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EFFECTS OF ELEVATED ATMOSPHERIC CARBON DIOXIDE CONCENTRATIONS ON WATER AND ACID REQUIREMENTS OF SOYBEANS GROWN IN A RECIRCULATING HYDROPONIC SYSTEM

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ABSTRACT
Establishing mass budgets of various crop needs, i.e. water and nutrients, in different environments is essential for a Controlled Ecological Life Support System (CELSS). The effects of [CO_2], 500 and 1000 umol mol^{-1}, on water and acid use (for pH control) by soybeans in a recirculating hydroponic system were examined. Plants of cvs. McCall and Pixie were grown for 90 days using nutrient film technique (NFT) and a nitrate-based nutrient solution. System acid use for both CO_2 levels peaked near 4 weeks, during a phase of rapid vegetative growth, but acid use decreased more rapidly under 500 compared to 1000 umol mol^{-1} CO_2. Total system water use by 500 and 1000 umol mol^{-1} plants was similar, leveling off at 5 weeks and declining as plants senesced (ca. 9 weeks). However, single-leaf transpiration rates were consistently lower at 1000 umol mol^{-1}. The data suggest that high CO_2 concentrations increase system acid (and nutrient) use because of increased vegetative growth, which in turn negates the benefit of reduced water use (lower transpiration rates) per unit leaf area.

INTRODUCTION

Establishing mass budgets of plant needs is essential for a Controlled Ecological Life Support System (CELSS), especially when focusing on system efficiency. Measuring the amount of water, minerals, and carbon dioxide a particular crop needs when grown in various environments will provide important data for the modeling and development of future CELSS. Work is under way at

NASA and various universities to model and emulate a CELSS with data collected from field studies and short term (vegetative) studies in controlled environments. Obtaining accurate information on system budgets is best done with data from production studies in controlled environments rather than field studies since results can differ (1,2). As part of a series of studies involving the effect of CO_2 on soybean production (two cultivars at two planting densities), the mass budgets of water and acid use of the recirculating hydroponic system were monitored.

MATERIALS AND METHODS

Each study was carried out in a 1.8 m x 2.4 m walk-in growth chamber (model M48, EGC Inc, Chagrin Falls, OH). Plants were grown in eight trapezoidal-shaped PVC plastic trays, 0.25 m^2 (Fig 1) which is the same as those used in the Biomass Production Chamber (BPC) at NASA's Kennedy Space Center (3).

A complete nutrient solution was continuously pumped from the same reservoir to each tray at a flow rate of approximately 1 L min^{-1}. The back (wide) end of each tray was elevated 2 cm to allow passive (gravity) flow of nutrient solution to the front (narrow) end, where the solution returned to the reservoir (Fig 2).

The nutrient solution was a modified 1/2 strength Hoagland's solution. Since only nitrate-nitrogen was used in the nutrient solution, the pH tended to increase during periods of rapid growth and heavy nitrate uptake (4). To balance this, an

automatic pH controller was used to add dilute HNO_3 (2.5% v/v) to continuously maintain the pH 5.7 $\pm$ 0.5 units. Each day deionized water was added to the reservoir to replenish water taken up (transpired) by the plants. Twice each week nutrients were replenished by adding stock solutions of nutrients that were removed from the solution. Weekly samples of the nutrient solution were collected for inorganic nutrient analysis.

Seeds of cvs McCall and Pixie were planted onto each tray top and covered by a Plexiglas cover for 4 days (Fig 1), after which the cover was removed and plants were thinned to either three or six per tray. Both studies used a 12-hr photoperiod with a canopy photosynthetic photon flux (PPF) of 294 $\pm$ 33 umol m^{-2} s^{-1} for the 500-CO_2 treatment, and 318 $\pm$ 44 umol m^{-2} s^{-1} for the 1000-CO_2 treatment. Daily light-period temperatures averaged 25.6 $\pm$ 0.6°C and 25.8 $\pm$ 0.1°C for the 500- and 1000-treatment, respectively, while dark-period temperatures averaged 20.1 $\pm$ 0.6°C and 20.2 $\pm$ 0.1°C. Relative humidities were kept constant and averaged 62 $\pm$ 2% and 64 $\pm$ 3% for the 500 and 1000-treatments. The CO_2 was monitored and controlled at either 500 or 1000 $\pm$ 50 umol mol^{-1} using an infrared analyzer. Four weeks after planting white, vinyl-plastic coated cages (60 cm high) were placed around the perimeter of each tray for support and to confine each tray to 0.25 m^2 of growing area. Single-leaf transpiration measurements of the abaxial (lower) leaf surface were taken at regular intervals throughout the studies using a steady state porometer (LI-1600, LI-COR Inc, Lincoln, NE). All

plants were harvested at 90 days. The results represent total system (chamber) averages and are not segregated by cultivar or density.

RESULTS AND DISCUSSION

Based on individual leaves, transpiration rates (ug cm^{-2} s^{-1}) were lower in the study having 1000 umol mol^{-1} CO_2 versus 500 umol mol^{-1} (Fig 3). Similar findings for soybean were recorded by Rogers et al. (5). Under both CO_2 concentrations leaf transpiration rates were relatively stable until 10 weeks, when rates declined rapidly as the crop senesced. Although the single-leaf transpiration rates differed between CO_2 treatments, total system (i.e. canopy) water use was equivalent over time (Fig 4). However more biomass was produced at 1000 umol mol^{-1} treatment and thus water use efficiency (WUE), based on total biomass/total water (g L^{-1}), was greater at 1000 umol mol^{-1} CO_2 (Table). Valle et al. (6) have found that 94% of the WUE increase was from increased photosynthetic rates (not decreased transpiration) at elevated CO_2 levels.

The amount of HNO_3 needed for controlling pH was much greater for plants grown at 1000 than 500 umol mol^{-1} CO_2 (Fig 5). As plants are grown with NO_3^- as the N source, the pH tends to increase over time, whereas NH_4^+ causes solution pH to decrease (4). Work has been done to maintain pH homeostasis in hydroponically-grown soybeans by using a 3:1 (KNO_3:NH_4) ratio (7). This may be a practical alternative to controlling pH in a CELSS, where acids and bases could be costly.

Creating budgets of acid and water use for soybean growth led to some interesting results. In doubling the CO_2 from 500 to 1000 umol mol^{-1}, biomass increased 18%, HNO_3 use increased 48%, and water use remained constant on a per area basis (Table 1). Although the high-CO_2-grown plants have a greater WUE, they are less efficient in acid use per unit dry weight. The acid and water requirements can be calculated per hectare (Table 1), an area approximately twice the size of a farm needed to support a large lunar colony (8). Approximately 45,000 L of water per day would be needed, and depending on the CO_2 treatment, between 5 and 10 L of 15.7 M HNO_3 would be needed for nutrient solution pH control. Similar NFT production studies with potatoes at cooler temperatures and ambient CO_2 (350-450 umol mol^{-1}) used half the amount of water per day and similar quantities of acid when compared to the 500 umol mol^{-1} soybean treatment (9). Although such numbers initially appear staggering, it is interesting to note that typical water consumption for greenhouse hydroponic systems range from 21,500-134,000 L $ha^{-1}d^{-1}$, depending on the crop (10). Unlike greenhouse situations, where transpired water is lost, the transpired water in a CELSS will be recycled as high purity (potable) water. This translates into a system where condensing and recycling equipment must handle at least 45,000 L ha^{-1} d^{-1} water, based on the data. The orchestration of various crops with the other components of a CELSS will require more information of the type shown in order to create the most productive and efficient system possible.

Table 1. Effects of carbon dioxide based on the growing area

CO_2 TREATMENT (μmol·mol)	EXTRAPOLATED AREA	WATER USE (L·day)	CONCENTRATED HNO_3 USE (L·day)	TOTAL DRY MATTER (Kg)	SEED DRY MATTER (Kg)
500	m^2	4.67	5.0×10^{-4}	1.02	0.451
500	hectare	46700	5.0	10200	4510
1000	m^2	4.55	9.6×10^{-4}	1.244	0.516
1000	hectare	45000	9.6	12440	5160

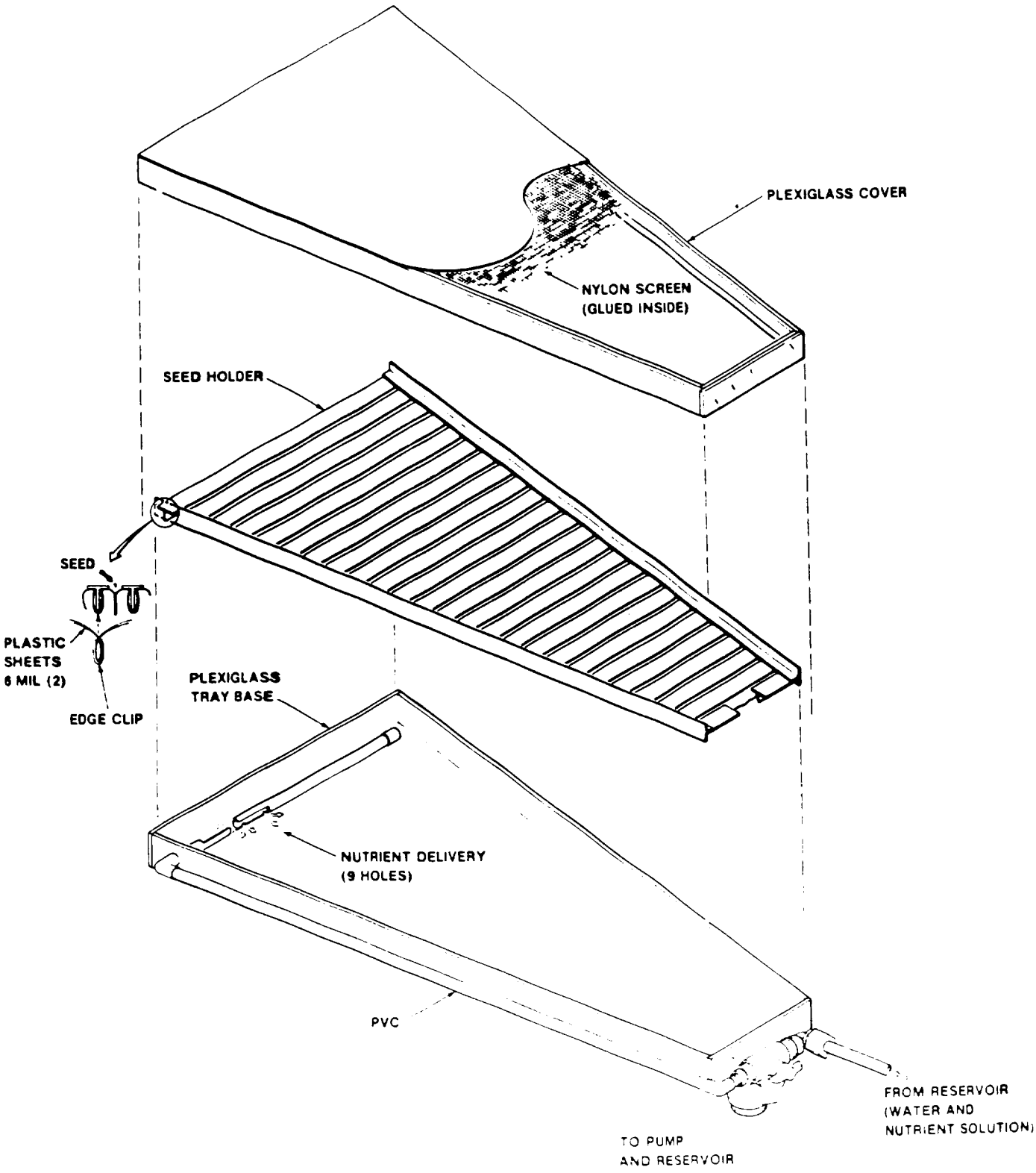

Fig 1. Hydroponic growing tray bottom, top, and germination cover.

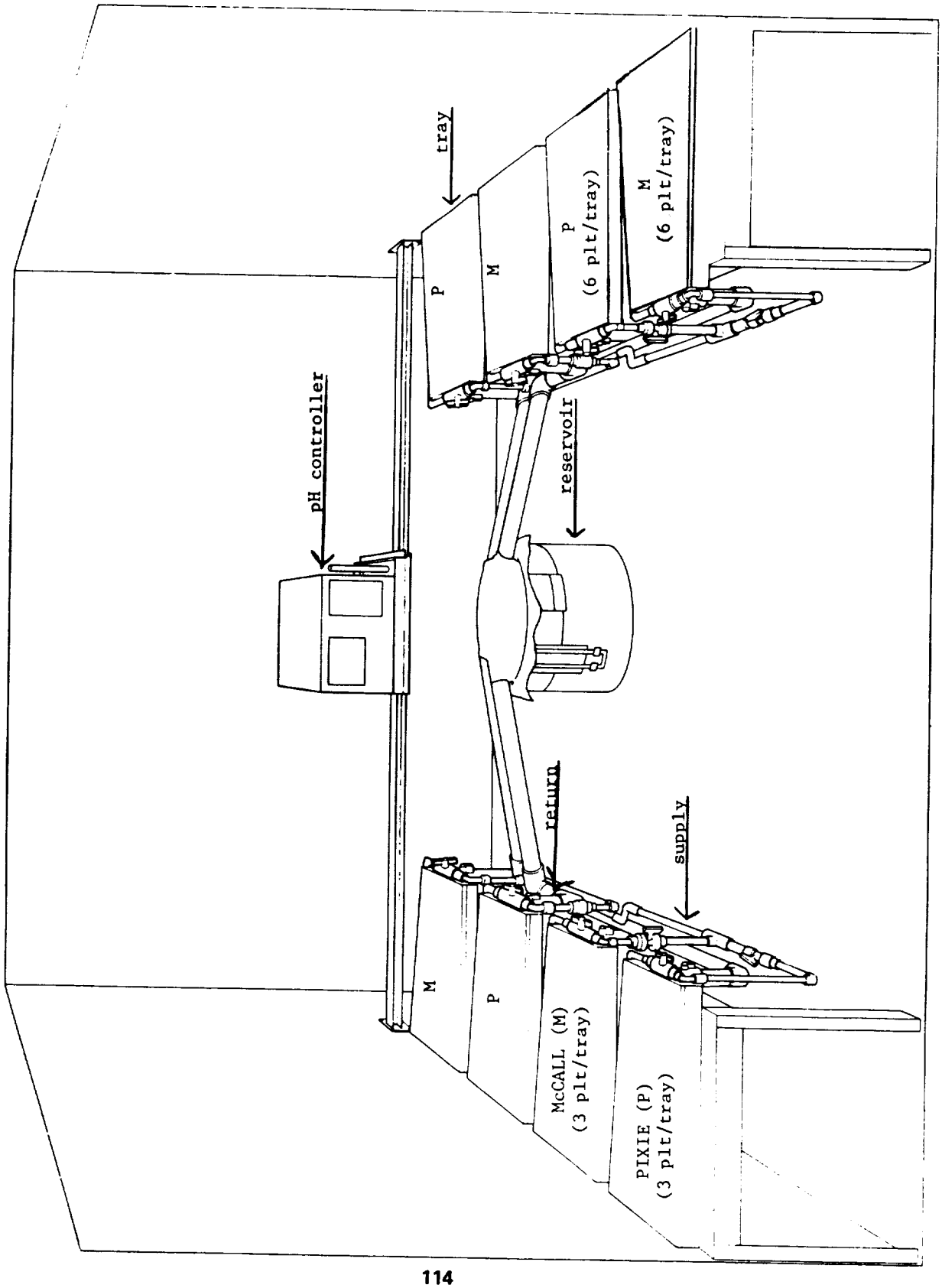

Fig 2. Growth chamber (4.4 m^2) layout showing growing trays and nutrient delivery system.

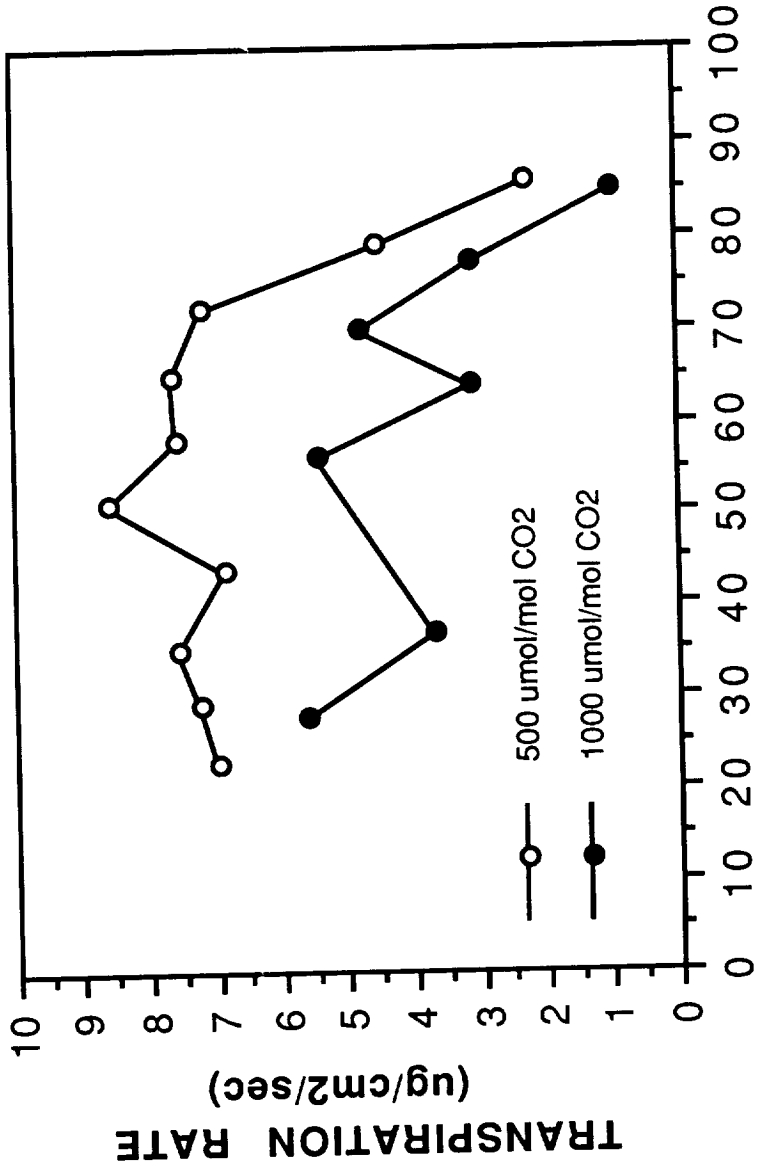

Fig 3. The effect of carbon dioxide on soybean leaf transpiration rates.

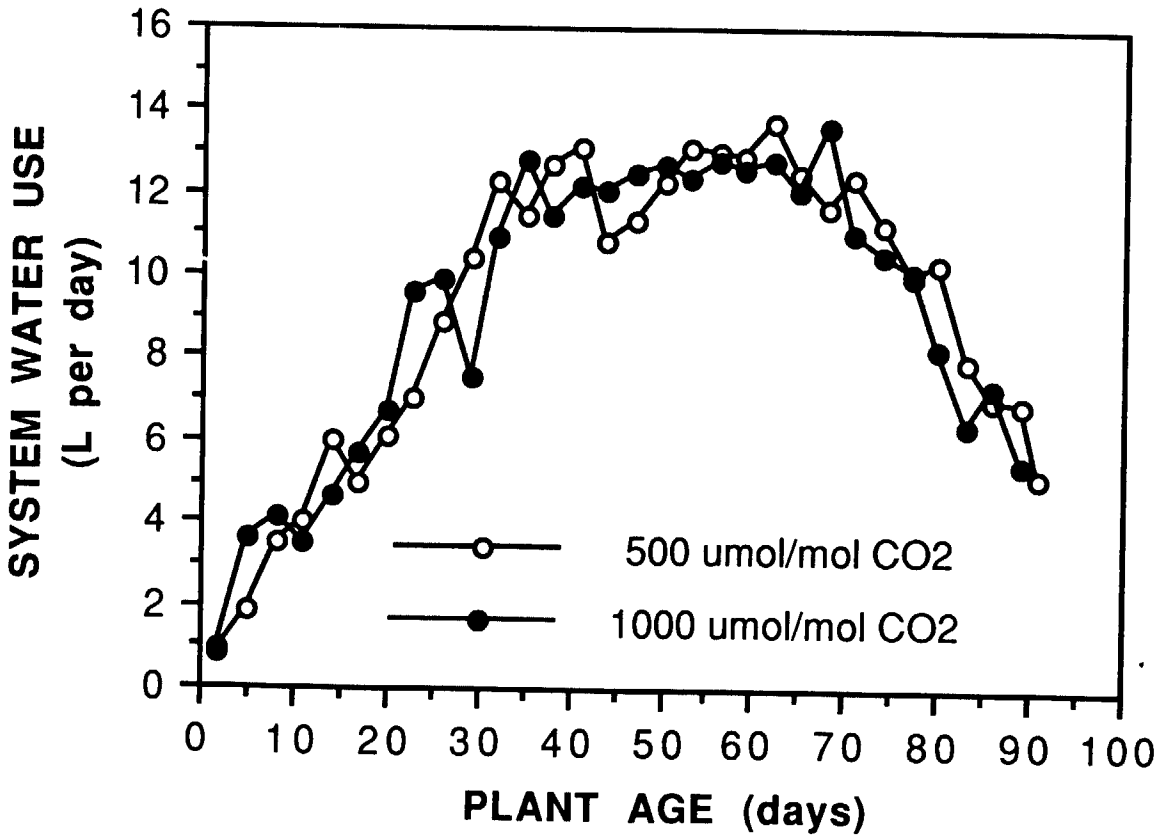

Fig 4. The effect of carbon dioxide on water use by soybean crops.

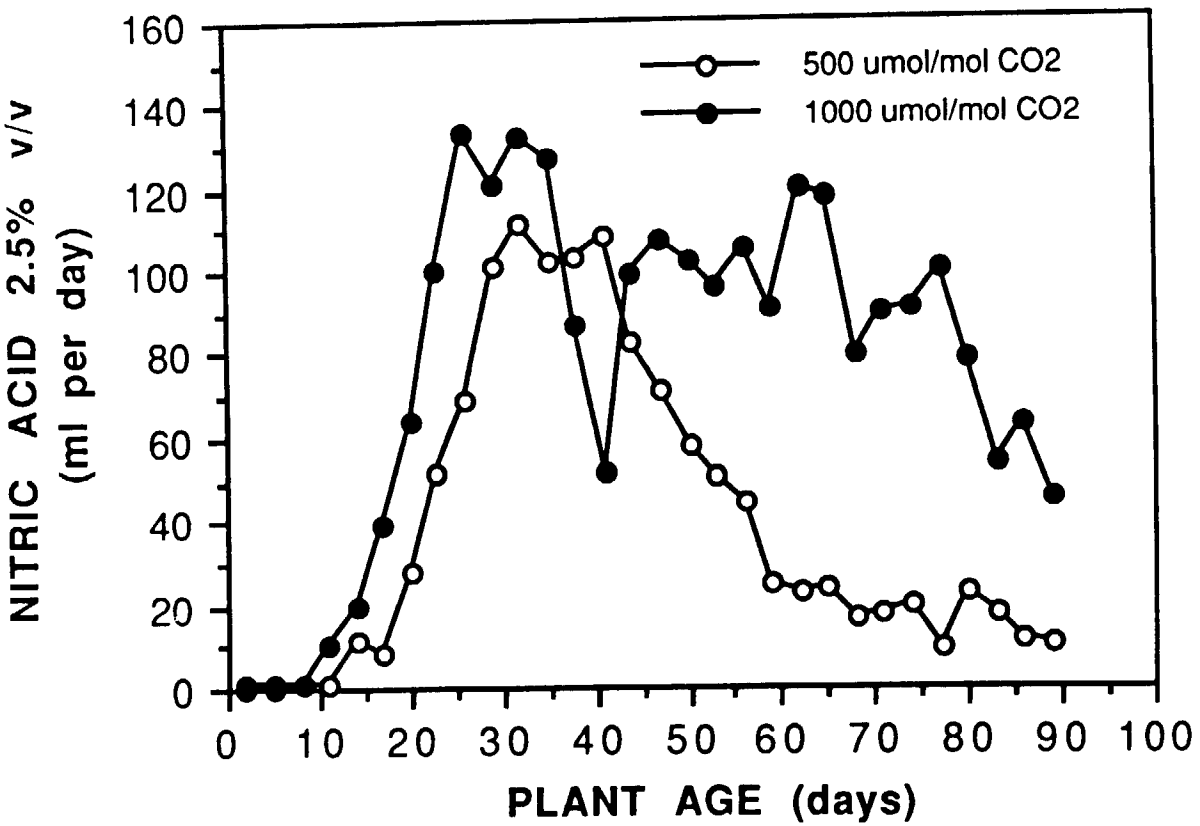

Fig 5. The effect of carbon dioxide on acid use by soybean crops.

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