THESIS

YIELD RESPONSE OF MULCHED FIELD GROWN TOMATOES IRRIGATED WITH CARBONATED WATER

Submitted by
Ricardo Pegenia Novero
Department of Horticulture

In partial fulfillment of the requirements
for the Degree of Master of Science
Colorado State University
Fort Collins, Colorado
Spring 1991

COLORADO STATE UNIVERSITY

March 29, 1991

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY RICARDO PEGENIA NOVERO ENTITLED YIELD RESPONSE OF MULCHED FIELD GROWN TOMATOES IRRIGATED WITH CARBONATED WATER BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

<u>Committee on Graduate Work</u>

Leigh E Towill

John F. Shanahan

DH Smith

Frank D. Moore III
Adviser

K.H. [illegible]
Department Head

ABSTRACT

YIELD RESPONSE OF MULCHED FIELD GROWN TOMATOES IRRIGATED WITH CARBONATED WATER

Hundreds of literature citations report positive responses of crops to CO_2 enrichment of greenhouse atmospheres. Carbon dioxide enrichment was done, either by open air fumigation with CO_2 gas or irrigation with carbonated water. In the open field where wind movement deters CO_2 enrichment, open air fumigation techniques were mostly a failure and the benefits of irrigation with carbonated water to plants has yet to be established.

The response of mulched field-grown tomatoes to irrigation with carbonated water using drip irrigation system was studied during 1988 and 1989. Injecting CO_2 into the irrigation water decreased water pH and, consequently, lowered soil pH. The decrease in soil pH, which was expected to increase the availability of P, Ca, and metallic elements such as Zn, Fe, and Mn, did not affect the plant uptake of any of the aforementioned elements except for Zn. Zinc concentration in the leaves of CO_2 treated plants was higher than that of the control plants for the 1988 experiment. Above ground enrichment at the crop canopy level was evident primarily during irrigation. However, residual soil CO_2 was observed for the mulched plots irrigated with carbonated water. Soil CO_2 concentrations for the control and carbonated water treated plots were similar under unmulched conditions.

Mulching alone increased fruit yield by 8%, and further yield increases ranging from 7 to 23% were attributed to irrigation with carbonated water. The yield component contributing most to increased fruit yield in plots irrigated with carbonated water was fruit size. The observed yield increase for carbonated water irrigated plants was probably due to enhancement of photosynthesis. Plants treated with carbonated water produced fruits with higher soluble solids, a quality factor that may be preferred.

Ricardo Pegenia Novero
Horticulture Department
Colorado State University
Fort Collins, CO 80523
Spring, 1991

ACKNOWLEDGEMENTS

The author recognizes the following organizations and individuals for their assistance and input: AIRCO Carbon Dioxide, Coastal Chemical, and the Colorado State University Agricultural Experiment Station for their financial support; Dr. Kenneth M. Brink, Head, Department of Horticulture for accepting me as a graduate research assistant; my adviser, Dr. Frank D. Moore, III, who was like a good father to me, for his guidance and advice; the members of my graduate committee, Drs. Danny H. Smith, John F. Shanahan, and Leigh E. Towill, for all their help in the conduct of the field experiments and their valued suggestions in the preparation of this thesis; the graduate students and staff of the Department of Horticulture for their friendship and support; my parents, who have been very supportive since my childhood days for instilling in me the value of a good education; all of our hospitable Filipino friends, especially Olga Corral, who made Fort Collins our home away from home; and my very active and inquisitive son, Paolo, who was then 4 years old and made graduate work very challenging -- he was a darling.

To all those mentioned above and others who in one way or another have helped me make my goal a reality, I wish to express my sincerest thanks and gratitude.

Most importantly, I express my sincerest gratitude to my lovely wife, Anna, for all her understanding, encouragement, support, and unending love. She kept me going during those trying times.

TABLE OF CONTENTS

INTRODUCTION

Tomato (Lycopersicon esculentum Mill.), a fruit commonly treated as a vegetable and a perennial plant that is usually cultivated as an annual, is a crop of great commercial value. Once thought to be poisonous because of its known family relation to nightshade (Solanaceae), tomatoes consumed in the United States either as a fresh food commodity or as processed products have become the major vegetable source of essential nutrients (Rick, 1978). While tomatoes are eaten directly as a raw vegetable, they are generally added to other food items such as salads and sandwiches. Complementing the use of tomatoes are a number of processed products including paste, whole peeled tomatoes, diced products, and various forms of juices and soups. Catsup, pizza, and pasta sauces have become an integral part of the American diet (Nevins, 1987). Because of these multiple uses and the ease of cultivation, tomato is now a crop with an annual farm value in excess of one billion dollars in the United States (Martin and Olmstead, 1985).

Mulching is the practice of covering the soil around plants to make conditions favorable for growth, development and efficient crop production (Hopen and Oebker, 1976). This practice dates back to very early agriculture and has been proven to increase yields and quality of field-grown food crops (Rowe-Dutton, 1957; Courter and Oebker, 1964; Hopen and Oebker, 1975). Higher yields were attributed primarily to more favorable temperature, less competition from weeds and greater soil moisture availability under the mulch (Schales and Sheldrake Jr., 1963; Vandenberg and Tiessen, 1972; Tiessen, 1973). However, elevated levels of CO_2 in the mulched plant microenvironment were found concomitant with increased growth in lettuce (Tarter, 1983) and plant growth and fruit yield, fruit size, in tomato (McCoy, 1978).

During the latter part of the 19th century, CO_2 enrichment of greenhouse atmospheres for crop production was begun and is used today with great success. To circumvent wind effects on CO_2 enrichment in the field, Wittwer (1979) suggested mixing CO_2 with irrigation water using a drip irrigation system. Nakayama and Bucks (1980) tested the system in the field and, in addition, buried the irrigation tubing. Significant yield increases were obtained from CO_2-treated plots of wheat. The use of carbonated water for irrigation was also employed with success by Mauney and Hendrix (1988) in a cotton greenhouse pot experiment. In addition to a significant yield increase in CO_2 treated plants, increase in uptake of Zn and Mn was also reported. These studies suggest that CO_2 enrichment of field grown crops may be feasible if CO_2 is mixed with the irrigation water and delivered through a drip system.

This research was conducted to determine the effects of irrigation with carbonated water on growth and yield of mulched field grown tomato.

REVIEW OF LITERATURE

Many studies on plant nutrition focused on the mineral nutrients supplied by the soil. Carbon, an essential nutrient required by plants in greatest quantity, about ten times more than nitrogen (Hartman et al., 1981; Salisbury and Ross, 1985), is often ignored as a plant nutrient thereby limiting growth. Through the process of photosynthesis, plants acquire carbon in the form of CO_2 from the surrounding air. Plants process a very large volume of air to meet their demand for CO_2. A maize crop for example, needs about 9,090 kg of CO_2 to provide 2,500 kg carbon for the organic structure of a crop for yielding 6.7 metric tons/ha of grain (Norman 1962). At the current level of atmospheric CO_2, corn plants must therefore process about 35,000 metric tons of air to procure the 2,500 kg of carbon for the crop (Wittwer, 1978). Current CO_2 concentrations, 350 μLL^{-1} may be suboptimal for photosynthesis as well as for crop yield (Wittwer, 1982; Dietz, 1986), and CO_2 enrichment of the crop atmosphere may be one of the avenues whereby crop yields can be maximized.

As early as 1888, benefits of CO_2 enrichment were recognized and reported for practical greenhouse crop production in Germany (Wittwer, 1986). A few years later in England and about 20 years later in the United States, similar results were noted (Plass, 1959; Wittwer and Robb, 1964). Although yield increases during those times were obtained for many crops, CO_2 enrichment of greenhouse atmospheres did not gain general acceptance (Wittwer, 1986). Instead, interest declined presumably because of phyto toxic impurities from CO_2 sources. For the United States, it took until the early 1960's to re-establish the benefits and economics of CO_2 enrichment of greenhouse atmospheres for enhancement of plant productivity. More recently, there has been a remarkable reawakening of interest in the potential benefits of elevated CO_2 because of global atmospheric increase and the presumed indirect effects on climate changes such as global warming, changing precipitation patterns, and longer growing seasons (Idso, 1982; Wittwer, 1983).

Enrichment of the air with CO_2 is an economic practice with regard to many species grown commercially in greenhouses and other controlled environment facilities (Wittwer, 1978; Kimball, 1986). Strain and Sionit (1982) have prepared an extensive bibliography on the direct effects of CO_2 on plants. Included are effects on photosynthesis, primary productivity, crop yields, biomass, tuberization, water use efficiency, biological nitrogen fixation, mycorrhizal activities, flowering phenology, and pest-crop interactions.

Effects of elevated levels of atmospheric CO_2 on different plant biological processes are well known. It has been conservatively suggested that a doubling of the current atmospheric CO_2 will result in a 50% increase in photosynthesis in C_3 plants with yield and dry weight increases ranging from 20 to 45% and a 45% increase in primary productivity (Bassham, 1977; Baker and Enoch, 1983; Bjorkman and Pearcy, 1983; Tolbert and Zelitch, 1983; Bravdo, 1986). In potato, there is strong evidence that tuberization benefits the most from high CO_2 (Arteca et al., 1979; Baker and Enoch, 1983). Water use efficiency accompanied by decrease in water requirements of many plant species improved with elevated levels of atmospheric CO_2 (Carlson and Bazzaz, 1980; Rosenberg, 1981). The results obtained with elevated levels of atmospheric CO_2 on the growth, nodulation, and nitrogen fixation of the soybean plant suggest that significant increases in biological nitrogen fixation systems may occur as well as an increase in mycorrhizal fungal activity (Wittwer, 1983). Favorable effects of elevated levels of CO_2 on the aforementioned plant biological processes were reviewed at length by Wittwer (1983).

Further biological effects of higher than normal CO_2 concentration in the atmosphere relate to stress phenomena and resistance to stresses such as drought, low light intensities, high temperature, nutrient deficiencies, soil salinity, other soil problems, and air pollutants (Kimball, 1983). Bjorkman and Pearcy (1983) reviewed crop responses to CO_2 enrichment considering different environmental stresses. They concluded that doubling of the current atmospheric CO_2 concentration would result in improved adaptation and drought resistance of most crops, enhancement of photosynthesis even at low light levels, and increased optimum temperatures for growth and development. Furthermore, doubling CO_2 level may partially offset the yield decreasing effect of nitrogen deficiencies, and may increase salt tolerance of crops (Baker and Enoch, 1983). Detrimental effects of air pollutants such as SO_2, O_3 and NO_2 compounds were mitigated by increasing CO_2 levels (Strain and Bazzaz, 1983).

Favorable effects of elevated levels of CO_2 on various crops particularly C_3 plants were demonstrated in greenhouses and growth chambers (Kimball, 1983). A number of researchers attempted similar studies either in the open field or simulation of open field conditions but noted the difficulty and impracticality of open air fumigation technique due to the dispersion of CO_2 by turbulent air (Kretchman and Howlett, 1970; Allen et al., 1971; Allen et al., 1974; Allen, 1979). Wittwer (1979) stated that devising methods for elevating CO_2 levels to the optimum for photosynthesis under field conditions is a great challenge. He suggested mixing CO_2 with water using trickle irrigation system. The system was adapted and modified by Nakayama and Bucks (1980), who buried the irrigation tubing to circumvent the limitation of rapid gas dissipation. Significant yield increases were observed from CO_2-treated plots of wheat and potato but not for cantaloupe plots, the latter were infected with powdery mildew.

Carbon dioxide-water mixture supplied via drip irrigation may have potential benefit in the open field. Wind velocity above 1 or 2 m/sec may still negate above ground CO_2 enrichment (Allen et al 1971). However, gradual degassing of the carbonated irrigation water may help alleviate the problem (Cahn, 1989). Since it is known that plant roots are capable of absorbing and fixing CO_2 (Stolwijk and Thimann, 1957; Skok et al., 1962;

Bergquist, 1964; Wium-Andersen, 1971; Coker III and Schubert, 1981; Arteca and Poovaiah, 1982; McClure et al., 1983; Baron and Gorski, 1986), this system would also stimulate CO_2 absorption by roots as suggested by Nakayama and Bucks, 1980.

Irrigation with carbonated water generally lowers the soil pH, which may make P and the metallic elements such as Zn, Mn, and Fe more easily available to the plant especially in alkaline soil. Mauney and Hendrix (1988) showed in a greenhouse pot culture experiment an increased uptake of Zn and Mn in cotton plants irrigated with carbonated water. These two elements were deficient in control plants. The increased Zn and Mn uptake supported a more robust photosynthetic apparatus in treated plants resulting in a significant yield increase.

The only foreseen disadvantage of CO_2 enrichment using carbonated irrigation water is the fact that enrichment can be done only according to the water requirement of the crop. Frequent rains during the growing season would mean less CO_2 enrichment for the crop since less irrigation water is required.

In the case of CO_2 enrichment using carbonated water via surface-drip irrigation system, the use of plastic mulch on top of the drip tubing would further retard the rapid dissipation of CO_2 gas. The mulch provides a physical barrier to the upward flux of CO_2 and funnels the CO_2 out to the holes where the plants are located. This phenomenon was described by Sheldrake (1963) as the "chimney effect", which increases CO_2 levels immediately around the leaves and thus photosynthesis may be enhanced, especially on windless days.

Pallas (1979) reported that CO_2 enrichment may not only influence dry weight, photosynthetic rate, and transpiration but also chemical composition such as protein and chlorophyll content as well as enzyme activity. Carbon dioxide enrichment therefore may not only enhance production but also fruit quality. In tomato, fruit quality is measured in terms of appearance, size, color, texture, and flavor; the latter is a function of fruit pH and sugar content (Yamaguchi et al., 1964).

Tomato is one of the crops of high commercial value that was found to respond positively with CO_2 enrichment of the greenhouse atmosphere. In commercial tomato production, plastic mulches have become an integral part of cultivation. One of the more promising techniques of CO_2 enrichment in the open field is mixing CO_2 with the irrigation water via a drip system. Thus, this study was conducted for two growing seasons (summer, 1988 and 1989) to determine the response of field-grown tomato plants to mulching, irrigation with carbonated water, and different irrigation frequencies.

MATERIALS AND METHODS

Research began in the summer of 1988 and was repeated during the summer of 1989. All seedlings were started in the greenhouse and were transferred outside for hardening, approximately three weeks before transplanting. Field experiments were conducted at the Horticulture Farm, Colorado State University.

Growing Transplants

All seedlings were grown in a temperature-controlled greenhouse. Before seeding, the benches were steam sterilized to minimize the danger of soil pathogens. Steam was applied for 12 hours to the surface of benches which were covered and sealed with a canvass.

A fresh market "bush" type tomato (Lycopersicon esculentum Mill.) 'Patio Prize' seeds were sown on 4 April 1988 in plastic nursery flats (52.0 x 25.5 x 6.0 cm) with nutrient-containing synthetic soil mix 'Metro Mix' from the American Clay Co. The flats were watered with tap water until most of the seeds germinated and reached the first true leaf stage. About three weeks after seeding, seedlings were transferred to plastic six-pack cells (6.0 x 5.5 x 5.5 cm) containing the same medium. A single seedling was placed in each cell. From that time on, the seedlings were watered daily with Peter's Mix nutrient solution containing N, P, and K at a ratio of 10:20:10. Watering was done at 0700h followed by misting for 30 seconds every two hours from 1000h to 1800h.

Three weeks before transplanting to the field, the seedlings were transferred outdoors to a partially shaded concrete pad for hardening. Daily watering with nutrient solution was continued. Yellowing of the plants was observed in spite of watering with nutrient solution and the nutrient containing growing medium. Seedlings were sprayed to point of run-off with a solution of Acme Green Fe++ liquid iron chelate at a rate of 5g/L Fe. Yellowing disappeared within a week. A second seeding took place a week later after the first seeding using the same materials and cultural practices. This was done to assure sufficient numbers of seedlings at the optimum stage for transplanting.

For 1989, seeding was done on 11 and 17 April, a week later than the previous year. Seedlings were produced in the same greenhouse using the same materials and methods as in 1988.

Field Experiments

During the summer (June - September), 1988, a field experiment was conducted at the Horticulture Field Research Center, Fort Collins, Colorado. The study consisted of two separate experiments, one mulched and he other unmulched. Control(C) and carbonated water(CW) irrigation treatments were replicated eight times in a randomized complete block (RCB) design for both experiments. Field plot design of the 1988 experiments is presented in Figure 1.

Land preparation included incorporation of N and P fertilizers at 85 and 130 kg/ha, respectively, and field cultivation to obtain 75-cm width beds. A single layer of 1-mil (0.025 mm) thick black polyethylene mulch with 9.5-cm diameter holes spaced 40 cm apart was placed over each bed of the mulched plots prior to transplanting. The greenhouse-grown tomato seedlings were transplanted to the field on 2 June. Transplants were spaced 40 cm apart on the beds of both mulched and unmulched plots. Each plot to which a single treatment was applied consisted of a 3 x 3 m area planted to tomato. Surrounding each plot was a 9 x 9 m area of soybeans (Glycine max Merr.) seeded on 75-cm rows. Soybean served as a buffer between treatments. An aerial view of the research area is presented in Figure 2.

Water was applied twice weekly by drip irrigation throughout the growing season at a rate consistent with weekly evapotranspiration. All plots were uniformly irrigated with uncarbonated water at first.

Carbonated water treatments began on 16 July, six weeks after transplanting. Irrigation with CW was accomplished using an Aquatector carbonator (Figure 3). Irrigation with uncarbonated water served as control. Water and soil pH and above and below-ground CO_2 concentrations were monitored during irrigation events. In addition, below-ground CO_2 concentration was also measured on selected days before irrigation to determine residual CO_2 enrichment effects. The third fully expanded leaf was sampled for nutrient analysis on 18 August and 30 September. Harvesting of fruits from the two middle rows of each plot (16 plants) was done twice weekly starting 29 July. First frost occurred on 20 September and the last harvest was on 26 September.

Field research in 1989 incorporated a few modifications based on the results from the previous year. The experimental design was a RCB with four replications. Treatments consisted of a factorial combination of C and CW application at intervals of 2, 4 , or 6 days throughout the growing season. All plots were mulched as described for the mulched treatments used in 1988. The field plot design in 1989 showing the six treatment combinations is presented in Figure 4. Plot size and soybean buffer area were the same as in 1988.

The amounts of N and P fertilizers applied and the cultural practices employed were the same as in 1988. Tomato seedlings were transplanted through the holes in the plastic mulch on 7 and 8 June. All plots were irrigated with either C or CW on 9 June depending on the treatment. Thereafter, plots were irrigated at 2, 4, or 6 day intervals and at a rate calculated to fully replace evapotranspiration associated with each of the three frequencies. Similar to the previous year, water and soil pH, and above-ground CO_2 concentrations were monitored during irrigation events. Furthermore, above-ground CO_2 concentrations were measured before irrigation and at one hour and one day after irrigation. Below-ground CO_2 concentrations were measured for each frequency immediately before irrigation and on the succeeding days until the next irrigation. Leaf samples for nutrient analysis were taken on 28 July and

28 August. Fruit harvest began on 11 August and continued at approximately weekly intervals until 3 October. Fruits were picked from plants in the two middle rows (12 plants) of each plot excluding the end plants. It snowed on 11 September so harvest plants were covered with burlap sacks for two consecutive nights to prevent the possibility of frost damage. Minimum temperature on 12 September was 0.3°C

After the final harvest on 3 October, plants were cut at the soil surface and oven dried to determine the total plant dry matter production. On 15 September, twenty fruits were randomly picked out of the harvest from each of the C and CW treated plots after counting and weighing. The fruits were weighed, dried, and weighed again to determine the percent dry matter for the C and CW treatments. Percent fruit dry matter for each treatment was multiplied by the total fruit fresh weight and then added to the total plant dry matter to estimate total season dry matter production.

On three selected harvest dates (24 August and 7 and 15 September), four fruits of similar ripeness from each plot were set aside after weighing and counting. Those fruits were later used for fruit quality evaluation.

Irrigation System

The irrigation system consisted of the water source, CO_2 tank, CO_2 injector, pressure gauges and regulators, flow meters, two main manifolds of 5.1 cm inside diameter (I.D.) PVC pipes, valves, fixed pressure regulators (0.14 MPa), couplers, reducers, flexible plastic tubing (25.4 and 12.7 mm I.D.), and drip tubing. The drip tubing was laid on top along the length of each bed in each plot. The number of emitters per bed were all the same to insure uniform amount of water applied. Proper carbonation was maintained with 0.21 MPa water pressure coming from the source and with 0.24 MPa CO_2 gas pressure. Fixed pressure regulators (0.14 MPa) were installed in the system to facilitate water delivery of 1.9 L/h.

A total of 12.7 mm of water was applied to each plot during the first irrigation to the bring the soil moisture content to approximately field capacity. The volumes of water applied for the succeeding irrigations were determined by neutron probe readings within access tubes installed at the middle of selected plots. Installation of access tubes was facilitated by drilling a hole 75 cm deep into the soil using a motor driven auger.

Neutron probe readings were taken weekly, normally one day before irrigation. Readings were taken at 25, 50, and 75 cm. The measures of soil water depletion from neutron probe readings were compared to evapotranspiration (ET) data from the nearby weather station and the amount of water previously applied. Based on both water depletion and ET data, the water volume for the succeeding irrigation was determined. Water was applied at a rate calculated to fully replace ET. The length of irrigation time to deliver such volume of water was calculated based on the number of emitters per plot and the water delivery rate of each emitter.

Although similar materials were used, a different irrigation system configuration was installed in 1989. An electric pump was installed as part of the irrigation system to provide water pressure. In addition, water bypass and pressure regulator were connected to the system to deliver the right water pressure for carbonation. A valve was also installed at the end of the CW main manifold to regulate water flow rate for better carbonation. Water from a reservoir was used as the source.

Water And Soil pH Measurement

During irrigations in 1988, water samples for both C and CW treatments were collected in plastic beakers from plots farthest from the CO_2 injector to determine if there was carbonation. Samples were brought to the field laboratory and pH was measured with an Orion Research analog model 301 pH meter. Three to five pH measurements were taken during each irrigation event to be sure that carbonation in the CW treatment was maintained. Maintenance of lower pH in the CW treatment meant an efficient injection of CO_2 into the irrigation water.

Towards the end of each irrigation, soil samples to 10-cm depth were collected for pH measurement. Pastes were made out of the soil samples and pH was measured. Soil pH was also monitored on the succeeding days after irrigation.

In 1989, the same procedure for water and soil pH measurement was followed. However, a more sensitive battery-operated digital Gallenkamp-PHK-120B portable pH meter was used.

Air Sampling And CO_2 Measurement

During the times of irrigation on selected days in 1988, air samples above- and below-ground were collected for CO_2 measurement. Samples were collected during periods when turbulence was not excessive. Below-ground air samples from 10-cm depth were also collected on days after irrigation. Aboveground air samples were collected in 10-ml Luer-Lok syringes with 17-gauge, 4-cm long hypodermic needles. Samples of 10-ml volume replicated four times were collected one at a time from 1- and 15-cm height above the ground. In the case of the mulched experiment, air samples were taken at the same heights but above the hole in the mulch. After each sample was taken, needles were sealed with neoprene stoppers. Samples were brought to the field laboratory and 2 ml of each sample was immediately injected into a previously calibrated Beckman model 865-25 infrared gas analyzer (IRGA) for CO_2 measurement (Clegg et al., 1978).

Below-ground air samples were taken immediately after irrigation and on the day before irrigation. Below-ground air sample collection from 10-cm depth was facilitated using a method described by Hanan (1964). Glass tubes of 10-cm I.D. were cut into 5-cm length and then sealed at one end with one-holed rubber stopper. One end of a 25-cm nylon tube of 1-mm I.D. was inserted into the hole of the stopper and the other end heat sealed with a flame. The tubes were buried horizontally in the soil 10 cm from the surface with about 15 cm of the nylon tube extending above the ground. A schematic diagram of the soil-air sampling tube buried in the ground is presented in Figure 5. On sampling days, soil air samples were drawn from the heat-sealed ends of the nylon tubes with syringes and needles (1 mm O.D.) similar to those used for above-ground air samplings. After drawing samples, needles were sealed with neoprene stoppers. The nylon tubes were cut at the point where the needles were inserted and heat-sealed as described before. Figure 6 shows three photographs illustrating how soil air samples were taken. Samples were analyzed in a previously calibrated IRGA (see Appendix).

In 1989, the above-ground air sampling technique was modified. Galvanized iron wires were attached to the syringe plungers and a hook was tied to each end of a 2-m long string. An aluminum rod was driven into the soil such that the clamps attached to it were at 1- and 15-cm above the ground. The clamps held the syringes in place and samples for both 1- and 15-cm height were drawn simultaneously by pulling the string. The technique avoided CO_2 contamination of the samples by workers as Well as undue turbulence within the plot during sampling. A photo showing how above-ground air samples were taken in 1989 is shown in Figure 7.

The below-ground air sampling procedure in 1989 was similar to that used in 1988. However, samplings were done on days after irrigation and immediately before irrigation on an irrigation day. The IRGA was calibrated each day prior to injection of samples. Additional calibration was done if sampling time lasted for more than four hours. The calibration curves generated were used for both above- and below-ground air samples.

Leaf Sample Preparation For Nutrient Analysis

The third fully expanded leaf was removed from each of the 16 plants from the two middle rows of each plot on dates mentioned earlier. Samples were washed twice in distilled water and dried in an oven at 70°C for two days. A stainless steel mill was used to grind the dried leaf samples. Ground leaf samples were analyzed for P, K, Ca, Mg, Na, Zn, Fe, Mn, Cu and B by nitric acid digest method as described by Havlin and Soltanpour (1980). In 1989, N was added to the list of nutrients determined.

Fruit Harvesting

Harvesting from plants in the two middle rows was started as soon as the fruits began to ripen. Harvest for 1988 began on 29 July and continued twice weekly until 26 September. For 1989, harvesting was done on a weekly interval from 11 August to 3 October. On each harvest date, fruits were separated into marketable and nonmarketable fractions based on fruit size, appearance, and ripeness (for last harvest). Fruits in each fraction were counted and weighed, and cumulative fruit weight and number were noted for each plot. After counting and weighing, four fruits of similar ripeness from each plot were set aside on 24 August (third harvest) and on 7 and 15 September 1989 (fifth and sixth harvests) for pH and sugar content measurement.

Fruit Quality Evaluation

Fruits were cleaned and blended for one minute in a Waring blender for pH and sugar content measurement. Fruit pH was measured by dipping the Gallenkamp portable pH meter electrode into the blended fruit. Values were noted as soon as the readings stabilized. After pH measurement, the blended fruit was filtered through Whatman #42 ashless filter paper and a drop of the filtrate was used for soluble solid measurement using a Bausch and Lomb hand refractometer as described by MacGillivray and Clemente (1956). These authors reported percent sugar based on soluble solid contents of tomatoes measured with a hand refractometer. A refractometer is an instrument for measuring the refractive index of a substance by comparing the speed of light passing through that substance to the speed at which it passes through the air. A direct relationship between the total soluble solids and the refractive index of a solution has been established (Gould, 1974). The same author reported percent sucrose based on the resultant index in accordance with the 'International Scale of Refractive Indices of Sucrose'.

Statistical Analyses

For both years, 1988 and 1989, t-tests were done on all water and soil pH , and on all above- and below-ground CO_2 data. Fruit pH and sugar content were analyzed using the t-test also. T-tests were used because there were only two treatments compared in all instances. Nutrient uptake for 1988 was analyzed by ANOVA separately as a RCB for the mulched and the unmulched experiments. Harvest data were also analyzed as a RCB.

For 1989, fruit yield and dry matter production data were analyzed by ANOVA as a RCB. Analysis by ANOVA was also used for the nutrient uptake data using a split-plot design. Split-plot design was used in this case because the two sampling dates were not random and therefore considered as a sub-plot. T-tests were done on the combined data on three sampling dates for fruit pH and sugar content.

Student-Newman-Keul's (SNK) test at $P = 0.05$ was employed for all mean comparisons except when there was interaction between factors where Duncan's Multiple Range Test was used.

RESULTS AND DISCUSSION

Field Experiment, 1988

The baseline climatic data at the Horticulture Field Research Center for the duration of the experiment are shown in Figure 8. Evapotranspiration (ET) was calculated using the Penman (1963) equation. During periods when there were significant amounts of rainfall, irrigation treatments were withheld. For the whole growing season, water volume applied in 16 irrigations totaled 176 mm for the treatment period.

Injection of CO_2 into the irrigation water decreased the water pH from 6.4 to 4.5. As a consequence, soil pH at approximately 10-cm depth dropped by about a unit (from 7.7 to 6.8) during irrigation events. However, soil pH levels were the same for the C and CW treatments in both the mulched and unmulched experiments the day after irrigation. The temporary lowering of soil pH by the CW treatment in this study was to the upper limit of the optimum range reported for tomato (White and Collins, 1980). Furthermore, the availability of P, Ca and metal elements such as Fe, Mn and Zn in high pH soils may be expected to increase as a consequence of the lower soil pH. Among the elements mentioned, Zn seemed to have been made more available to the plants as shown by the significantly higher Zn uptake of plants receiving CW under mulched condition (Table 1). These results were similar to those reported by Mauney and Hendrix (1988) who observed increased uptake of Zn and Mn in greenhouse-grown cotton (Gossypium hirsutum L.) irrigated with CO_2-saturated water. Uptake of the other elements mentioned previously was not affected by the CW treatment in either the mulched or unmulched experiment.

Average above-ground CO_2 concentrations at 1- and 15-cm heights during irrigation are shown in Table 2. In the unmulched experiment, CO_2 concentrations at 15-cm height for the C and CW treatments were the same. At 1-cm height, CO_2 concentrations were significantly higher in the CW compared to the C treatment. In the case of the mulched experiment, CO_2 concentrations in the CW treatment were significantly higher than those of the C treatment for both sampling heights. The higher concentration of CO_2 at 1-cm height in the CW treatment was expected since samples were taken very close to the drip emitters.

Table 3 shows the below-ground (10 cm) mean CO_2 concentration, immediately after and on the day before irrigation. In the unmulched experiment, below-ground CO_2 concentrations for the C and CW treatments did not differ for either of the sampling times. On the contrary, CO_2 concentrations in the mulched experiment for the CW treatment were significantly higher than the C treatment for both sampling times. Acidification of the soil may also have served as a source of CO_2 because it contained 7.0% $CaCO_3$. Since the irrigation interval was three or four days, observations on the day before irrigation were a measure of residual CO_2 in the soil atmosphere. These results suggest the importance of mulch in providing a physical barrier to the upward flux of CO_2. Carbon dioxide released from the soil atmosphere would be funneled out of the mulch through the holes where the plants were in a position to use it for photosynthesis.

The total seasonal marketable fruit yields are presented in Figure 9. A significant difference was found between fruit yields of the C and CW treatments in the mulched experiment only. However, there were no differences in marketable fruit yields between C and CW treatments for the unmulched experiment. Figure 10 presents the total seasonal marketable fruit numbers. For both the mulched and unmulched experiment, fruit numbers for the C and CW treatments were not different. The average fruit weight of marketable fruits are presented in Figure 11. Under unmulched condition, average fruit weight for the C and CW treatments were the same.

On the contrary, average fruit weight for the CW treatment with mulch was significantly higher than that of the C treatment indicating that the yield increase associated with CW treatment was due primarily to fruit size rather than fruit number. These results were similar to those observed by Wittwer and Robb (1963) and Kretchman and Howlett (1979) who found that one of the responses of tomato to CO_2 enrichment in the greenhouse was increased fruit size.

Total (marketable and non-marketable) seasonal fruit yields for the mulched and unmulched experiments are presented in Figure 12. Total fruit yields of the C and CW treatments were not different under unmulched condition. On the other hand, total fruit yield for the CW treatment was significantly higher than that of the C treatment under the mulched experiment. These results were very similar to the marketable yield, indicating that the total fruit yield is dominated primarily by the marketable yield fraction.

Field Experiment, 1989

The baseline climatic data at the experimental site for 1989 are shown in Figure 13. In general, the climatic conditions during the growing season were favorable for tomato production, except during early July when maximum temperatures were 32°C or higher. Temperatures as high as these can cause tomato flowers to abort which may ultimately lead to lower fruit set percentage (Magoon, 1969). The total volume of water applied during the treatment period was 358 mm, which was more than twice that applied in 1988. More water was applied because irrigation with CW began much earlier during the 1989 than 1988 season.

Similar to 1988, injection of CO_2 into the irrigation water lowered the water pH from 7.3 to 4.6 ($P<0.01$). This resulted in a lowering of soil pH in CW treated plots. Table 4 shows mean soil pH for the three irrigation frequencies on days after irrigation. For all the three irrigation frequencies, soil pH stayed lower in CW treated plots throughout the time intervals between successive irrigation events. These results were inconsistent with those of the previous year wherein the soil pH in CW treated plots was the same as that of the C treatment one day after irrigation. This inconsistency may have been due to the different pH meters used.

The decrease in soil pH was expected to increase the availability of P, Ca, and metallic elements such as Fe, Mn and Zn in alkaline soils (Mengel and Kirkby, 1978). However, the tomato leaf content of these nutrients were the same for both the C and CW treatments indicating that the availability of these nutrients may not have been increased by the lower soil pH. The decrease in soil pH would probably be more effective in increasing the availability of such nutrients if they were deficient in the experimental soil. Mauney and Hendrix (1988) reported increased uptake of Mn and Zn by greenhouse-grown cotton irrigated with carbonated water. Mn and Zn were deficient in the experimental soil. Table 5 presents some selected mean nutrient content of the tomato leaves for the C and CW treatments considering the three irrigation frequencies. Other nutrients which were analyzed were also similar in concentration between C and CW treatments. No significant differences between treatments were found; $P = 0.05$.

The above-ground CO_2 concentrations found at different times for the 2-day irrigation frequency are shown in Figure 14 (15-cm height) and Figure 15 (1-cm height). At the 15-cm sampling height, CO_2 concentration for the CW treatment was higher than that of the C treatment during (P 0.01) and at 1 hour after irrigation ($P = 0.05$). One day after irrigation and immediately before the succeeding irrigation, CO_2 concentrations for the C and CW treatments were not different. At 1-cm height, CO_2 concentrations for the CW treatment was significantly higher than that of the C treatment during irrigation, at 1 hour after and 1 day after irrigation. Carbon dioxide concentrations immediately before irrigation were similar for the C and CW treatments.

Figures 16 and 17 present the above-ground CO_2 concentrations taken at 15- and 1-cm height, respectively, for the 4-day irrigation frequency.

Similar to the 2-day irrigation frequency, CO_2 concentration at 15-cm height for the CW treatment was significantly higher than that of the C treatment during the time of irrigation. One hour after irrigation, CO_2 concentrations were the same for the C and CW treatments and this condition held until the day of the succeeding irrigation. At the 1-cm height, CO_2 concentrations for the CW treatment was significantly higher than that of the C treatment during irrigation and at 1 hour after irrigation. Carbon dioxide concentrations for the C and CW treatments were not significantly different at 1 day after irrigation and immediately before the succeeding irrigation.

The above-ground CO_2 concentrations sampled at different times for the 6-day irrigation frequency are presented in Figure 18 (15-cm height) and Figure 19 (1-cm height). Results showed that at 15-cm height, CO_2 concentration for the CW treatment was significantly higher than that of the C treatment during the time of irrigation and at 1 hour after irrigation. One day after irrigation, CO_2 concentrations for the C and CW treatments were not different. This condition held until the next irrigation event. At the 1-cm height, CO_2 concentration for the CW treatment was significantly higher than that of the C treatment during the time of, and at 1 hour after irrigation. For the rest of the sampling times, CO_2 concentrations for the C and CW treatments were the same.

Although the wind movement during the time of sampling may have affected both the differences and magnitude of CO_2 readings, results of the CO_2 concentration measurements for the three irrigation frequencies were consistent. Carbon dioxide concentration during irrigation for the CW treatment was consistently higher than that of the C treatment at both 1- and 15-cm height. In addition, CO_2 concentration for the CW treatment at 1-cm height was also consistently higher than that of the C treatment, 1 hour after irrigation.

Figure 20 shows the soil CO_2 concentration from plots with 2-day irrigation frequency. Air samples were collected immediately before irrigation on an irrigation day and on days after irrigation. Considering both sampling times, CO_2 concentration for the CW treatment was consistently higher than that of the C treatment. For the 4-day (Figure 21) and 6-day (Figure 22) irrigation frequencies, soil CO_2 concentrations for the CW treatment on days after irrigation and even immediately before the succeeding irrigation were consistently higher than those of the C treatment. As in the previous year, these results indicate the presence of residual CO_2 in the soil atmosphere derived from the CW irrigation.

Comparisons of total seasonal marketable fruit yields between the C and CW treatments over the three irrigation frequencies are shown in Figure 23. Total marketable fruit yields for the CW treatments were significantly higher than those of the C treatment over all the three irrigation frequencies. Marketable fruit yield for the three irrigation frequencies averaged over the carbonation treatments were also significantly different. Although all irrigation frequencies received the same amount of water, less frequent irrigation resulted in less fruit yield. This could probably be due to the more even distribution of water with frequent irrigation and the apparent tendency for plants to be exposed to drought stress in less frequently irrigated plots. For example, high ET rate on the succeeding days after irrigation may not cause a drought stress in plots with 2-day irrigation frequency since the amount of water lost is immediately replaced on the second day after the previous irrigation event. On the contrary, the same condition may cause a drought stress to plants irrigated at a 6-day interval simply because the amount of water lost through ET is not replaced immediately. The greatest relative response to CW was observed for the 6-day irrigation frequency probably because of increased water use efficiency and greater resistance to drought stress of the CW irrigated plants (Wittwer, 1983; Wittwer, 1986).

Figure 24 presents the total seasonal marketable fruit numbers for the C and CW treatments across the three irrigation frequencies. Although carbonation effect was significant as revealed by the statistical analysis, the interaction between carbonation and irrigation frequency treatments was also significant. An explanation for the interaction can be seen by examining the response to carbonation across irrigation frequencies (Figure 24). For the less frequent irrigation interval, i.e. 6-day interval, the yield component that was responsible for increased yield CW treatment was fruit number. On the contrary, fruit size that accounted for the increase in yield for the CW treatment with less frequent irrigation intervals i.e. 2- and 4-day frequency (Figure 25).

To determine what yield component was really dictating fruit yield for the CW treatment, average fruit weight was calculated for each irrigation frequency. Figure 25 shows the average marketable fruit weight for the C and CW treatments in all the three irrigation frequencies. The average of the CW treatment mean fruit weight over all three frequencies was higher than that of the C treatment. The analysis shows fruit size as the dominant factor associated with yield increase in CW treated plots but it was also very clear that there was hardly a difference in this variable between the C and CW treatments for the 6-day irrigation frequency (Figure 25). Therefore, fruit size was really the dominant yield component associated with yield increase in CW treated plots with 2- and 4-day irrigation frequencies. On the other hand, it is the number of fruits that dictate the increase in yield associated with CW treatment for the 6-day irrigation frequency as was shown by the large difference in fruit numbers between the C and CW treatment in Figure 24.

The total seasonal fruit yields (marketable and nonmarketable) for the C and CW treatments in all the three irrigation frequencies are shown in Figure 26. Yield differences between C and CW treatments for all the three irrigation frequencies were significant, similar to the marketable fruit yield. This indicates that the main component of total yield was the marketable fruit fraction. Total seasonal fruit numbers (marketable and non-marketable) for the C and CW treatments in all the three irrigation frequencies are presented in Figure 27. The total marketable fruit number was the dominant yield fraction in this case. These results were consistent with those of 1988 indicating that the non-marketable fruit fraction may be totally ignored.

Literature regarding fruit yield increases in CO_2-enriched greenhouse-grown tomato plants reported varied results with respect to the yield component contributing most to fruit yield. For example, Morgan (1971), Calvert and Slack (1975), and Nilsen, et.al. (1983) observed plants. Wittwer and Robb (1964), and Kretchman and Howlett (1970) on the other hand, observed an increase in weight per fruit, while Kimball and Mitchell (1979) found no change in the size of tomatoes cultivated in higher than ambient CO_2. Whichever was the case, total yield increases in CO_2 enriched plants was attributed to increase in net photosynthesis.

Figure 28 presents the total seasonal plant dry matter for the C and CW treatments in all the three irrigation frequencies. Similar to the marketable fruit yield, total plant dry matter was also influenced by the CW treatment and irrigation frequency. Mean total plant dry matter in CW treatment was significantly higher than that of the C treatment. Mean total plant dry matter for the 2-day irrigation frequency was significantly higher than those of the 4- and 6-day irrigation frequencies.

The total seasonal dry matter (plants and fruits) for the C and CW treatments in all three irrigation frequencies are presented in Figure 29. Similar to marketable fruit yield and total plant dry matter, total seasonal dry matter was also influenced by the CW treatment and irrigation frequency. Total seasonal dry matter increased with CW treatment and with more frequent irrigation. These findings were a clear indication of an increase in production and that the best treatment combination for dry matter production was CW applied at a 2-day frequency. An increase in total dry matter production was also observed by Nilsen et al. (1983) in their study on CO_2-enriched greenhouse grown tomatoes.

Fruit quality in terms of pH and percent sugar content was monitored. Fruit pH for CW treatment averaged over the three irrigation frequencies was not significantly different from the C treatment.

However, sugar content of tomato fruit (n = 36 vs. n = 36) i.e. refractometer reading converted to percent sucrose, averaged 3.99 and 4.38 for C and CW respectively. The two means were significantly different at the 5 % level of probability.

SUMMARY AND CONCLUSIONS

Field Experiment, 1988

The injection of CO_2 into the irrigation water lowered the water pH from 6.4 to 4.5. As a consequence, soil pH dropped by about a unit(from 7.7 to 6.8) during irrigation. However, soil pH levels were the same for the C and CW treatments the day after irrigation. The temporary decrease in soil pH might have increased Zn availability as was shown by the higher plant Zn concentration for the CW treatment in the mulched experiment.

Above-ground CO_2 concentrations at 1- and 15-cm heights for the CW treatment were significantly higher than the C treatment in the mulched experiment during irrigation. In the unmulched experiment, above-ground CO_2 concentrations for the CW treatment were significantly higher than the C treatment at 1-cm height only.

Below-ground CO_2 concentrations for the CW treatment on the day of, and the day before irrigation were significantly higher than the C treatment under mulched condition. No significant differences were observed between C and CW treatments under unmulched conditions when below-ground CO_2 concentrations were compared.

Fruit yield for the CW treatment in the mulched experiment was significantly higher than the C treatment. However, number of fruits were the same. Mulching alone increased both fruit yield and number but no statistical comparisons were made for the mulched vs. unmulched plots because they were in separate experiments. The yield increase in CW treatment was due primarily to fruit size and not to fruit number.

The increase in Zn uptake, which was probably due to the temporary reduction in soil pH, may have promoted a more robust photosynthetic apparatus in the mulched-CW treated plants. However, this increased Zn uptake may not have helped increase total fruit yield in CW treated plots since C and CW treated plants both exhibited leaf Zn contents in the sufficiency range (>21ppm) according to Boehle and Lindsay (1969) for tomato. Interestingly, Bhella (1988) reported higher petiole Zn concentrations in watermelon plants mulched with the same type of black polyethylene as used in the present study.

The higher above-ground CO_2 concentrations during irrigation for both 1- and 15-cm height for the CW treatment in the mulched experiment could have triggered an increase in photosynthetic rate on windless sunny days. The consistently higher below-ground CO_2 concentrations for the CW treatment in the mulched experiment both during and before the day of irrigation suggest that CO_2 may have been made more available to the plants either via the root system (Bergquist, 1964; Nakayama and Bucks, 1980) or by gradual release of CO_2 gas (Cahn, 1989), which was funneled out to the plants for use in photosynthesis. Each of the above-mentioned conditions likely contributed to the significant increase in fruit yield in CW treated plants in the mulched experiment. Tomato yield response to CO_2 enrichment in the open field could probably be maximized if CW treatment can be applied earlier to physiologically younger transplants.

Field Experiment, 1989

Injecting CO_2 into the irrigation water lowered the water pH from 7.3 to 4.6 resulting in a decrease in soil pH. Soil pH for the CW treated plots remained comparatively lower than those of the C treatment even on the day of the succeeding irrigation. However, no significant increase in uptake of the metallic elements, P, or Ca was observed. The same was true for other nutrients (not shown) that were analyzed. Therefore, any form of yield increase was probably not due to the greater availability of any soil nutrient due to the lower soil pH.

At canopy level (15-cm height), CO_2 enrichment was observed only while the irrigation system was on, while at 1-cm height, elevated levels of CO_2 were observed even at 1 hour after irrigation. Since the study was conducted in the open field where wind was unpredictable, monitoring of the above-ground CO_2 on a discontinuous basis may not be the best measure of enrichment.

Below-ground CO_2 was consistently higher for the CW treatment than that of the C treatment for all three irrigation frequencies even on the day of the following irrigation, or up to 6 days after irrigation. Since below-ground CO_2 was not affected by wind movement, observations done on succeeding days after an irrigation event were a good measure of residual CO_2.

The above-ground CO_2 enrichment during irrigation, and the consistently higher soil CO_2 level for the CW treated plots may have both contributed to the 17% average increase in marketable yield for all the three irrigation frequencies. This increase, which was more than double the yield increase in 1988 may be attributed to the earlier application of carbonated water during the growing season. For more frequent irrigation, i.e. 2- and 4-day intervals, fruit size was the yield component that was associated with the yield increase in CW treated plants as shown by their higher average fruit weight. On the other hand, the number of fruit produced was responsible for the yield increase in CW treated plants for the less frequent irrigation interval e.g. the 6-day interval. This is probably due to the fact that plants irrigated on a 6-day interval may have been exposed to drought stress and that CO_2 enrichment may have increased the water use efficiency of the plants (Acock and Pasternak, 1986).

In addition to the increased fruit yield, clear evidence of response to carbonated water was the observed increase in total seasonal plant dry matter for the CW treated plants. With the total seasonal fruit and plant dry matter combined (total seasonal dry matter), the observed increase in total seasonal dry matter for the CW treated plots ranged from 13 to 23% and averaged 17% over the three irrigation frequencies. Carbonated water treated plants produced fruits with significantly higher ($p = 0.05\%$) sugar content, 4.0 vs. 4.4%, a quality factor that may be preferred.

General

The reduction in soil pH due to the lower pH of the irrigation water in CW treatment could have increased the availability of Zn in 1988 since more of this element would be in solution when the soil pH is low. However, plants from the C and CW treated plots contained Zn in greater than sufficiency levels; thus, higher Zn content for CW treated plants probably did not contribute to the increase in fruit or dry matter yield. The significant increase in CO_2 concentration at canopy level during irrigation and the yield response associated with the CW treatment suggest enhancement of photosynthesis. The consistently higher soil CO_2 concentration for the CW treatment under the mulch was an indication of residual CO_2. This also strengthens the possibility of CO_2 absorption through the roots. However, a recent study on wheat, reported that only 0.44- 1.21% of the total CO_2 absorbed through the roots are assimilated by the plant during the growing season (Schafer, 1988). The study showed that root absorption of CO_2 may play a relatively small role in increasing the yield of a crop.

The mulch, which tends to prevent the rapid dissipation of CO_2 appears to be a necessary part of the system for the CW treatment to be effective. The greatest yield increase might be obtained if CW is applied early in the season to physiologically younger plants for longer CO_2 enrichment. Younger plants are more responsive to such treatment.

The results reported here seem to indicate that enhancement of photosynthesis may have contributed most to the increase in yield of CW treated plants. In addition to the measurements made here, further studies must be done to prove whether or not it was really the enhancement of photosynthesis that contributed to the yield increase in CW treated plants. Such studies might include physiological measurements involving carbon ratios C_{13}/C_{12} or $^{14}CO_2$ and measuring net assimilation rates.

Monitoring of the starch content of the leaves of the plant may be an indirect way of determining whether irrigating with carbonated water enhances photosynthesis.

Table 1. Concentration of selected nutrients in most recently expanded leaves sampled on two dates in 1988 from control (C) and carbonated water (CW) treatments under mulched and unmulched conditions.

Nutrient	Sampling Date	Mulched		Unmulched	
		CW	C	CW	C
			mg kg^{-1}		
P	18 Aug.	2,600	2,490	2,360	2,410
	30 Sept.	2,360	2,220	1,800	1,780
Zn	18 Aug.	25	24	23	24
	30 Sept.	36	32*	34	34
Fe	18 Aug.	200	210	250	240
	30 Sept.	1,200	1,160	1,910	1,580
Mn	18 Aug.	61	64	65	72
	30 Sept.	103	100	103	99

* indicates significant difference between CW and C treatments at the 5% probability level.

Table 2. Above-ground CO_2 concentration during 16 irrigation events in 1988 for control (C) and carbonated water (CW) treatments under mulched and unmulched conditions.

Sampling height	Mulched		Unmulched	
	CW	C	CW	C
cm		$\mu L\ L^{-1}$		
15	572	435*	471	427
1	2,735	721*	1,091	418*

* indicates significant difference between CW and C treatments at the 5% probability level.

Table 3. Concentration of CO_2 in soil air immediately after irrigation and prior to subsequent irrigation events in 1988 for control (C) and carbonated water (CW) treatments under mulched and unmulched conditions.

		Treatments	
Time of sampling	Conditions	CW	C
		$\mu L\ L^{-1}$	
Day of irrig.[¶]	Mulched	5,970	2,550*
	Unmulched	2,220	2,270
Prior to irrig.[§]	Mulched	4,600	3,900*
	Unmulched	3,050	2,800

* indicates significant difference between CW and C treatments at the 5% probability level.

[¶] sampling conducted immediately after water delivery was terminated.

[§] sampling conducted in the morning of day prior to subsequent irrigation.

Table 4. Soil pH (to 10-cm depth) immediately before and between irrigation events for control (C) and carbonated water (CW) treatments applied at frequencies of every 2, 4, and 6 days throughout the growing season in 1989.

Application frequency days	Time of sampling days after irrigation	Treatment	
		C	CW
		------ pH	------
2	0[¶]	7.4**	6.2
	1	7.5**	6.7
4	0	7.4**	6.0
	1	7.6**	6.7
	2	7.4**	6.8
	3	7.4**	6.9
6	0	7.4**	5.9
	1	7.5**	6.5
	2	7.4**	6.7
	3	7.6*	6.9
	4	7.4*	7.0
	5	7.5*	7.1

[¶] day 0 indicates that sampling occurred immediately after the termination of irrigation on the day of irrigation.

**, * indicates significant difference between the C and CW treatments at the 1 and 5% probability levels, respectively.

Table 5. Concentration of selected nutrients in most recently expanded tomato leaves sampled on 28 July and 28 August (means averaged) in 1989 from three irrigation frequencies; 2, 4, and 6 days; and from control (c) and carbonated water (cw) treatments* under mulched conditions.

Nutrient	Irrigation Frequency					
	F1		F2		F3	
	CW	C	CW	C	CW	C
			kg -1			
Ca	3,400	3,900	4,200	4,100	4,200	4,300
P	2,800	2,900	2,700	2,800	2,700	2,700
Zn	22	23	21	24	24	22
Fe	128	114	126	109	123	114
Mn	80	76	81	77	79	76

* no significant differences existed between cw and c effects on nutrient concentrations at the 5% probability level.

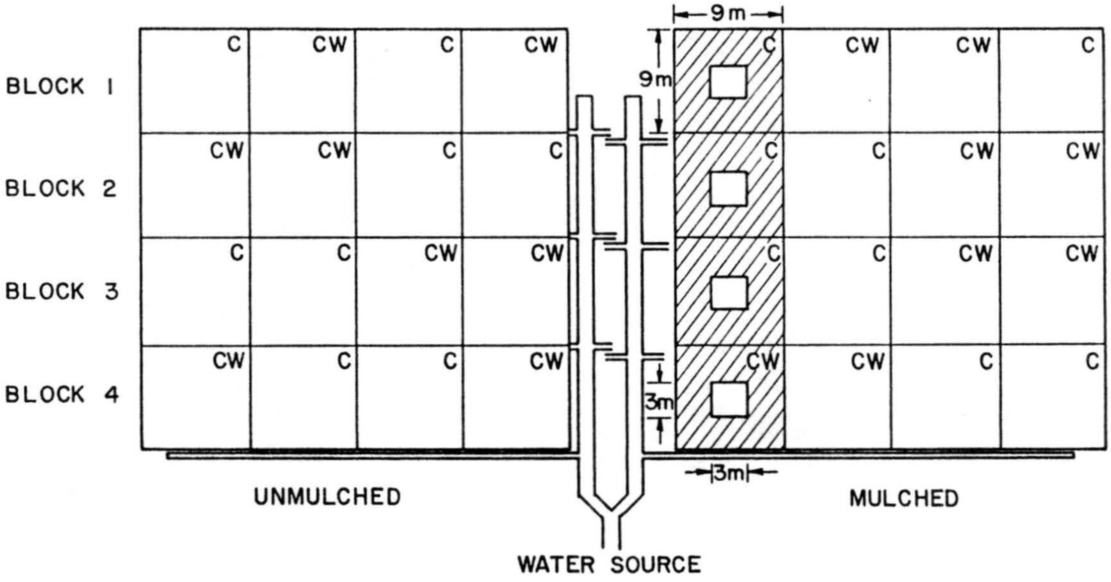


Figure 1. Field plot plan in 1988 indicating plot dimensions and treatments (C, control or plain water; CW, carbonated water). Shaded portions represent areas planted to soybean buffer. The area (9 m^2) inside shaded zones indicate tomato plots.

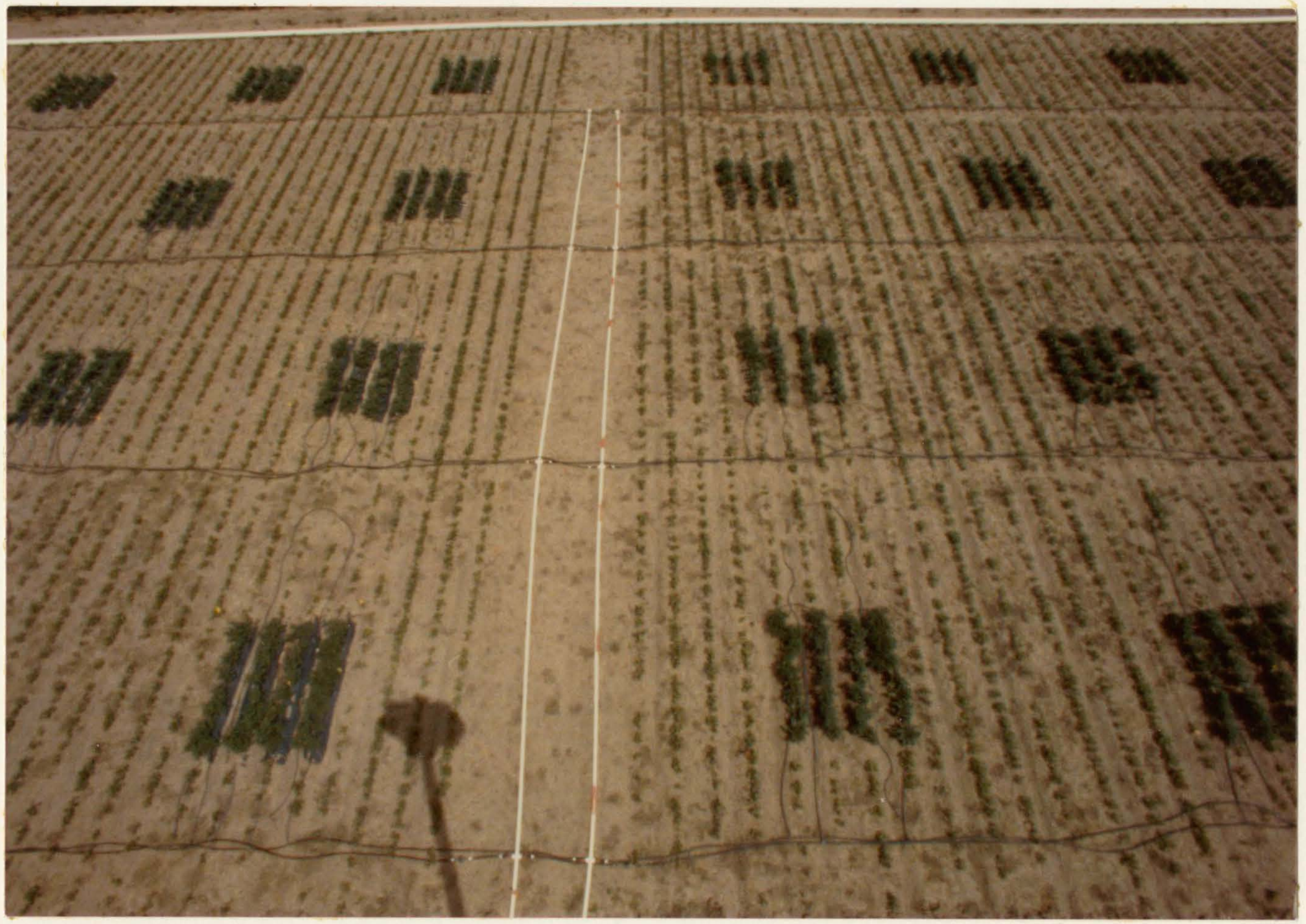


Figure 2. An aerial view of the 1988 field experiments showing the experimental plots surrounded by soybean buffer.

Figure 3. The 'Aquatector' CO_2 injector during one of the irrigation events. Water miniscus must be maintained within the two lines for proper carbonation.

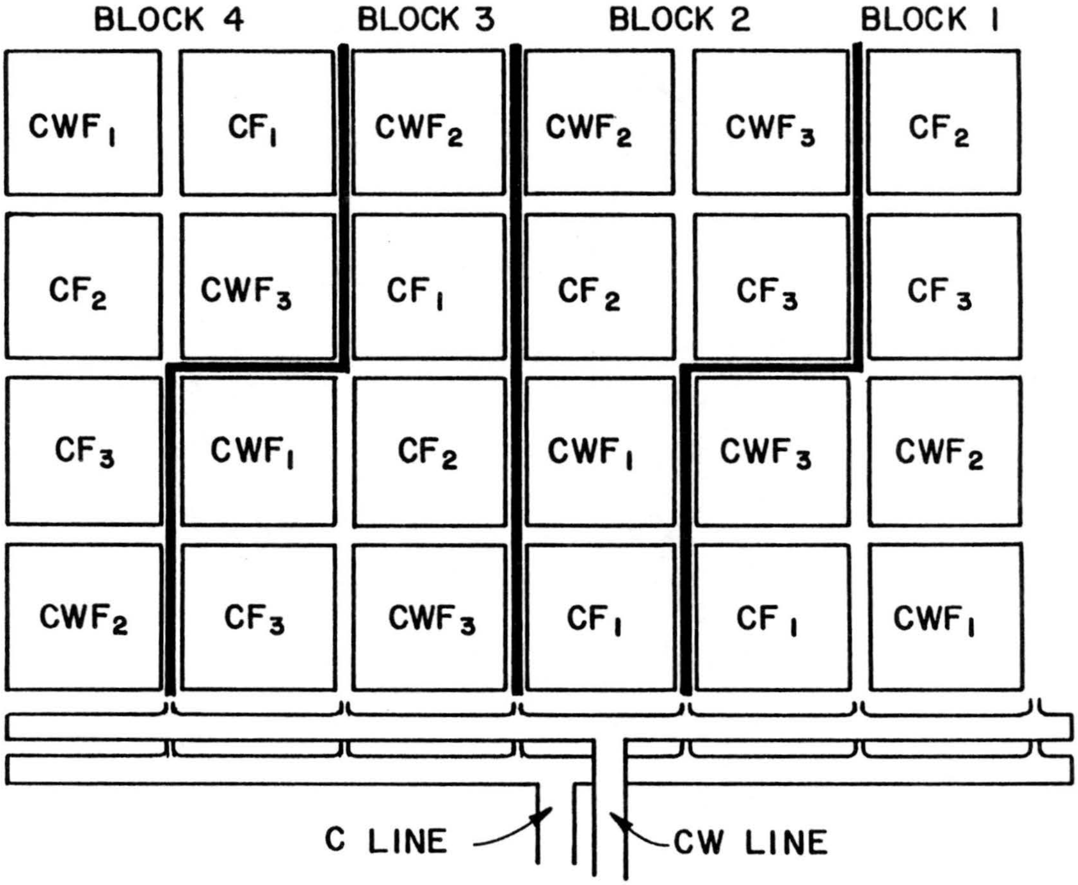


Figure 4. Field plot plan in 1989 indicating the treatment combinations (C, control; CW, carbonated water; F_1, F_2, and F_3 refers to irrigation frequencies of every 2, 4, and 6 days, respectively). Plot dimensions of soybean buffer and tomato were the same as in 1988.

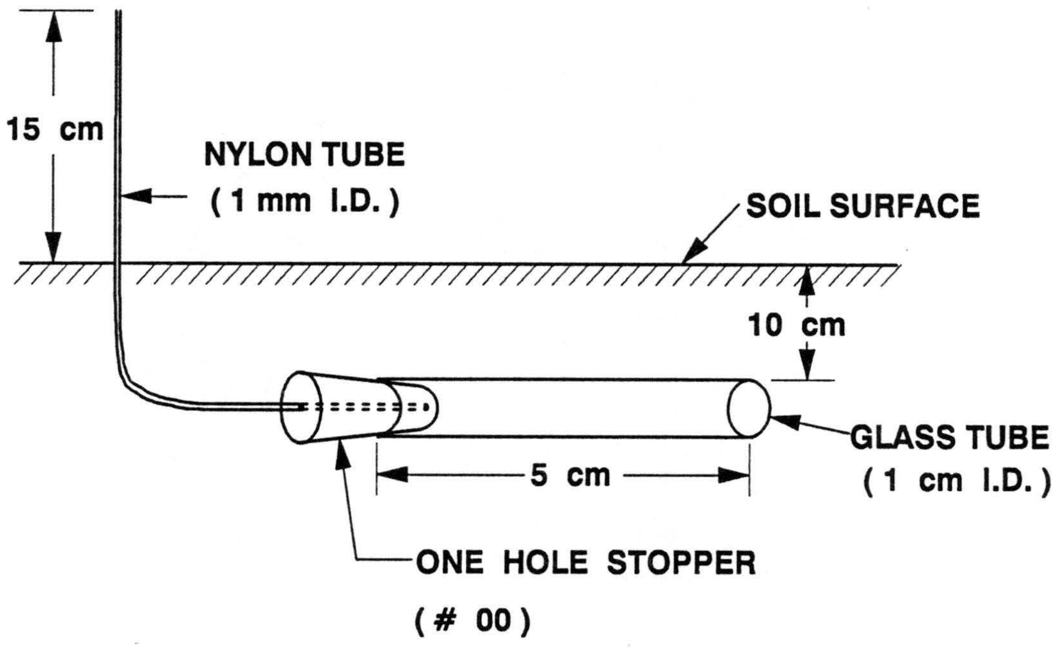


Figure 5. Schematic of soil sampling device used to determine concentration of CO_2 in soil air.

Figure 6. Collecting air samples; syringe is filled from sealed nylon tube (a), end is cut and heated with lighter (b), and sealed with pliers (c).

Figure 7. Above-ground air sampling (1989) using an upright rod with syringes attached. Two samples were drawn simultaneously by pulling the string attached to the ends of both plungers.

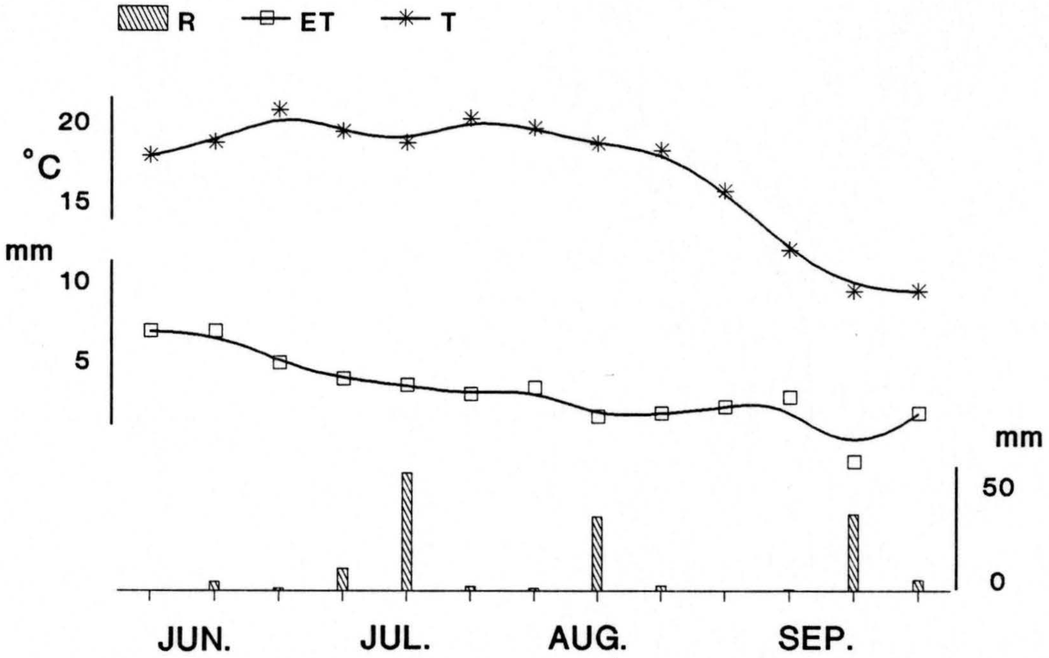


Figure 8. Average daily temperatures (T) and cumulative evapotranspiration (ET) and precipitation (R) over consecutive 7-day periods during the 1988 growing season.

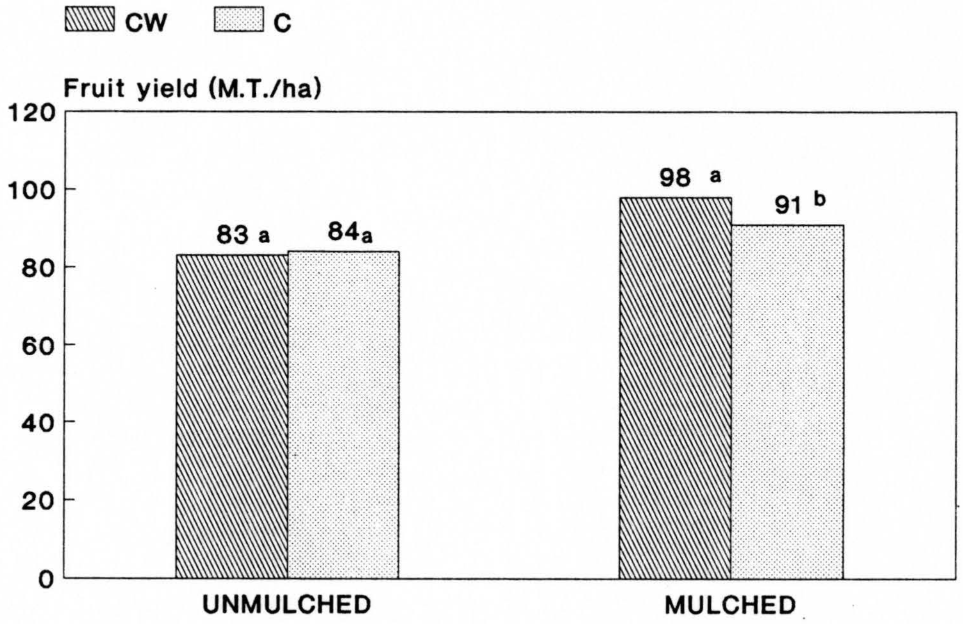


Figure 9. Total seasonal marketable fruit yields for control (C) and carbonated water (CW) treatments under mulched and unmulched conditions in 1988. Means within mulching treatments followed by the same letter are not significantly different (P=.05).

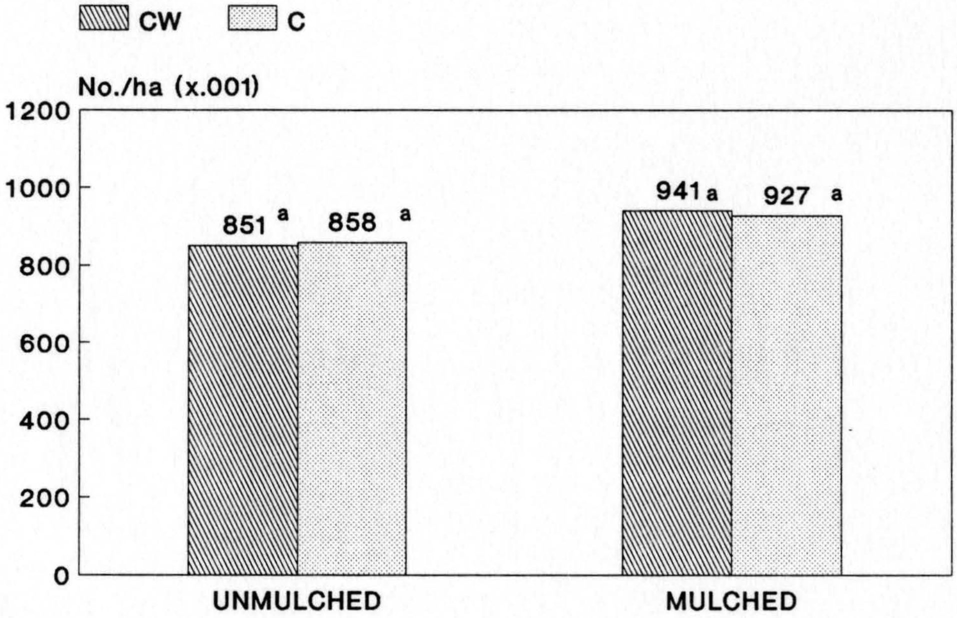


Figure 10. Total seasonal marketable fruit numbers for control (C) and carbonated water (CW) treatments under mulched and unmulched conditions in 1988. Means within mulching treatments followed by the same letter are not significantly different (P=.05).

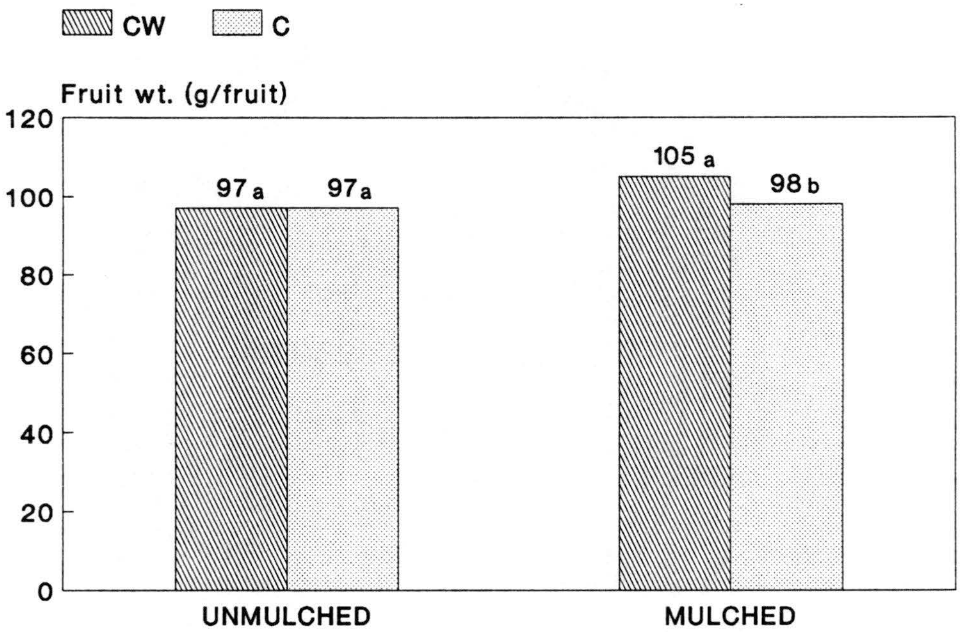


Figure 11. Average weight of marketable fruit for control (C) and carbonated water (CW) treatments under mulched and unmulched conditions in 1988. Means within mulching treatments followed by the same letter are not significantly different (P=.05).

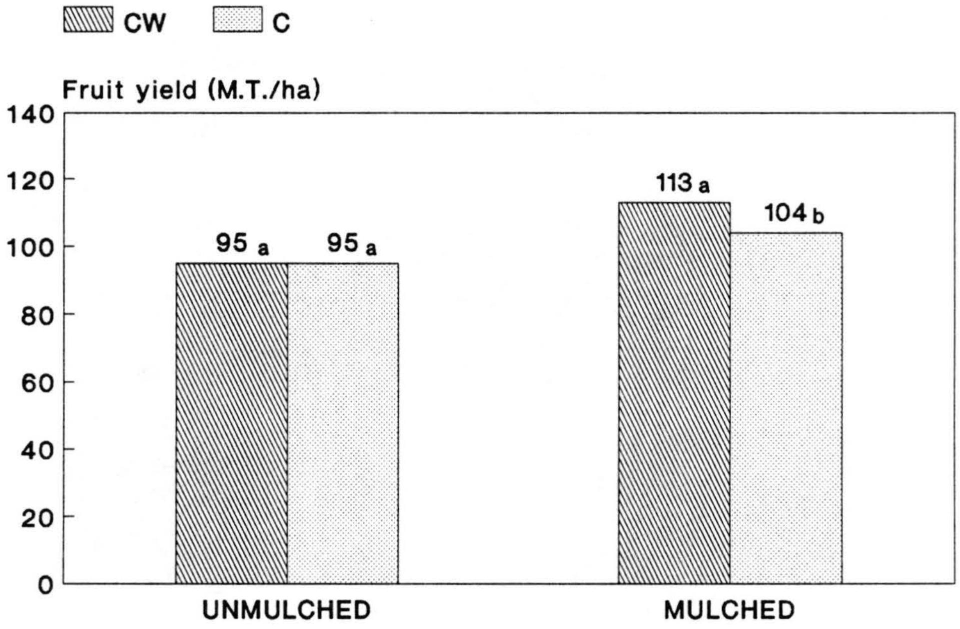


Figure 12. Total (marketable and nonmarketable) fruit yields for control (C) and carbonated water (CW) treatments under mulched and unmulched conditions in 1988. Means within mulching treatments followed by the same letter are not significantly different (P=.05).

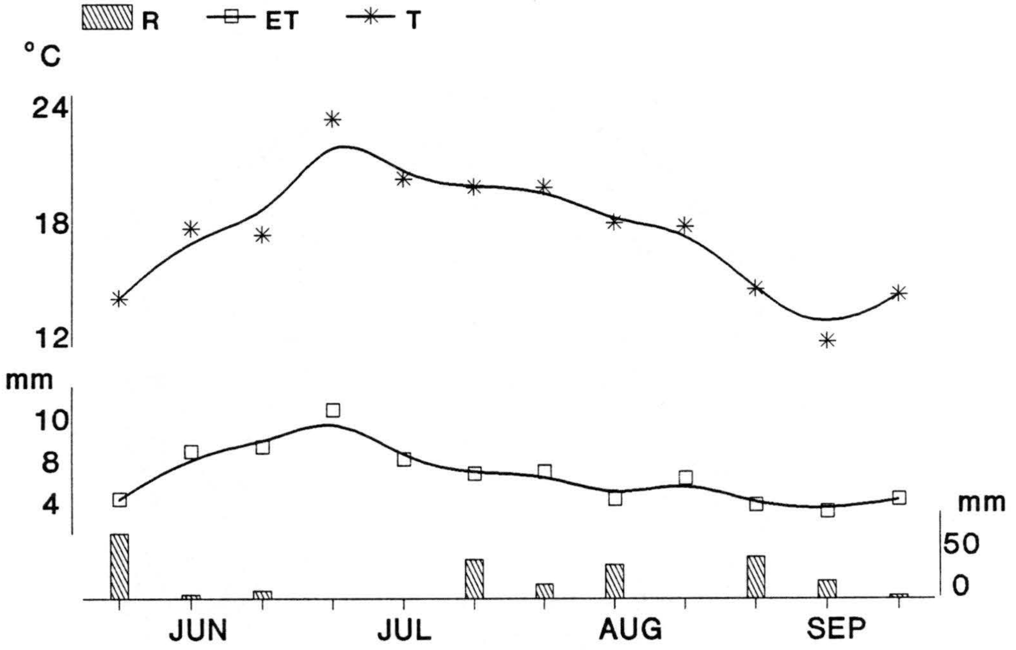


Figure 13. Average daily temperatures (T) and cumulative evapotranspiration (ET) and precipitation (R) over consecutive 7-day periods during the 1989 growing season.

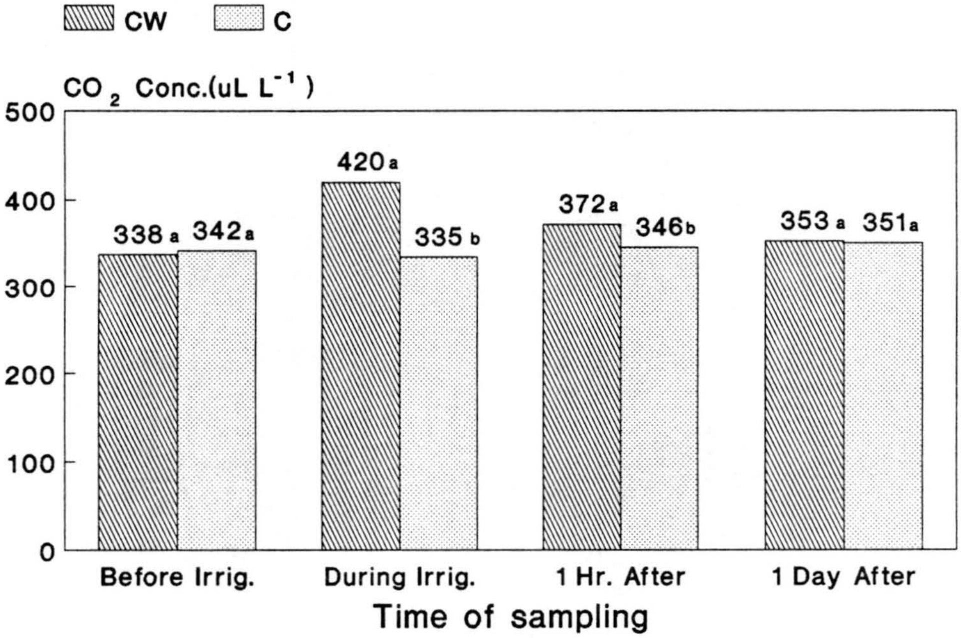


Figure 14. Above-ground CO_2 concentration at 15 cm above the soil surface for control (C) and carbonated water (CW) treatments at different sampling times for plots irrigated every 2 days during 1989. Means within sampling times followed by the same letter are not significantly different (P=.05).

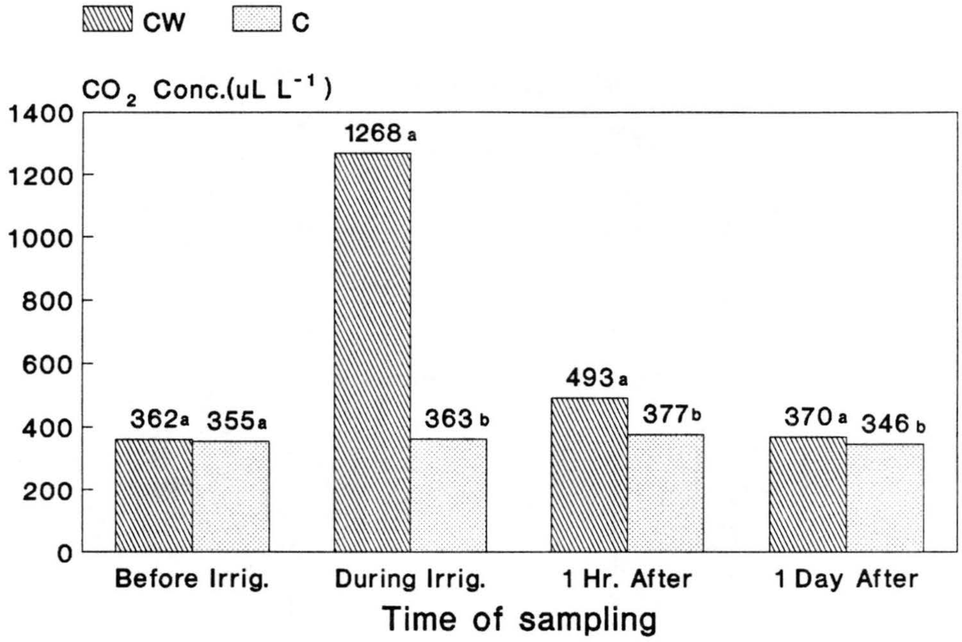


Figure 15. Above-ground CO_2 concentration at 1 cm above the soil surface for control (C) and carbonated water (CW) treatments at different sampling times for plots irrigated every 2 days during 1989. Means within sampling times followed by the same letter are not significantly different (P=.05).

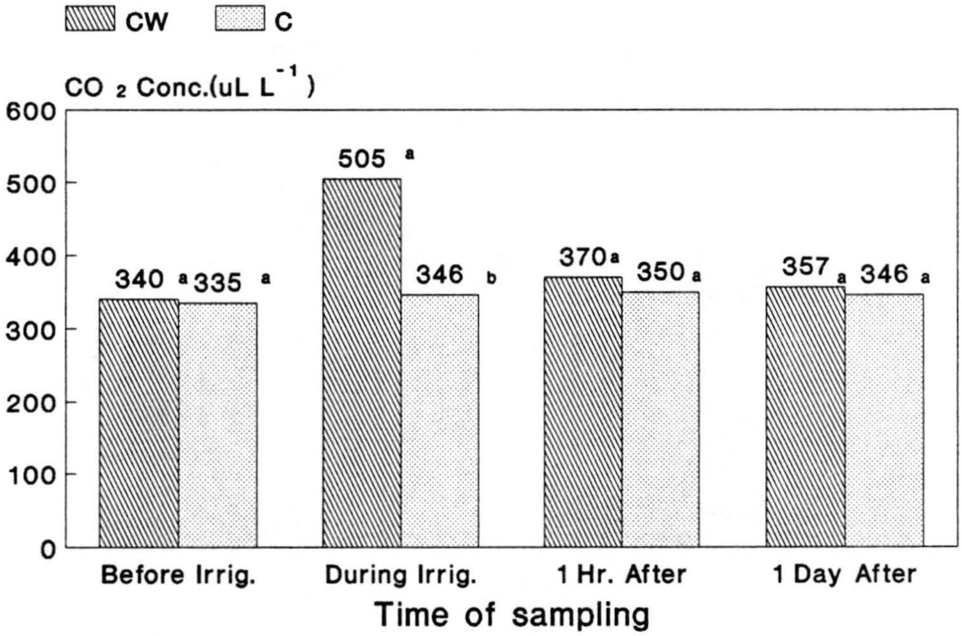


Figure 16. Above-ground CO_2 concentration at 15 cm above the soil surface for control (C) and carbonated water (CW) treatments at different sampling times for plots irrigated every 4 days during 1989. Means within sampling times followed by the same letter are not significantly different (P=.05).

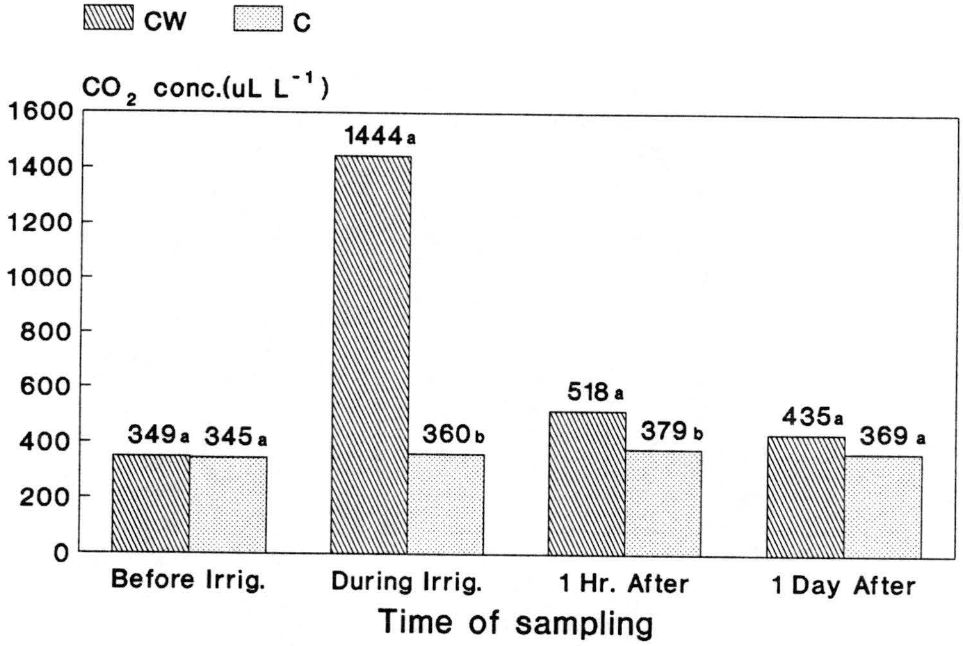


Figure 17. Above-ground CO_2 concentration at 1 cm above the soil surface for control (C) and carbonated water (CW) treatments at different sampling times for plots irrigated every 4 days during 1989. Means within sampling times followed by the same letter are not significantly different (P=.05).

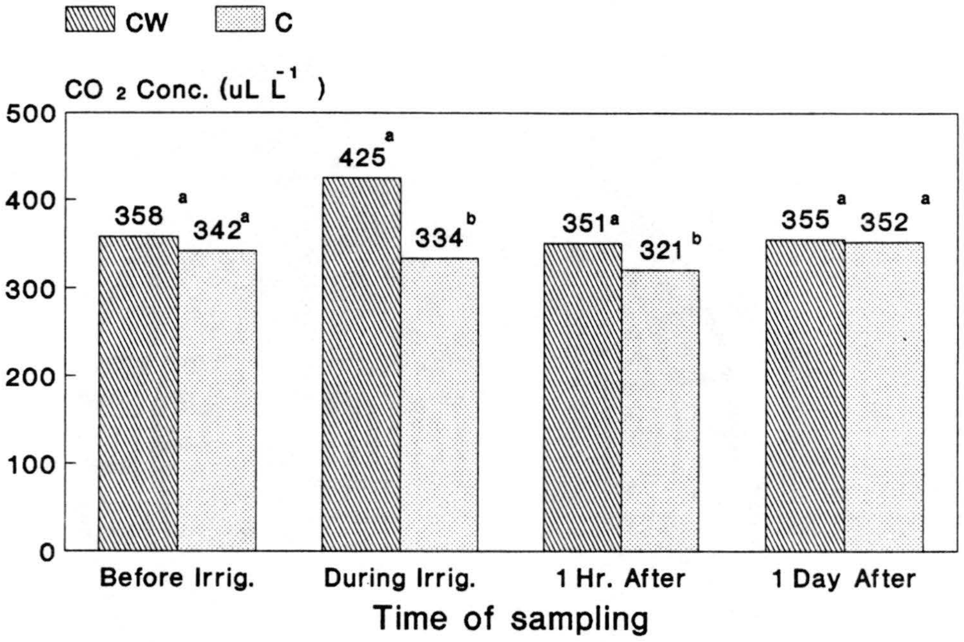


Figure 18. Above-ground CO_2 concentration at 15 cm above the soil surface for control (C) and carbonated water (CW) treatments at different sampling times for plots irrigated every 6 days during 1989. Means within sampling times followed by the same letter are not significantly different (P=.05).

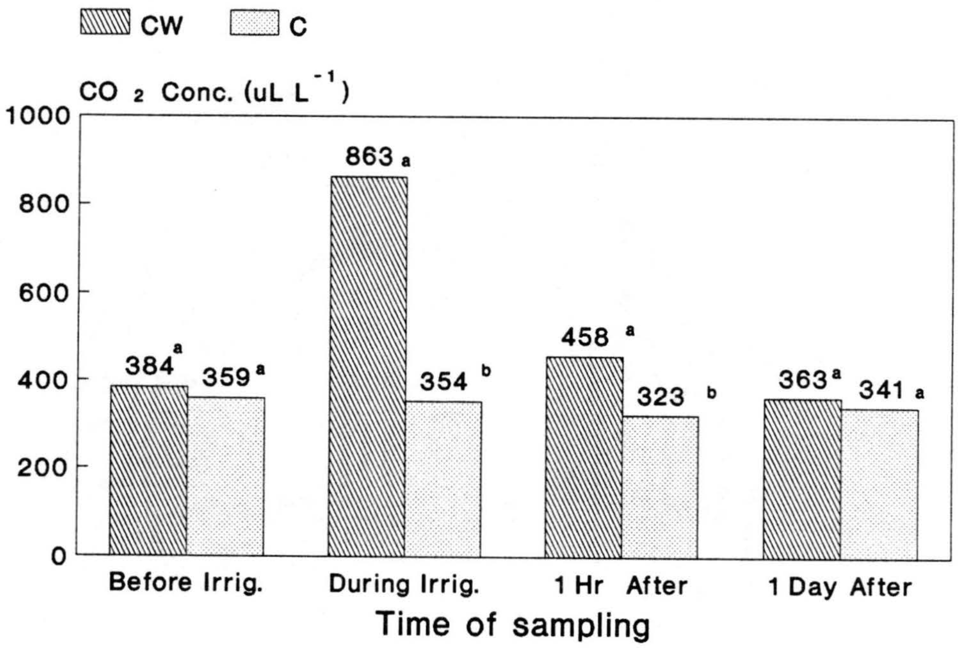


Figure 19. Above-ground CO_2 concentration at 1 cm above the soil surface for control (C) and carbonated water (CW) treatments at different sampling times for plots irrigated every 6 days during 1989. Means within sampling times followed by the same letter are not significantly different (P=.05).

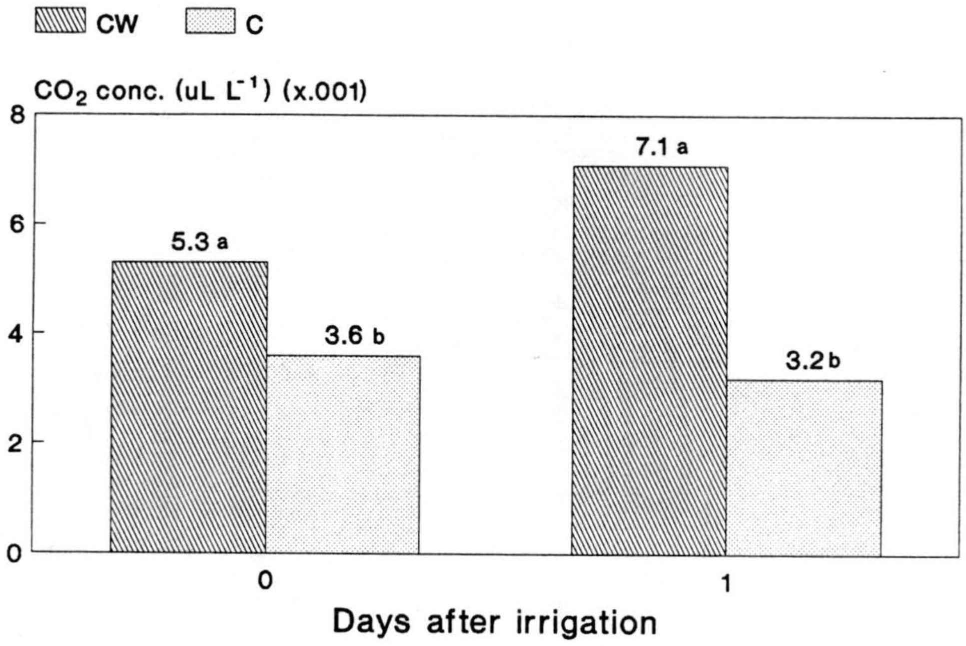


Figure 20. Soil CO_2 concentration at 10-cm depth for control (C) and carbonated water (CW) treatments at different sampling times from plots irrigated every 2 days during 1989. Day 0 refers to sampling immediately before an irrigation event on the day of irrigation. Means within a sampling time followed by the same letter are not significantly different (P=.01).

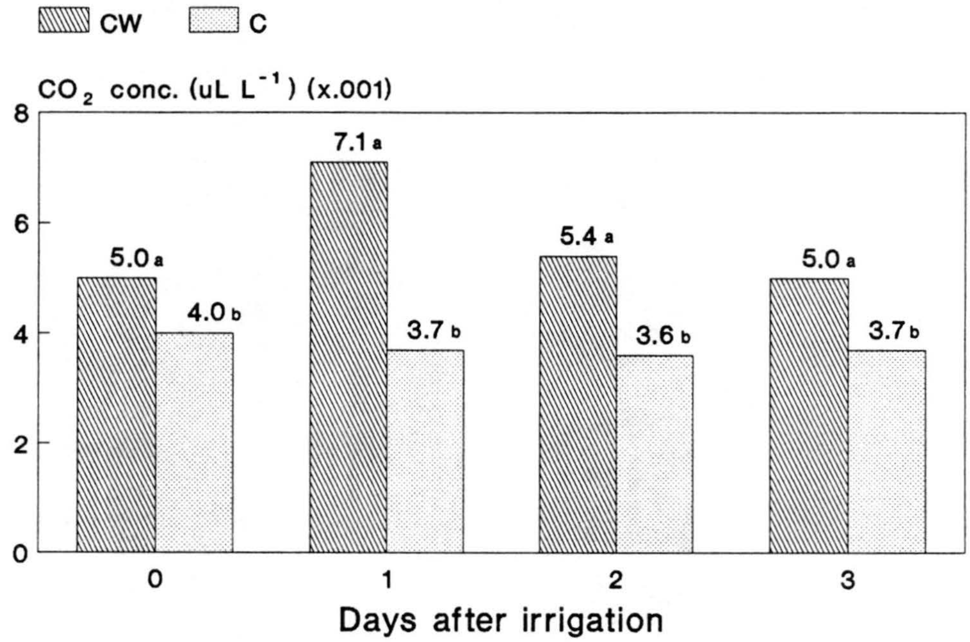


Figure 21. Soil CO_2 concentration at 10-cm depth for control (C) and carbonated water (CW) treatments at different sampling times from plots irrigated every 4 days during 1989. Day 0 refers to sampling immediately before an irrigation event on the day of irrigation. Means within a sampling time followed by the same letter are not significantly different (P=.01).

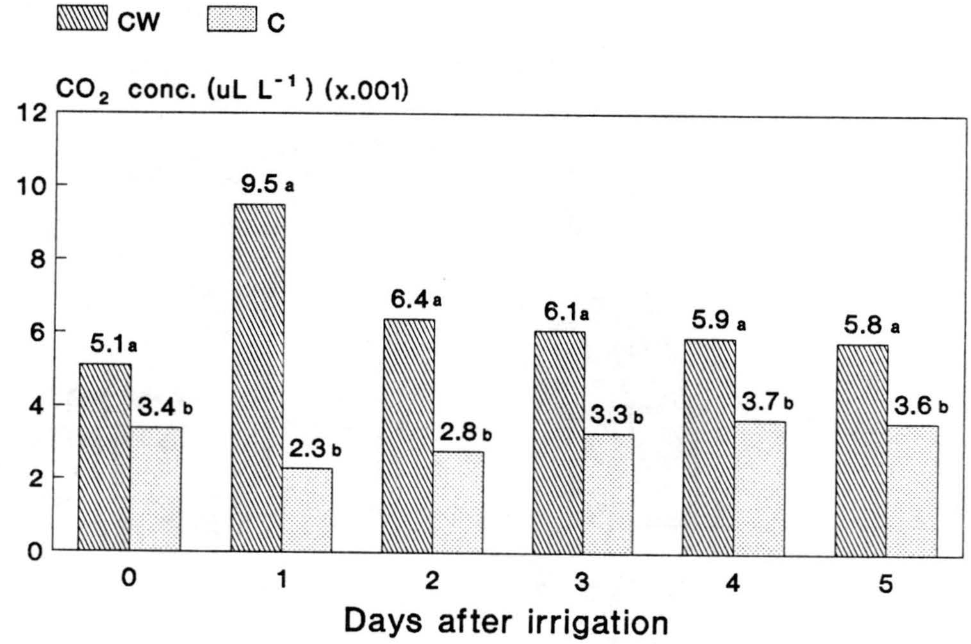


Figure 22. Soil CO_2 concentration at 10-cm depth for control (C) and carbonated water (CW) treatments at different sampling times from plots irrigated every 6 days during 1989. Day 0 refers to sampling immediately before an irrigation event on the day of irrigation. Means within a sampling time followed by the same letter are not significantly different (P=.01).

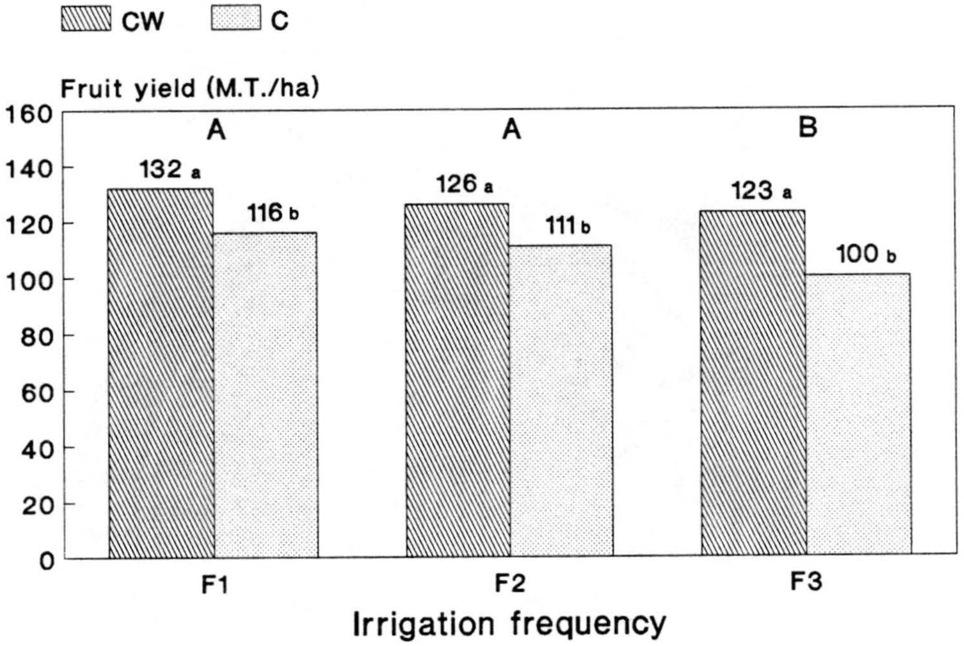


Figure 23. Total seasonal marketable fruit yields in 1989 for control (C) and carbonated water (CW) treatments applied at frequencies of every 2 (F1), 4 (F2), and 6 (F3) days throughout the growing season. Means within an irrigation frequency followed by the same letter are not significantly different (P=.05). The same capital letters above irrigation frequencies indicates no difference in irrigation frequency means (P=.05).

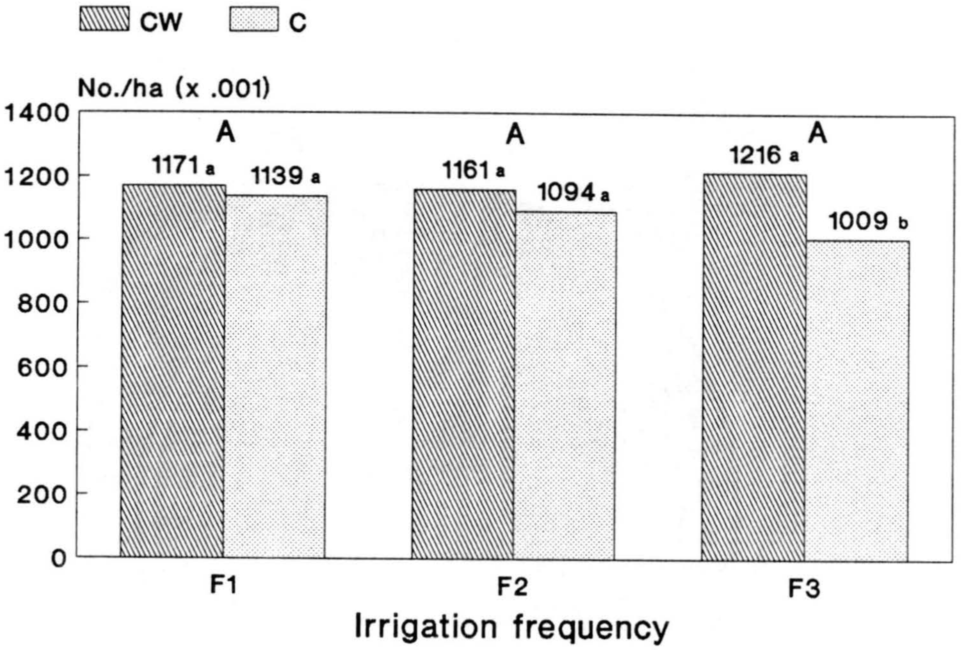


Figure 24. Total seasonal marketable fruit numbers in 1989 for control (C) and carbonated water (CW) treatments applied at frequencies of every 2 (F1), 4 (F2), and 6 (F3) days throughout the growing season. Means within an irrigation frequency followed by the same letter are not significantly different (P=.05). The same capital letters above irrigation frequencies indicates no difference in irrigation frequency means (P=.05).

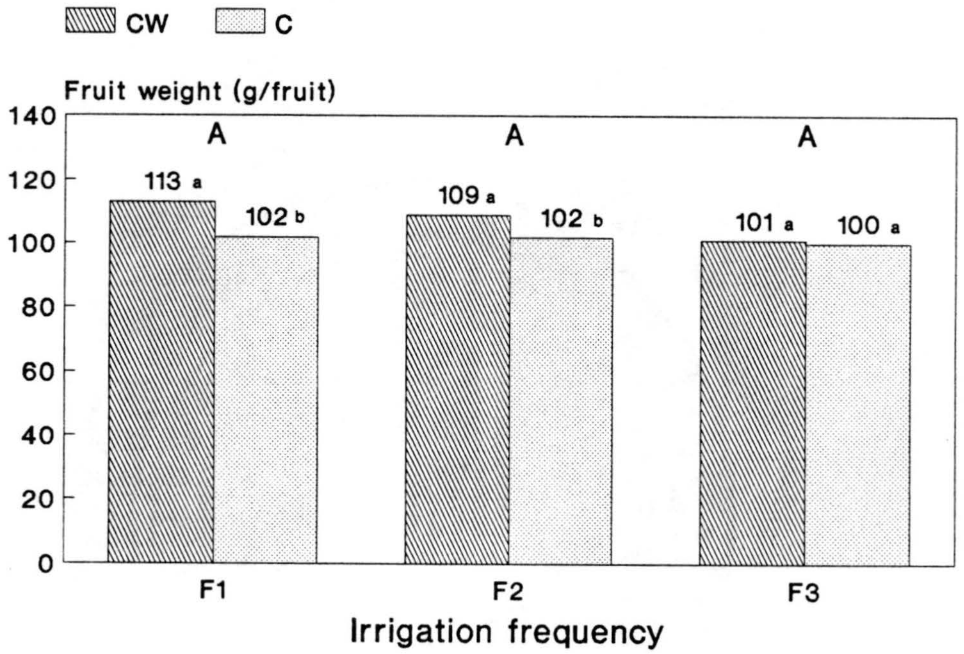


Figure 25. Marketable fruit weight in 1989 for control (C) and carbonated water (CW) treatments applied at frequencies of every 2 (F1), 4 (F2), and 6 (F3) days throughout the growing season. Means within an irrigation frequency followed by the same letter are not significantly different (P=.05). The same capital letters above irrigation frequencies indicates no difference in irrigation frequency means (P=.05).

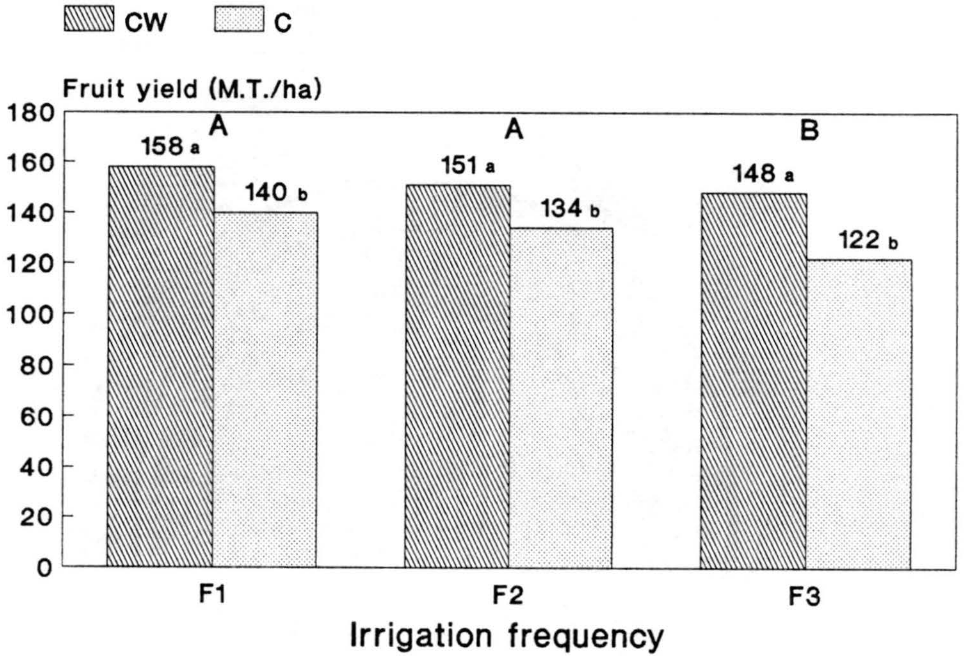


Figure 26. Total seasonal fruit yields (marketable and nonmarketable) in 1989 for control (C) and carbonated water (CW) treatments applied at frequencies of every 2 (F1), 4 (F2), and 6 (F3) days throughout the growing season. Means within an irrigation frequency followed by the same letter are not significantly different (P=.05). The same capital letters above irrigation frequencies indicates no difference in irrigation frequency means (P=.05).

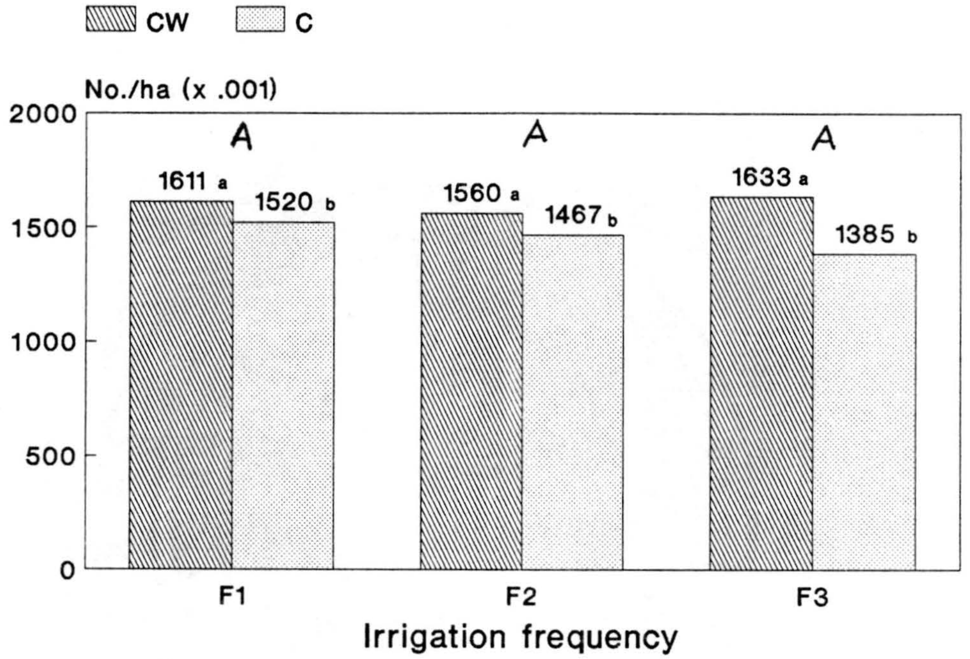


Figure 27. Total seasonal fruit numbers (marketable and nonmarketable) in 1989 for control (C) and carbonated water (CW) treatments applied at frequencies of every 2 (F1), 4 (F2), and 6 (F3) days throughout the growing season. Means within an irrigation frequency followed by the same letter are not significantly different (P=.05). The same capital letters above irrigation frequencies indicates no difference in irrigation frequency means (P=.05).

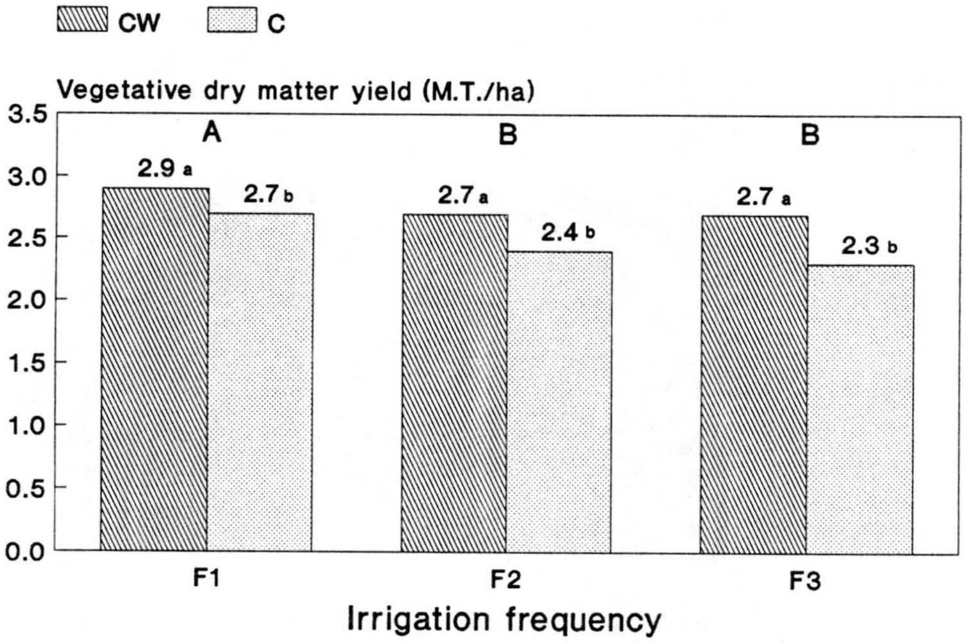


Figure 28. Total vegetative dry matter yields in 1989 for control (C) and carbonated water (CW) treatments applied at frequencies of every 2 (F1), 4 (F2), and 6 (F3) days throughout the growing season. Means within an irrigation frequency followed by the same letter are not significantly different (P=.05). The same capital letters above irrigation frequencies indicates no difference in irrigation frequency means (P=.05).

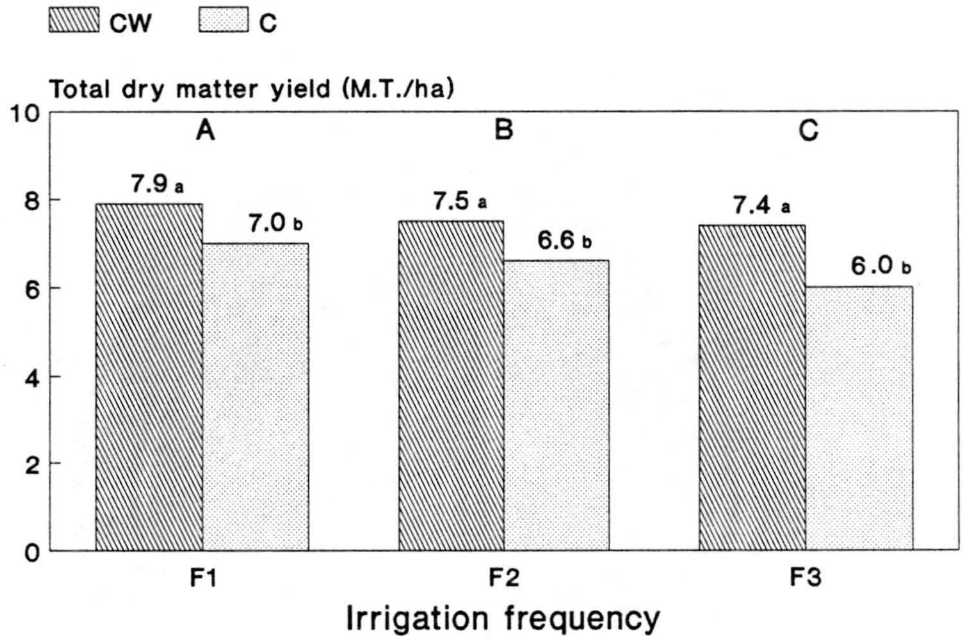


Figure 29. Total seasonal dry matter yields (fruit and vegetation) in 1989 for control (C) and carbonated water (CW) treatments applied at frequencies of every 2 (F1), 4 (F2), and 6 (F3) days throughout the growing season. Means within an irrigation frequency followed by the same letter are not significantly different (P=.05). The same capital letters above irrigation frequencies indicates no difference in irrigation frequency means (P=.05).

REFERENCES

Acock, B. and D. Pasternak. 1986. Effects of CO_2 concentration on composition, anatomy and morphology of plants. In H. Z. Enoch and B. A. Kimball, eds. Carbon Dioxide Enrichment of Greenhouse Crops, Volume II. Physiology, Yield, and Economics. CRC Press, Inc. Boca Raton, Florida. pp. 41-52.

Allen, L. H., Jr. 1979. Potentials for carbon dioxide enrichment. In B. J. Barfield and J. F. Gerber (ed.) Modification of the aerial environments of plants. Am. Soc. Agric. Engineers Monog., St. Joseph, Missouri. p. 500-519.

Allen, L. H., Jr., R. L. Desjardins and E. R. Lemon. 1974. Line source carbon dioxide release. I. Field experiment. Agron. J. 66: 609-615.

Allen, L. H., Jr., S. E. Junsen and E. R. Lemon. 1971. Plant response to carbon dioxide under field conditions: A simulation. Science 173: 256-258.

Arteca, R. N., B. W. Poovaiah and O. E. Smith. 1979. Changes in carbon dioxide fixation, tuberization, and growth induced by CO_2 applications to the root zone of potato plants. Science 205: 1, 279-280.

Arteca, R. N. and B. W. Poovaiah. 1982. Absorption of $^{14}CO_2$ by potato roots and its subsequent translocation. J. Amer. Soc. Hort. Sci. 107:398-401.

Baker, D. N. and H. Z. Enoch. 1983. Plant growth and development. In E. R. Lemon (ed.) CO_2 and plants. Westview Press, Boulder, Colorado. p. 107-130.

Baron, J. J. and S. F. Gorski. 1986. Response of eggplant to a root environment enriched with CO_2. HortSci. 21(3):495-498.

Bassham, J. A. 1977. Increasing crop production through more controlled photosynthesis. Science 197:630-638.

Bergquist, N. O. 1964. Absorption of carbon dioxide by plant roots. Bot. Not. 117:249-261.

Bhella, H. S. 1988. Effect of trickle irrigation and black mulch on growth yield and mineral composition of watermelon. HortSci. 23(1):123-125.

Bjorkman, O. and R. W. Pearcy. 1983. Physiological responses to increasing atmospheric carbon dioxide. In E. R. Lemon (ed.) CO_2 and plants. Westview Press, Boulder, Colorado. p. 65-105.

Boehle, J. jr. and W. L. Lindsay. Micronutrients. The Fertilizer Shoe-Nails. Pt. 6, In the Limelight-Zinc, Fertilizer solutions 13(1), 6-12 (1969).

Bravdo, B. A. 1986. Effect of CO_2 enrichment on photosynthesis of C_3 plants. In: Carbon Dioxide Enrichment Of Greenhouse Crops. Vol. II. CRC Press Inc., Boca Raton, Florida. p. 13-27.

Cahn, H. K. 1989. CO_2 profiles in the field and response to enriched atmospheres using strawberry. M.S. Thesis, Colorado State University. 179 p.

Calvert, A. and G. Slack. 1975. Effects of carbon dioxide enrichment on growth, development and yield of glasshouse tomatoes. I. Responses to controlled concentrations. J. Hort. Sci. 50:61-71.

Carlson, R. W. and F. A. Bazzaz. 1980. The effects of elevated CO_2 on growth, photosynthesis, transpiration and water use efficiency of plants. In J. Singh and A. Deepak (ed.) Environmental and climatic impact of coal utilization. Academic Press, New York. p. 609-623.

Clegg, M. D., C. Y. Sullivan, and J. D. Eastin. 1978. A sensitive technique for the rapid measurement of carbon dioxide concentration. Plant Physiol. 62:924-926.

Coker III, G. T. and K. R. Schubert. 1981. Carbon dioxide fixation in soybean roots and nodules. Plant Physiol. 67:691-696.

Courter, J. W. and N. F. Oebker. 1964. Comparisons of paper and polyethylene mulches on certain vegetable crops. Proc. Am. Soc. Hort. Sci. 85:526-531.

Dietz, K. J. 1986. An evaluation of light and CO_2 limitations of leaf photosynthesis by CO_2 gas analysis. Planta. 167:260-263.

Gould, W. A. 1974. Tomato Production, Processing And Quality Evaluation. AVI Publ. Co. Inc., Westport, Connecticut. 445p.

Hanan, J. J. 1964. Oxygen and carbon dioxide concentrations in greenhouse soil-air. Proc. Am. Soc. Hort. Sci. 84:648-652.

Hartman, H. T., W. J. Flocker and A. M. Kofranek. 1981. Plant science: Growth, development and utilization of cultivated plants. Prentice Hall, Inc., Englewood Cliffs, New Jersey. 676 p.

Havlin, J. L. and P. W. Soltanpour. 1980. A nitric acid plant tissue digest method for use with inductively coupled plasma spectrometry. Commun. Soil Sci. Plant Anal. 1(10):969-980.

Hopen, H. J. and N. F. Oebker. 1975. Mulch effects on ambient carbon dioxide levels and growth of several vegetables. HortSci. 10:159-161.

Hopen, H. J. and N. F. Oebker. 1976. Vegetable crop responses to synthetic mulches. An annotated bibliography. NAPA Tech. Bull. 1. Nat. Agric. Plast. Assoc. 48 p.

Idso, S. B. 1982. Carbon dioxide: Friend or foe? IBR Press, Tempe, Arizona. 92 p.

Kimball, B. A. 1983. Carbon dioxide and agricultural yield: An assemblage and analysis of 430 prior observations. Agron. J. 75:779-788.

Kimball, B. A. 1986. Influence of elevated CO_2 on crop yield. In H. Z. Enoch and B. A. Kimball (ed.) Carbon dioxide enrichment of greenhouse crops. Vol. II. CRC Press, Inc., Boca Raton, Florida. p. 105-115.

Kimball, B. A. and S. T. Mitchell. 1979. Tomato yields from CO_2 enrichment in unventilated and conventionally ventilated greenhouses. J. Am. Soc. Hort. Sci. 104:515-520.

Kretchman, D. W. and F. S. Howlett. 1970. CO_2 enrichment for vegetable production. Bio. Sci. 31:29-33.

MacGillivray, J. H. and L. J. Clemente. 1956. Effect of tomato size on solids content. Proc. Am. Soc. Hort. Sci. 68:466-469.

Magoon, C. E. 1969. Fruit and vegetable facts and pointers-Tomatoes. United Fresh Fruits And Veg. Assoc. 777 14th St. N.W., Washington D.C. 44p.

Martin, P. L. and A. L. Olmstead. 1985. The agricultural mechanization controversy. Science 227:601-606.

Mauney, J. R. and D. L. Hendrix. 1988. Responses of glasshouse grown cotton to irrigation with carbon dioxide-saturated water. Crop Sci. 28:835-838.

Mengel, K. and E. A. Kirkly. 1982. Principles of plant nutrition. 3rd ed. International Potash Institute, Bern, Switzerland. 655 p.

McClure, P. R., G. T. Coker III and K. R. Schubert. 1983. Carbon dioxide fixation in roots and nodules of Alnus glutinosa. Plant Physiol. 71:652-657.

McCoy, P. A. 1978. Carbon dioxide in the tomato plant microenvironment. M.S. Thesis, Colorado State University. 44p.

Morgan, J. V. 1971. The influence of supplementary illumination and CO_2-environment on the growth, flowering and fruiting of the tomato. Acta Hort. 22:187-198.

Nakayama, F. S. and D. A. Bucks. 1980. Using subsurface trickle system for carbon dioxide enrichment. In Proceedings of the 15th national agricultural plastic congress. University of Arizona, Tucson, Arizona. p. 13-18.

Nevins, D. J. 1987. Why tomato biotechnology? A potential to accelerate applications. In D. J. Nevins and R. A. Jones (ed.) Tomato biotechnology. Alan R. Liss, Inc., New York. p. 3-14.

Nilsen, S., K. Hovland, C. Dons and S. P. Sletten. 1983. Effects of CO_2 enrichment on photosynthesis, growth and yield of tomato. Scientia Hort. 20:1-14.

Norman, A. G. 1962. The uniqueness of plants. Am. Sci. 50:436-449.

Pallas, J. E. Jr. 1979. Carbon dioxide. In T. W. Tibbits and T. T. Koslowski (ed.) Controlled environment guidelines for plant research. Academic Press, New York. 207 p.

Penman, H. L. 1963. Vegetation and hydrology. Tech. Commun. No. 53, Commonwealth Bur. Soils., Harpenden, England.

Plass, G. N. 1959. Carbon dioxide and climate. Sci. Am. 201:41-47.

Rick, C. M. 1978. The tomato. Sci. Am. 239:77-87.

Rosenberg, N. J. 1981. The increasing CO_2 concentration in the atmosphere and its implication in agricultural productivity. I. Effects in photosynthesis, transpiration and water use efficiency. Climate Change 3:265-279.

Rowe-Dutton, P. 1957. The mulching of vegetables. Comm. Bull. Hort. Plant Crops Tech. Commun. No. 24. 169 p.

Salisbury, F. B. and C. W. Ross. 1985. Plant physiology, 3rd ed. Wadsworth Publ. Co., Belmont, California. 540 p.

Schafer, W. 1988. Pflanzurachstrum durch CO_2/HCO_3 - Eintrag irber die Wurzel. J. Agron. and Crop Sci. 160:228-234.

Schales, F. D. and R. Sheldrake Jr. 1963. Mulch effects on soil conditions and tomato plant response. Proc. Nat. Agr. Plast. Conf. 4:78-90.

Sheldrake, R., Jr. 1963. Carbon dioxide levels in the microclimate as influenced by the permeability of mulches. Proc. Nat. Agri. Plast. Conf. 4:93-96.

Skok, J., W. Chorney, and W. S. Broecker. 1962. Uptake of CO_2 by roots of xanthium plants. Bot. Gaz. 124:118-120.

Stolwijk, J. A. J. and K. V. Thimann. 1957. On the uptake of carbon dioxide and bicarbonate by roots and its influence on growth. Plant Physiol. 32:513-520.

Strain, B. R. and F. Bazzaz. 1983. Terrestrial plant communities. In E. R. Lemon (ed.) CO_2 and plants. Westview Press, Boulder, Colorado. p. 177-222.

Strain, B. R. and N. Sionit. 1982. Direct effects of carbon dioxide on plants: A bibliography. Dept. of Botany, Duke University, Durham, North Carolina

Tarter, C. K. 1983. Carbon dioxide levels in the plant microenvironment as influenced by a poly-coated paper mulch. M. S. Thesis, Colorado State University. 90 p.

Tiessen, H. 1973. Effects of paper mulches on vegetable yields. Acta Horticulturae 27:204-218.

Tolbert, N. E. and I. Zelitch. 1983. Carbon metabolism. In E. R. Lemon (ed.) CO_2 and plants. Westview Press, Boulder, Colorado. p. 21-24.

Vandenberg, J. and H. Tiessen. 1972. Influence of wax-coated and polyethylene-coated paper mulch on growth and flowering of tomato. HortSci. 7(5):464-465.

White, W. C. and D. N. Collins. 1980. The fertilizer handbook. The Fertilizer Institute, Washington D. C.

Wittwer, S. H. 1978. Carbon dioxide fertilization of crop plants. In U. S. Gupta (ed.) Crop physiology. Oxford and IBH Publ. Co., New Delhi, India. p. 310-333.

Wittwer, S. H. 1979. Carbon dioxide fertilization of crop plants. In U. S. Gupta (ed.) Problems in crop physiology. Haryana Agric. Univ., Hissar, India. p. 310-330.

Wittwer, S. H. 1982. Rising atmospheric CO_2 and crop productivity. HortSci. 17(3):529 (Abstr. 472).

Wittwer, S. H. 1983. Rising atmospheric CO_2 and crop productivity. HortSci. 18(5):667-673.

Wittwer, S. H. 1986. Worldwide status and history of CO_2 enrichment-An overview. In Carbon Dioxide Enrichment Of Greenhouse Crops. Vol. I. CRC Press, Inc., Boca Raton, Florida. Pp. 3-15.

Wittwer, S. H. and W. Robb. 1964. Carbon dioxide enrichment of greenhouse atmospheres for food crop production. Econ. Bot. 18:34-56

Wium-Andersen, S. 1971. Photosynthetic uptake of free CO_2 by the roots of Lobelia dortmanna. Physiol. Plant. 25:245-248

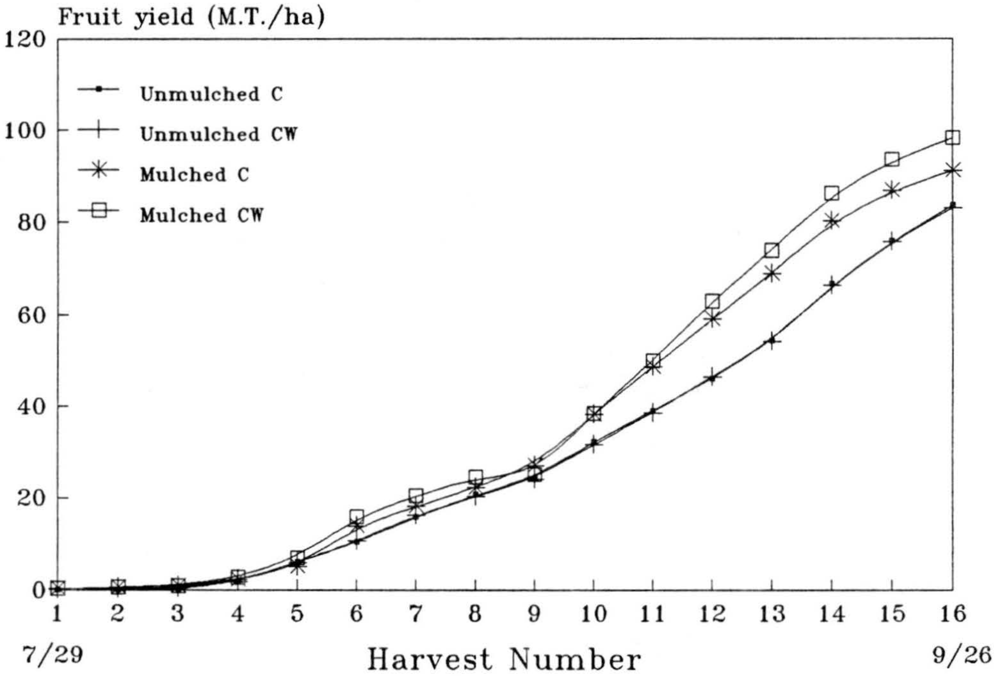
Yamaguchi, M., F. D. Howard, B. S. Luh and S. J. Leonard. 1964. Effect of ripeness and harvest dates on the quality and composition of fresh canning tomatoes. Proc. Am. Soc. Hort. Sci. 76:560-567.

APPENDIX

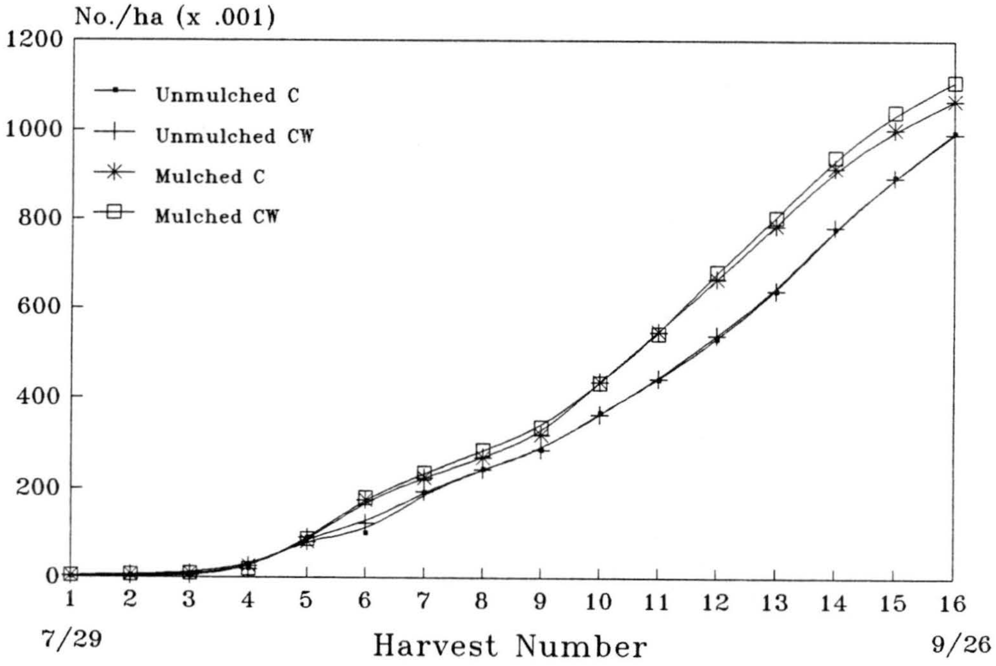
Appendix Table 1. Mean squares from the analyses of variance for yield variables from 1989 study.

		Marketable fruit			Total fruit or dry matter			
Source of variation	df	Fruit yield	Fruit number	Fruit size	Fruit yield	Fruit number	Total veg. yield	Total yield
Blocks	3	0.14	886.5	45.57	3.16	1,390	13,904**	22,161**
Freq. (F)	2	42.30**	535.9	99.35	52.25**	1,106	32,524**	152,060**
Carb. (C)	1	270.09**	8,702.0**	262.68*	357.64**	17,388**	58,411**	901,651**
F X C	2	4.55	2,385.5*	49.78	6.72	2,243	2,887	10,662
Residual	15	4.55	538.6	31.18	6.06	1,114	1,076	6,561

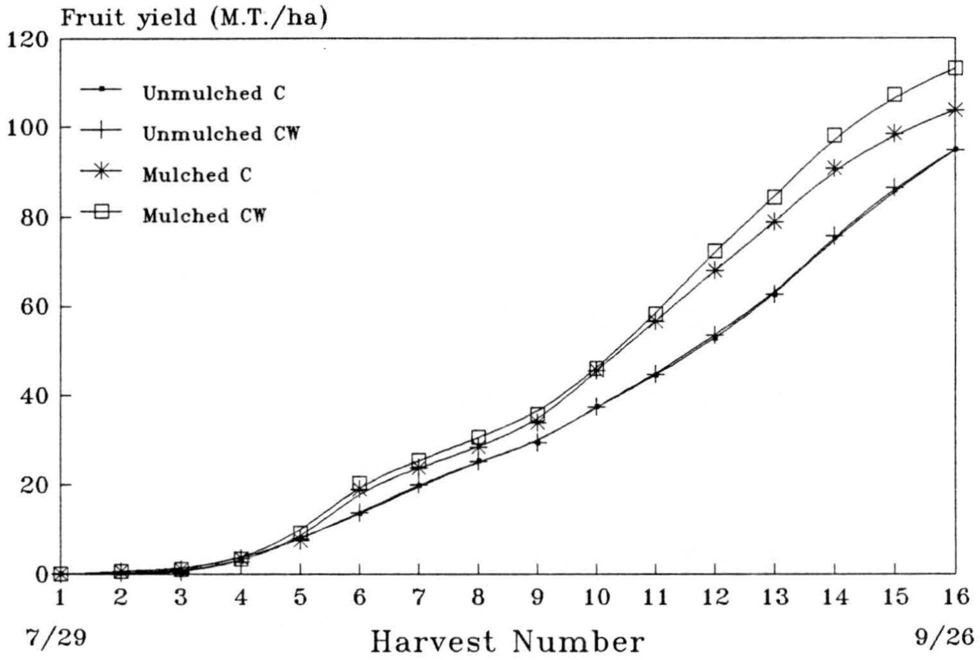
*,** indicates significant effects at 5 and 1% probability levels, respectively.



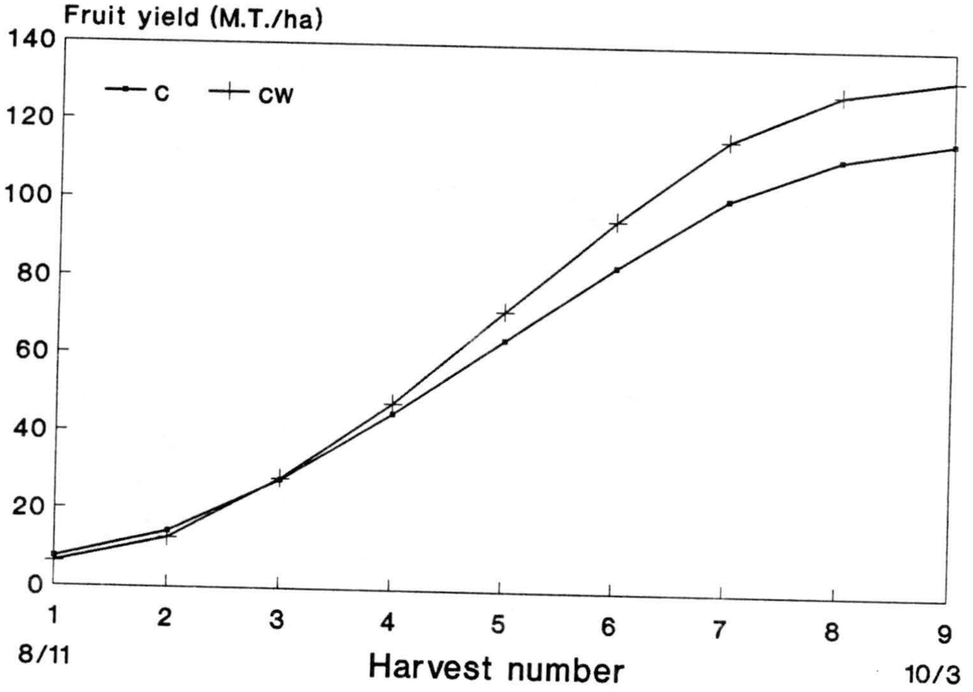
Appendix Figure 1. Seasonal trend of cumulative marketable fruit yields for control (C) and carbonated water (CW) treatments under mulched and unmulched conditions during 1988.



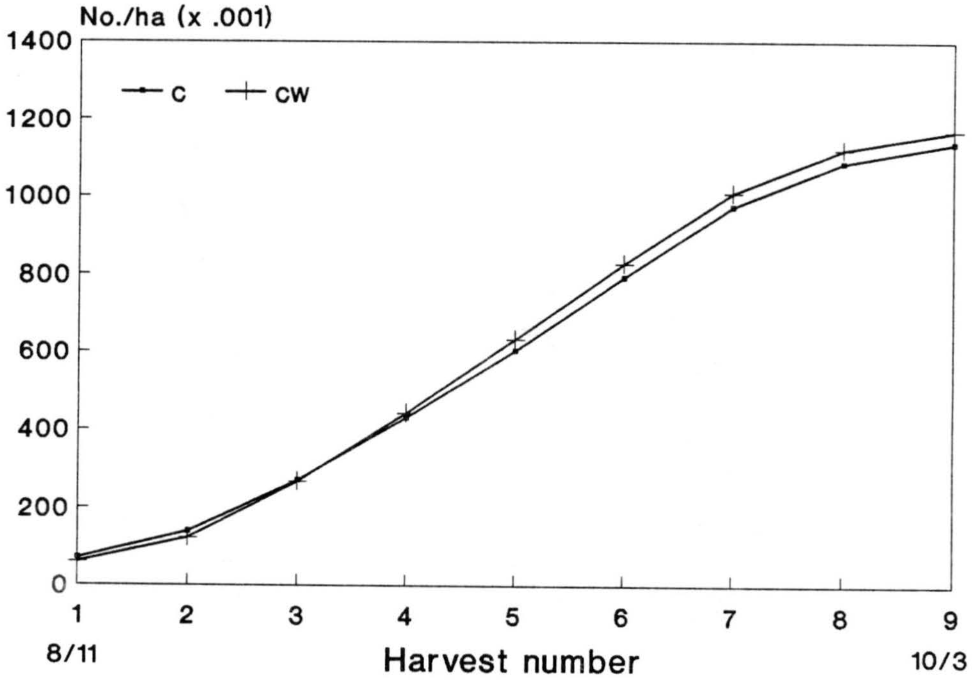
Appendix Figure 2. Seasonal trend of cumulative marketable fruit numbers for control (C) and carbonated water (CW) treatments under mulched and unmulched conditions during 1988.



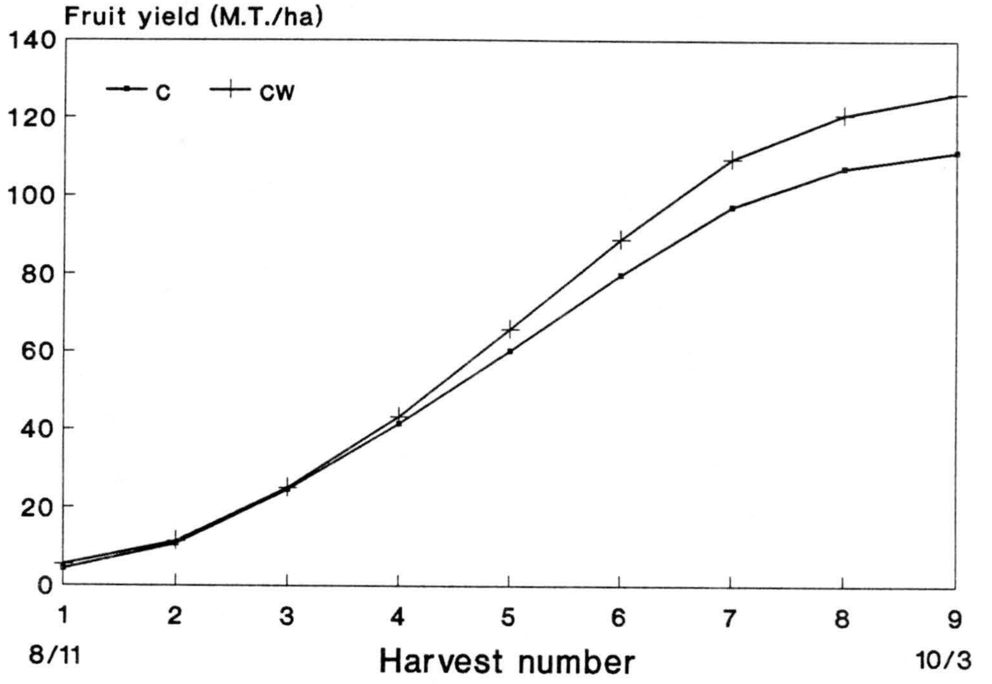
Appendix Figure 3. Seasonal trend of cumulative total (marketable and nonmarketable) fruit yields for control (C) and carbonated water (CW) treatments under mulched and unmulched conditions during 1988.



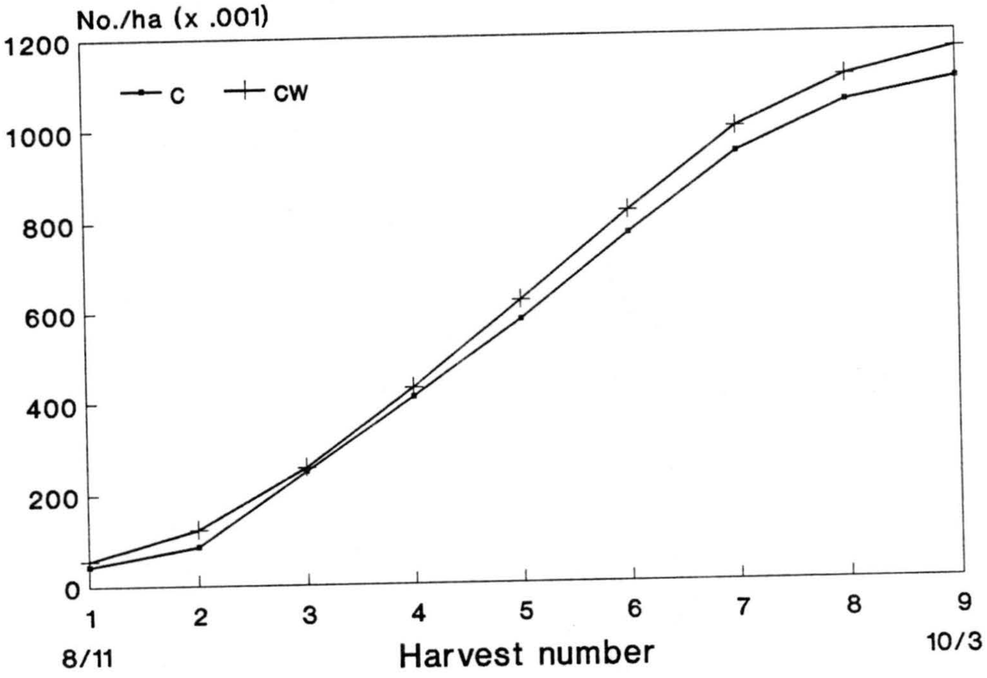
Appendix Figure 4. Seasonal trend of cumulative marketable fruit yields for control (C) and carbonated water (CW) treatments irrigated every 2 days during 1989.



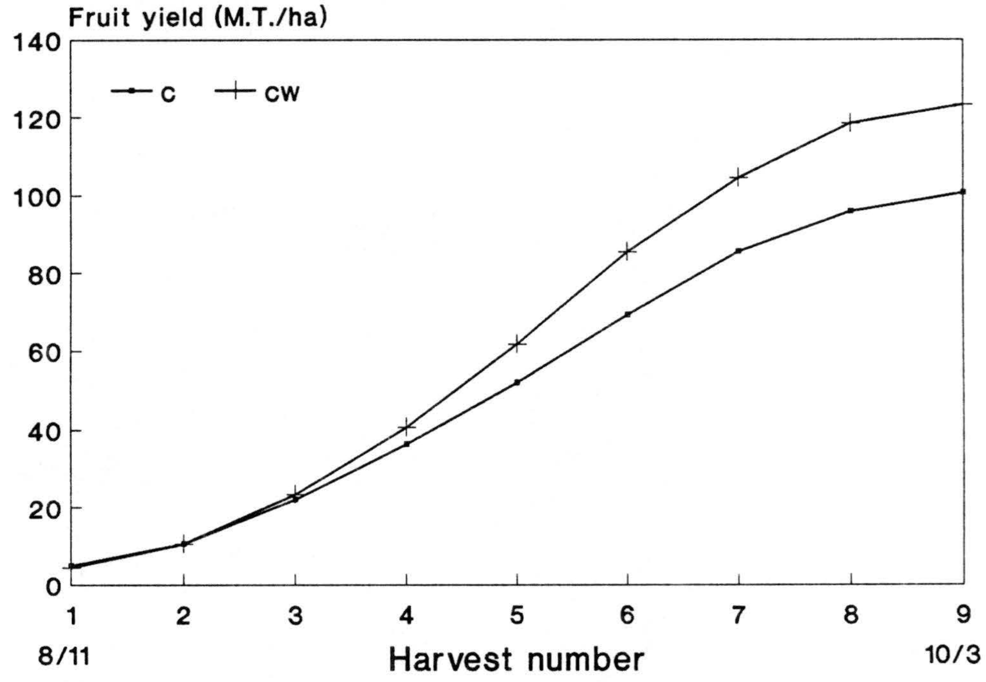
Appendix Figure 5. Seasonal trend of cumulative marketable fruit numbers for control (C) and carbonated water (CW) treatments irrigated every 2 days during 1989.



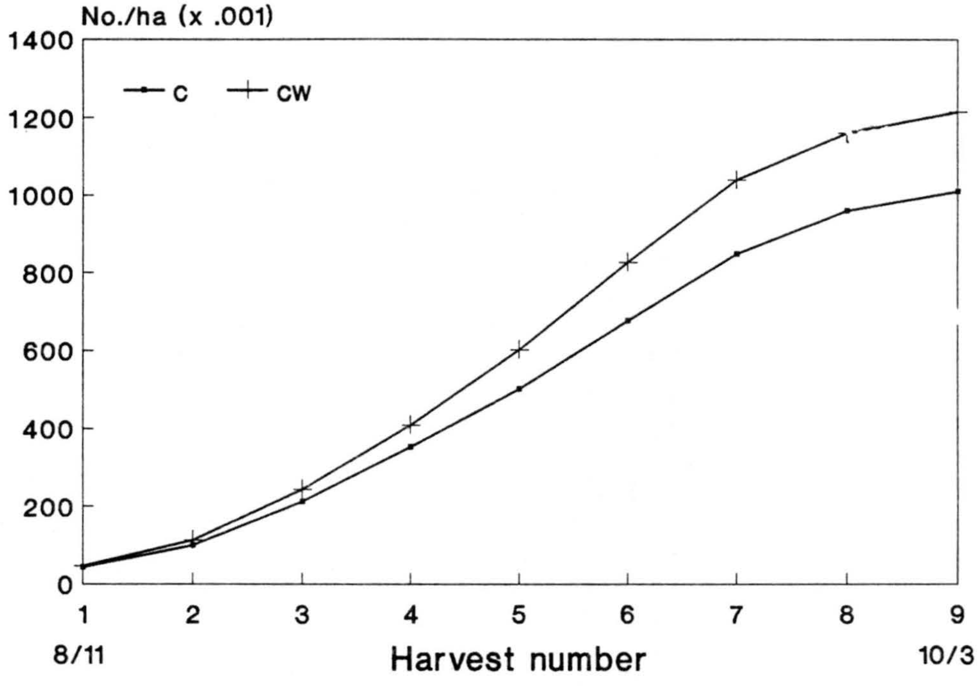
Appendix Figure 6. Seasonal trend of cumulative marketable fruit yields for control (C) and carbonated water (CW) treatments irrigated every 4 days during 1989.



Appendix Figure 7. Seasonal trend of cumulative marketable fruit numbers for control (C) and carbonated water (CW) treatments irrigated every 4 days during 1989.



Appendix Figure 8. Seasonal trend of cumulative marketable fruit yields for control (C) and carbonated water (CW) treatments irrigated every 6 days during 1989.



Appendix Figure 9. Seasonal trend of cumulative marketable fruit numbers for control (C) and carbonated water (CW) treatments irrigated every 6 days during 1989.

Appendix Figure 10. Canopy and rootzone air samples were injected into a Beckman 865 infrared gas analyzer (IRGA).