves, stems and grain. Grain moisture

^{*1} Mention of trademark or proprietary product in this report does not imply approval by the Kansas Agricultural Experimental Station to the exclusion of other products that may also be suitable.

content was determined with the Burrows digital moisture meter (Model 700; Burrows Equipment Company, Evanston, Illinois). Grain yield and other plant components were adjusted to a 14 percent moisture content by weight.

Root measurements:

Roots were observed during the growing season through the glass side of each rhizotron. The observations were taken on the same days that the rhizotrons were weighed. At four depths, (35, 70, 105, and 135 cm) root intersections with a 25 cm x 25 cm grided area were counted. Each grid area consisted of 100, 2.5 cm x 2.5 cm boxes. When a root crossed a line on the grid, it was counted as an intersection. Total number of root intersections were counted for each depth. From these data, total root length may be calculated (Newman, 1965).

After harvesting the shoots, each box was removed from the site and soil was washed out of the box with tap water. Washing was done gently to keep the roots intact. Differently sized sieves were used to capture any detached roots. After most of the soil was removed, the roots were cut at different depths. The cut roots were then cleaned in the laboratory with a chemical dispersant [sodium hexametaphosphate $(\text{NaPO}_3)_6$] and water (Al-Khafab et al., 1977). The cleaned roots were oven-dried at 70°C for 5 days, and the weight of the roots then recorded.

Enrichment Chamber Design

As shown in Fig. 3, the enrichment chambers used in this study are of closed type, similar in design to those used by Sij et al (1972) with slight modification. The chamber (121 cm by 92cm by 168cm) had an arc dome at the top. The three sides of the chamber, framed with 0.6 cm thick plexiglas, were held together by right-angled aluminum channels (1.3 cm). Inlet and outlet ducts were placed in the chamber end at a height of 51 m and 81 cm from the ground.

The Air Delivery System:

The delivery system consisted of a centrifugal blower attached to a custom fabricated delivery tube (Fig. 4). To facilitate both the vigorous mixing of CO_2 and the measurement of mass transfer rates, a turbulent flow condition was created within the tube. This was accomplished by:

- (1) Abruptly changing the diameter (25cm to 18cm) of the tube downstream of the flow.
- (2) Placement of a wooden baffle at the point of the flow constriction.

The turbulent flow creates a flat (approximately constant) velocity profile across the tube. The velocity profile in the tube was measured using a portable velocity meter (Teledyne - Hastings Radist Model AAB-27). To measure air velocity, the instrument was placed into the tube downstream of the baffle, through an access hole. The wind speeds were measured at regular

Figure 3. CO₂ enrichment chamber: front, side and plan view.
Dimensions given in cm.

Figure 4. Air duct system for enrichment chamber.

intervals across the diameter of the tube. The resulting wind speed was then used in the calculation of the mass transfer rates of air, carbon dioxide, and water vapor through the chamber.

CO₂ Enrichment Systems:

Carbon dioxide was supplied to the system from a series of six commercially available CO₂ tanks hooked into a common manifold. From the manifold a regulator reduced the pressure from 3500 KPa to 70 KPa. The CO₂ was then separated into six individual lines and each line was fed into a valve and flow meter (Gilmont Instruments Model No. F1100) assembly. The rate of flow to supply different CO₂ concentration to each chamber was regulated by the valves. From the flow meter, the CO₂ was fed into copper refrigerator tubing (0.6 cm diameter) to each chamber. The CO₂ was injected into the air duct of the chamber.

CO₂ Sampling System:

A schematic diagram of the enrichment and sampling system is shown in Fig. 5. Carbon dioxide enrichment levels were determined by sampling inside the inlet duct. Air samples were drawn from across the diameter of the intake duct through 0.6 cm diameter tubing by a pump (Cole-Palmer Model 706S-20) situated a building at the side. Copper lines from each chamber were brought into the building where each sample was passed

Figure 5. Schematic diagram of CO₂ enrichment and sampling system.

L volumetric mixing flasks to uniformly mix the air. Individual lines from each flask were connected to a sampling manifold. The sampling manifold was comprised of a series of solenoid valves (one for each chamber line) directed to a common sampling line. The CO_2 sample was then chilled by a refrigeration unit to condense most of the moisture from the sample. The sample was then directed into a flow meter and then finally into an infra-red gas analyzer (ADC 225 MK3 Analytical Development Co., Hoddenson, Herts., England).

To select a particular chamber for sampling, the corresponding solenoid valve was energized allowing the sample to be tested. Automatic sampling control was accomplished by using a custom made stepper device. The stepper device energized the solenoids in a sequential manner, at selectable time intervals. A seven minute per chamber sampling interval was used.

To determine photosynthetic rates, a sample was drawn in a similar manner from the outlet of the chamber. This sample was analyzed by a second infra-red gas analyzer operating in a differential mode. The samples from the inlet and outlet streams were used to determine the net change in CO_2 concentration. From this, and the calculation of the flow rate, a mass balance of CO_2 can be used to determine photosynthetic rates. The gas analyzers had an accuracy of $\pm 1\%$ fsd (10 g L^{-1} absolute; 1 g L^{-1} differential). Each analyzer was calibrated with standard-concentration CO_2 gas (Scott Environmental Laboratories, San Bernardino, CA) on a daily basis. For the inlet CO_2 concentration the analyzer was operated in the absolute mode and CO_2 concentrations were determined in absolute concentration.

The outputs of both the analyzers were connected to a two-pen continuous strip chart recorder.

Mass transfer rates of water vapor through the chamber were measured with two shielded wet-dry psychrometers. One psychrometer was placed in the outlet tube of the chamber and the other outside the chamber. The thermocouple temperatures were monitored by the CR-5 recorder (Campbell Scientific, Logan, Utah).

Soil temperature at different depths (2, 10, 20, 60, 90 cm) were measured inside the rhizotron and outside in the field. A wooden dowel with Cu-constantan thermocouples taped on the side was buried into the ground to measure the soil temperature. A Campbell CR-5 (Campbell Scientific Co.) data logger recorded the temperature of the thermocouples at 15 minute intervals.

Several light interception measurements of the rhizotron canopies were made with a light bar (LICOR Inc. Model Line Quantum Licor Instruments, Lincoln, NE). The results were recorded in a polycorder (Model 516A). Licor sensors were installed in the field (Fig. 6) to measure the total incoming radiation, photosynthetically active radiation, canopy and soil reflection throughout the growing season. These readings were recorded by a polycorder.

Figure 6. Plan view of the research plot.

RESULTS AND DISCUSSION

Chamber performance test:

Three major concerns in the operation of CO_2 enrichment chambers were:

1. CO_2 distribution within the chambers
2. Temperature differences between the outside and inside of the chambers
3. Degree of fluctuation in air delivery to the chambers
4. Diurnal fluctuation of CO_2 concentrations in the chambers

1. CO_2 distribution: To study the pattern of CO_2 dispersion inside the chamber, a colored smoke was placed in the inlet stream. Sequenced photographs of the test are shown in Fig. 7. Visual observations indicated that the mixing within the chamber was sufficient to ensure a constant concentration of CO_2 throughout the chamber.

2. Temperature:

Dry bulb temperatures from the psychometric data were used in this evaluation. The temperature of the chamber was assumed to be the temperature of the outlet stream. Figure 8 shows the outside and inside temperatures for a 24 hour period. In general, the environment inside the chamber was warmer than on the outside. The maximum difference occurred at 2000 hours and was 2.7°C . Values were relatively similar during the early hours of the morning. After sunrise the chambers became consistently higher than the external temperature. This difference continued until the end of the day.

Figure 7. Smoke distribution inside chamber.

Figure 8. Diurnal temperature variation inside and outside the enrichment chamber.

3. Air delivery:

To study the fluctuation in air delivery rates over a daily period, air stream flow rates were measured every 30 minutes for 6 consecutive hours. Air exchange rates were calculated using the stream flow rates. Each measurement of air stream velocity in the cross section of the tube was used to calculate the air exchange rate. The determination was given by:

$$\text{Air exchange rate} = \sum_{i=0}^L \pi (r_{L+1}^2 - r_L^2) V_i$$

where r_i = radius

V_i = velocity at

Figure 9 shows a reasonably constant air exchange rate over the six hour period. The maximum and minimum flow rates were $1.52 \text{ m}^3 \text{ min}^{-1}$ and $1.49 \text{ m}^3 \text{ min}^{-1}$. Figure 10 shows the daily air exchange values for the times period between July 20, 1984, and August 3, 1984. As with the six hour period, the air delivery rate was approximately constant.

4. Carbon dioxide delivery:

Figure 11 shows the carbon dioxide concentration in the delivery stream over a 24 hour period on August 26, 1984. Values shown represent hourly average concentrations. The high concentrations showed somewhat greater variability than the low concentration.

Physiological growth stages:

The physiological stages were classified according to the method described by Vanderlip (1972). Elevated CO_2 concentration

Figure 9. Air delivery rate variation over a six hour period.

Figure 10. Air delivery rate variation over a two week period.

Figure 11. Diurnal variation in CO₂ delivery.

had a negative effect on the length of certain growth stages, especially reproductive stages of sorghum (Table 2). Increased CO_2 ($795 \mu\text{L L}^{-1} \text{CO}_2$) delayed the boot stage, half bloom, and soft dough stages compared with sorghum plants grown under ambient conditions ($330 \mu\text{L L}^{-1} \text{CO}_2$). Duration between boot to half bloom stage was most pronounced in case of enriched CO_2 compared to the ambient treatment. Similar results were also reported by Hesketh and Hellmers (1974) and Marc and Gifford (1984). Duration between the soft dough and maturity growth stages were similar for the treatments.

Agronomic parameters:

The canopy height, number of leaves per plant, and leaf area per plant were measured at different growth stages (Table 3). The CO_2 -enrichment treatments did not show any measurable effects on canopy height or leaf numbers. Leaf areas were recorded 4 times, starting from 10 days after CO_2 was injected into the chambers. The rate of increase in the leaf area was rapid soon after the CO_2 was applied, but gradually levelled off after the boot stage. Most of the increase in the leaf area in response to the high CO_2 treatments occurred up to the boot stage, which is the juvenile stage. Slightly higher leaf area during preboot and boot stages in the ambient chambers compared to the field grown sorghum might have been due to the higher canopy temperature (Fig.8). The increase in leaf area by elevated CO_2 concentration was associated with an increase leaf area per leaf rather than leaf number. In contrast, CO_2 enrichment had little or no effect on leaf number.

Table 2. Physiological growth stages as affected by enriched CO₂ (Manhattan, 1984).

Growth Stage	Description	Approximate days after emergence	
		795 ($\mu\text{L L}^{-1}\text{ CO}_2$)	330
0	Emergence	0	0
1	Collar of 3rd leaf visible	7	7
2	Collar of 5th leaf visible	15	15
4	Final leaf visible	32	32
5	Boot	42	40
6	Half bloom	56	50
7	Soft dough	68	61
8	Hard dough	82	75
9	Physiological maturity	91	86

Table 3: Summary of the agronomic parameters of sorghum as affected by enriched CO₂ (Manhattan, 1984)

A. Canopy height (cm):

CO ₂ Conc. μLL-1	Days after planting				
	25 (7.14)	31 (7.20)	36 (7.25)	44 (8.2)	50 (8.8)
795	48	54	64	69	82
660	46	57	65	72	85
485	47	57	65	71	78
330	45	51	62	70	85
Outside **	50	58	70	79	87

B. Leaf numbers per plant:

CO ₂ Conc. μLL-1	Days after planting				
	20 (7.10)	24 (7.14)	27 (7.17)	35 (7.25)	49 (8.7)
795	8.6	9.9	9.3	8.5	8.0
660	8.3	9.5	9.0	8.4	8.1
485	8.6	9.8	9.6	7.7	7.5
330	8.6	9.6	9.2	8.0	7.8
Outside	8.5	9.2	9.5	8.8	8.0

C. Leaf area per plant (dm²/plant):

CO ₂ Conc. μLL-1	Days after planting			
	31 (7.20)	35 (7.25)	44 (8.2)	56 (8.14)
795*	10.7	12.7	15.9	16.1
660	10.1	13.0	16.8	17.0
485	7.3	10.3	11.5	12.8
330	7.2	9.6	12.9	13.1
Outside	8.9	10.2	10.5	12.8

* Mean of 3 plants

** Mean of 5 plants

Yield parameters:

All of the yield components were increased with increased CO_2 concentration (Table 4). The yield responses due to enriched CO_2 levels were not as dramatic as would be expected in C_3 plants (Kramer, 1981; Lemon, 1983; Waggoner, 1984). There were gradual increases in the total phytomass (root + shoot) with increased CO_2 concentration. However, the increase was most pronounced from ambient to $485 \mu\text{L L}^{-1} \text{CO}_2$. The root:shoot ratios were similar irrespective of the CO_2 treatments. Similarly, harvest indices were similar for the enriched CO_2 treatments. The rhizotron without the plexiglass chamber had the lowest phytomass. This may be primarily due to the higher canopy temperature of the chamber plants.

Evapotranspiration (ET):

The lysimeter is the only hydrologic method in which the experimenter can obtain accurate and continuous measurements of evapotranspiration (Reicosky, 1981). The rhizotrons used in this experiment were modified form of lysimeters. Fig. 12 indicates that amount of total water used by sorghum plants was not similar for enriched CO_2 treatments. Total ET from the rhizotron at different CO_2 treatments ranged from 163 L to 182 L from emergence to physiological maturity. The variation of ET amount at different measurement intervals among the CO_2 treatments may be partially due to lack of accuracy associated with small differences measured from the very heavy rhizotrons. The weight of the rhizotrons during the measurements ranged from 645 kg to

Table 4: Summary of sorghum yield and yield components as affected by enriched CO₂ (Results from 10 plants)

CO ₂ -Conc (μ LL-l)	Leaf	Stem	Vegetative		Grain	Root	Harvest index	Root: shoot	Root: shoot+ grain
	(Weight in g)								
				Shoot					
795	140	235	87	462	238	68	0.52	0.15	0.10
660	128	217	76	420	197	56	0.47	0.13	0.09
485	116	221	61	398	178	45	0.45	0.11	0.08
330	109	147	55	311	150	42	0.48	0.14	0.09
No Chamber	86	127	59	272	158	38	0.58	0.14	0.09

Figure 12. Periodic evapotranspiration of sorghum as effected by enriched CO₂ from emergence to physiological maturity (1984).

540 kg.

Evaporation per day at different growth stages of sorghum as affected by enriched CO_2 is presented in Table 5. Maximum evaporation occurred between stage 3 (growing point differentiation) and stage 7 (soft dough) and minimum at early and late stages of growth. This was primarily due to high leaf area and rapid growth during that time. At early stage (0-3) the ET was primarily the evaporation from the soil. No definite trends of ET rate increases or decreases among the CO_2 treatments were observed.

Canopy temperature:

The canopy temperature of the chamber plants were warmer compared to the open field (Fig. 13). Similarly canopy temperature at higher CO_2 levels were warmer than at ambient CO_2 levels. The differences between the canopy temperatures were highest between the ambient ($330 \mu\text{L L}^{-1} \text{CO}_2$) and $795 \mu\text{L L}^{-1} \text{CO}_2$.

Stomatal and canopy resistance:

Stomatal resistance was higher for the CO_2 treatments compared to the ambient (Fig. 14). Plants in the rhizotron chambers showed higher stomatal resistance compared to the plants in the open field. Meidner and Mansfield (1968) indicated that raising the level of CO_2 tends to close the stomata and decrease transpiration. Although elevated CO_2 concentration increases the stomatal resistance, total water used was similar (Fig. 12). This may be primarily due to increased LAI area under

Table 5. Evapotranspiration per day at different growth stages of sorghum as affected by enriched CO₂ (Manhattan, 1984)

Interval (Days after emergence)	Approximate growth stages	CO ₂ Concentration ($\mu\text{L L}^{-1}$)			
		<u>330</u>	<u>485</u>	<u>600</u>	<u>795</u>
		(mm of evapotranspiration day ⁻¹)			
0-27	0 to 3	2.8	4.0	2.0	2.5
27-32	3 to 4	9.9	10.0	13.7	10.8
32-40	4 to 5	12.4	9.4	9.7	8.6
40-55	5 to 6	10.6	10.8	9.0	12.4
55-61	6 to 7	8.5	10.3	9.3	11.8
61-76	7 to 8	5.9	4.1	6.5	6.4
76-P. Mat.	8 to 9	2.3	2.0	2.3	2.8

Figure 13. Sorghum leaf temperature (°C) deviation from 330 μL L⁻¹ to different CO₂ concentration (1984).

(Fig. 12). This may be primarily due to increased LAI area under enriched CO₂ treatments resulting in similar canopy resistance (Table 6).

Water requirements and yield components:

Amount of water required to produce a gram of any yield components as affected by the enriched CO₂ treatments were calculated (Table 7). The results indicated that less water was required to produce a gram of any yield component at higher CO₂ concentration compared to the ambient. Lower water requirement is primarily due to higher yield (Table 4) and equal amount of total water (Fig. 12) used by different CO₂ treatments.

Root distribution:

The growth and the distribution of roots in soil is a dynamic process controlled by soil factors such as temperature, aeration, moisture content and availability of nutrients. There are reported experiments that demonstrate the effects of external conditions on the distribution of carbohydrates between shoots and roots (Brouwer, 1962). The root length (cm) per unit area (cm²) was measured at four different zones (35, 70, 105 and 135 cm) on seven different days between 27 to 76 DAP. However, Fig. 15 represents only the root length on four different days after planting (27, 40, 55 and 76) DAP to avoid clustering. Although these figures probably represent an underestimate of the total root length due to minute root hair size not visible through the thick glass, they provide a good indication of the root length with increased CO₂ levels and at different growth

stages.

The root length per unit area at different depths indicated that enriched CO_2 treatments increased the root length compared to the ambient treatment at all growth stages. The root length per unit area was usually higher at high concentrations (660 and $795 \mu\text{LL}^{-1}$) compared to at $485 \mu\text{LL}^{-1}$, although not very conspicuously. Root lengths per unit area reached maximum at 40 DAP, and thereafter there was little change in the total length. The differences in the root length were most pronounced in the top three soil depths (35, 70, 105 cm) for the sorghum plants receiving $795 \mu\text{LL}^{-1}$ compared to the other treatments. Figure 15 indicates that at $795 \mu\text{L L}^{-1}$ of CO_2 root growth was larger at all soil-profile depths compared to the roots in the rhizotron subjected to lower CO_2 treatments. The increases in total root weight and the root length per unit area due to enriched CO_2 levels were not as pronounced as in the case of the shoots. Primarily, roots are much less efficient than are the shoots in attracting carbohydrates from the general pool.

Table 6. Effective canopy resistance as affected by enriched CO₂
(Manhattan, 1984).

CO ₂ Conc. ($\mu\text{L L}^{-1}$)	Days after planting			
	31 (7.20)	35 (7.25)	40 (7.30)	56 (8.14)
	sec cm ⁻¹			
795	0.68	0.23	0.22	0.19
660	0.67	0.21	0.18	0.16
485	1.02	0.21	0.20	0.20
330	1.34	0.17	0.20	0.18

Table 7. Summary of water used to produce a gram of different yield components as affected by enriched CO₂ (Manhattan, 1984)

CO ₂ (μL L ⁻¹)	Leaf (L ⁻¹)	Stem	Chaff*	Vegetative shoot** (g/g)	Grain	Root	Total phytomass
795	1303	776	2097	395	776	2682	238
660	1273	750	2142	388	826	2907	242
485	1475	774	2805	430	961	3802	276
330	1490	1111	2968	525	1090	3893	325

* Vegetative shoot includes leaf, stem and shaft.

Figure 15. Sorghum root length (cm) per unit area (cm²) as affected by enriched CO₂ at different soil depths and at different growth stages.

Figure 16. Sorghum root weight (g) as affected by enriched CO₂ at different soil profile depth at maturity (1984).

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