

THESIS

CARBON DIOXIDE IN THE TOMATO
PLANT MICROENVIRONMENT

Submitted by

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ABSTRACT OF THESIS

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Paper and polyethylene mulches have proven effective in causing increased growth and yields of several field-grown vegetable crops. These increases cannot always be attributed entirely to temperature and moisture differences resulting from mulching. This indicates that another environmental factor, perhaps CO_2 , could be partially responsible. Carbon dioxide enrichment has met with great success in greenhouses. A slight CO_2 enrichment effect could result from the trapping of diffusing CO_2 by a mulch and its subsequent release directly around plants growing outdoors.

The relationship among polyethylene-coated black paper mulch, CO_2 in the plant microenvironment, and subsequent plant growth and yield was studied.

Spring Giant Hybrid tomato seedlings were transplanted into mulched and unmulched beds in the field. Similar soil moisture levels were maintained through separate drip irrigation systems for mulched and unmulched plots. Temperatures were monitored relative to both treatments and found not significantly different at a 5 cm depth in the soil or at a 30 cm height in the canopy. Gas samples were collected from within the plant canopy at 3-hour intervals over two 24-hour

periods. The CO_2 concentration at the base of the plants (1 cm) was greater in the mulched plots in both the light and the dark while the CO_2 level over the entire 34 cm profile was greater above the mulch in the dark. Carbon dioxide levels in the soil under the mulch and between the mulch and soil surface were greater relative to the bare soil. Plant tissue dry weights were greater by 18% in the mulched plots. Total marketable fruit yield per plant was increased 36% and a 23% increase in weight per fruit was noted in the mulched plots. The increased plant growth and fruit yields were attributed to elevated levels of CO_2 occurring in the mulched plant microenvironment.

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INTRODUCTION

Man is continually searching for new ways to increase the yields of food crops. Mineral fertilization, irrigation and pest control techniques are now well developed, and are widely used to increase yields. However, it has been observed that yields of major food crops have plateaued and increased very little since 1970.

Light, water, and carbon dioxide are the three raw materials directly involved in photosynthesis. Water deficiencies can be corrected with irrigation. Light is not often deficient in the field. Yet, CO_2 which occurs naturally at very low levels, is often limiting to photosynthesis. Efforts to increase yields by raising the CO_2 content of air have met with great success in greenhouses. However, little research has been done with CO_2 enrichment under field conditions.

Mulch has been effective in increasing the yields of food crops grown in the field. Mulch alters soil temperatures and generally retards soil moisture loss. It may also have the potential to raise the CO_2 content of air around plants in the field by serving as a reservoir for soil generated CO_2 with subsequent funneling into the canopy.

The purpose of this study was:

1. To determine if polyethylene-coated black paper mulch does increase the CO_2 content of the air in the plant microenvironment.

2. To determine if these increased CO₂ levels are effective in causing an increase in plant growth and yield.

LITERATURE REVIEW

Mulch, in this study, will refer to a continuous layer of material, usually plastic or paper, which is placed on the soil surface for agricultural purposes. Numerous researchers have found mulch effective in increasing the yield of several vegetable crops (1, 13, 20, 26, 28, 29, 33, 34, 35). The yield increases often occur in the form of greater numbers of fruit per plant (1, 33, 34, 35). However, mulch has also increased the weight per fruit in some cases (1, 34).

The larger yields resulting from mulching are often attributed primarily to warmer soil temperatures and greater soil moisture under the mulch (13, 20, 26, 33, 35). Mulching increases soil moisture uniformity by reducing evaporation from the soil surface by 10 to 50% or more (10). Clear plastic mulch reportedly has the greatest effect on surface soil temperatures, raising them as much as 7° to 10° C above bare soil temperature (15, 26, 30, 33). Clear plastic allows the solar radiation to reach the soil surface, heating it directly (7, 13, 26, 36). Black plastic and black paper have a lesser effect because they absorb the radiation, rather than transmitting it to the soil, and the air layer beneath the mulch, which has a lower conductivity than either the mulch or the soil, inhibits the transfer of heat from the mulch to the soil (7, 26, 36). Black plastic may raise maximum soil temperatures 4.4° C when unshaded by plant canopies (11). Others

have found that black paper mulch increased soil temperatures only slightly above bare soil (33), less than 2° C (22). Soil under the black paper is often cooler than bare soil (11).

The differences in soil temperature and moisture due to mulching are not always great enough to account for the increases in yield. Sheldrake (29) suggested that CO₂ might also be responsible. He described the "chimney effect" created when CO₂ diffusing out of the soil becomes trapped under the mulch, builds up to relatively high levels, and escapes through the holes in the mulch around the plants. Using a Kittagawa^R gas detector, he measured CO₂ in the holes in the black plastic mulch and found 1300 ppm CO₂. He credited this four-fold increase in CO₂ concentration for the increased yield of melons grown with the mulch; however, the Kittagawa detector has been shown to be imprecise (28).

Hopen and Oebker tested the effect of CO₂ as it was influenced by several types of mulches on broccoli, lettuce, and cucumber (20). They collected CO₂ samples in flasks that were allowed to equilibrate for 1.5 hours and analyzed the samples for CO₂ content using an infrared gas analyzer. They found increased levels of CO₂ under the mulch; 630-670 ppm under black polyethylene and 445-514 ppm under poly-coated black paper. They tested the mulch materials for permeability to gas and found black polyethylene to be less permeable than poly-coated paper. The CO₂ levels measured over holes in the mulch

ranged from 360 to 390 ppm. Measurements were made only twice, at 12:40 p.m., on 2 dates. From these limited data, they concluded that CO_2 was not responsible for the increase in yield of all 3 species. Instead, they attributed yield increase to temperature and moisture differences caused by mulching, as have many others.

Ambient CO_2 content of air is generally considered to be 0.032% by volume, or 320 ppm. During the day, when photosynthesis occurs, CO_2 concentrations as low as 200 to 250 ppm have been measured in fields where crops were growing (8, 9, 25). These low CO_2 concentrations are limiting the photosynthetic efficiency of the plants under light intensities common in the field, since plants may become light saturated at only 10 to 20% of full sunlight at ambient CO_2 levels (5, 38).

The success of CO_2 enrichment for vegetable crops in greenhouses is well-documented (21, 37, 38, 39). Tomatoes respond favorably with large increases in yield, reflected in both size and number of fruit (3, 21, 38, 39). Carbon dioxide concentrations of 1200 to 1500 ppm have been recommended for tomato production greenhouses (3).

Considering the limiting effect of low levels of CO_2 in the field on photosynthesis, and the success of CO_2 enrichment of greenhouse atmospheres, surprisingly few attempts have been made to research CO_2 enrichment in the field (38). Results of a computer simulation of field enrichment predicted increased CO_2 uptake by a crop at 2

windspeeds of 100 and 600 cm sec⁻¹, at several heights within and above the plant canopy (2). This study determined that field enrichment would be inefficient, due to rapid mixing of the added CO₂ with the atmosphere (2). Other studies where CO₂ enrichment was actually tested under field conditions proved that increased yields can be obtained. Harper et al. (17, 18) released CO₂ into a field of cotton and raised the CO₂ concentration at three-fourths plant height to 450 ppm at solar noon, with average windspeeds of 134 cm sec⁻¹. That particular CO₂ enrichment study resulted in a 26% increase in photosynthate production (17, 18). Harper (16) in a study of CO₂ enrichment of cotton and Bermuda grass concluded that if economical supplies of CO₂ were available, field enrichment would be a feasible way to increase crop yields.

MATERIALS AND METHODS

Spring Giant Hybrid tomato seeds were planted in a mica-peat medium, in cell packs, in the greenhouse, on April 5. The seedlings were transplanted into beds 75 cm wide, on June 3. The plot area, 347 m², was divided into 8 single rows. Between row spacing was 2 m and within row spacing was 1 m. The 2 outside rows, north and south, and the 3 plants on the east and west ends of all rows were treated as guard rows and plants, and were eliminated from data collection.

Initial chemical properties of the clay soil were as follows:

pH (paste)	7.8
Conductivity (mmhos/cm)	2.7
Organic Matter (%)	2.4
NO ₃ -N (ppm)	37.0
P (ppm)	27.0
K (ppm)	443.0
Zn (ppm)	2.2
Fe (ppm)	11.2
Lime	high

One hundred and three kg ha⁻¹ of 16-20-0 fertilizer was added to the soil before planting.

The test plots were drip irrigated. The irrigation system consisted of 2 linear polyethylene drip irrigation tubes extending the length of each row, one tube on either side of the plants. These tubes were capped at one end and connected at the other end to one of two 1.25 cm I.D. poly-supply tubes; one for the mulched rows and one for the unmulched rows. At this connection a 0.95 liter per minute flow rate control device was inserted into each drip line. There were separate systems for each of the 2 treatments, mulch and non mulch, because mulch prevents evaporation from the soil surface, resulting in different irrigation schedules between mulched and unmulched. The poly-supply lines were connected by a 1.25 cm I.D. hose to the water supply. Two flowmeters were inserted into the line to monitor the amount of water applied in each irrigation. Tensiometers placed in the soil at depths of 10 and 30 cm were used to determine when irrigation was needed. When the soil matric potential at appropriate depth was -0.5 bars, (average of 6 tensiometers per treatment) a treatment was irrigated. Irrigation was terminated when tensiometers deflected. When the soil matric potential was less negative than -0.5 bars, it was assumed that enough soil moisture was available to all plants to eliminate soil moisture as a variable affecting plant growth either with or without mulch. The soil type is classified as a clay, composed of 26% sand, 31% silt, and 43% clay by weight. The moisture release curve is shown in Fig. 1.

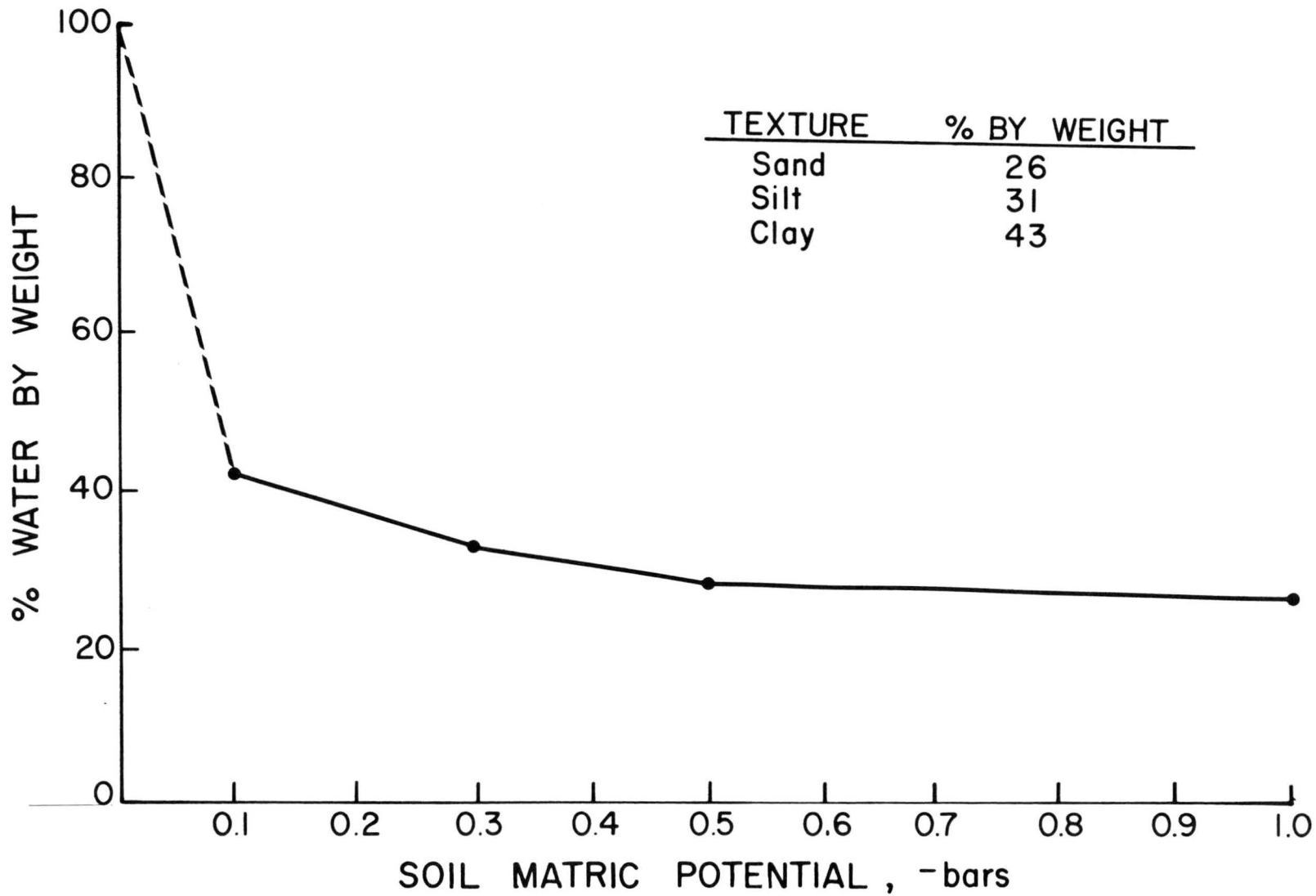


Figure 1. Soil moisture release curve.

The drip tubes in the unmulched plots were covered with 3 cm of soil, and the tubes under the mulch were not. It is recommended that the drip tubes placed under mulch also be covered with soil to prevent rodent damage.

The mulch was a paper material produced for agricultural use consisting of a 1 m wide layer of black paper with a 0.25 mil polyethylene coating on both sides. Prior to planting, the mulch was cut into 25 m lengths. Holes for the plants were punched out of the paper with a tool made from a 10 cm length of 9 cm I.D. pipe, sharpened at one end, and welded to a flat base at the other end. Holes 9 cm in diameter and 1 m apart on centers were thus provided. These pre-cut pieces of mulch were laid over the drip irrigation tubing on the soil surface, and anchored at the sides with soil. Seedlings were transplanted directly through the holes in the mulch, using a bulb-digging tool.

Weeds in the unmulched plots and in plant openings in the mulch were removed by hand.

Gas Sampling

Gas samples for CO₂ analysis were collected from the tomato plant canopies at 3-hour intervals over two 24-hour periods, on July 17-18, and September 11-12. Four plant canopies were sampled from each treatment at each time. Corresponding mulched and unmulched plants in each experimental unit were sampled simultaneously.

Samples were collected at 3 heights in the canopy; at the top (34 cm), in the middle (17 cm), and at the base (1 cm) of the plant. In the mulched rows, the basal samples were drawn directly over the center of the holes in the mulch paper.

Labeled 50 cc Plastipak^R syringes with 17-gauge hypodermic needles were used as the gas collection vessels. Neoprene stoppers were used to cap the needles to prevent gas leakage. Tests with calibrated gas showed no significant leakage within 3 hours.

One hundred cc gas samples were collected at each height in the canopy by holding two 50 cc syringes at the specified heights and pointing the tips of the needles toward the center of the plant, as shown in the photograph, Fig. 2. The plungers were then pulled back until at least 50 cc of gas had been collected in each syringe, and the needles were capped. Approximately 15 minutes were required to collect the samples. The samples were analyzed within 3 hours.

Gas samples were collected from the soil at 3 p.m. on September 14 and 15, using a method described by Hanan (14). Apparatus were constructed from 4 cm lengths of 1 cm I.D. glass tubing, sealed at one end with a one-hole stopper, and a 30-cm length of 1 mm I.D. poly-tubing extending through the stopper. The glass tubes were buried vertically with the open-end at 5 cm under the soil, with the poly-tube extending above the soil surface. Sampling tubes were positioned midway between 2 plants. The exposed end of the

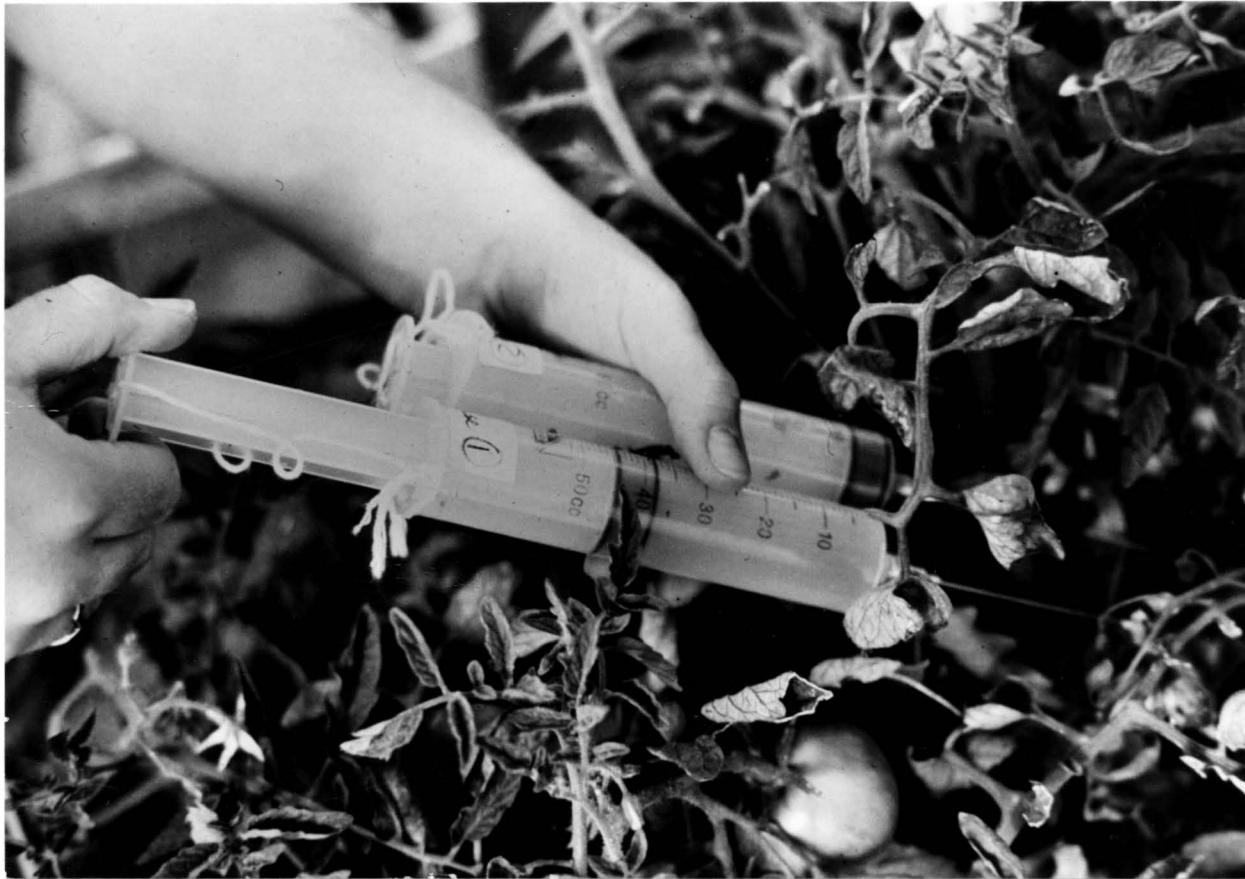


Figure 2. Canopy gas sampling.

poly-tubing was melted and pinched closed, to seal it from the atmosphere. This allowed air in the tube to equilibrate with the gases in the soil. To collect a sample, the melted end of the poly-tubing was cut off and an 18-gauge needle on a syringe was inserted into the tubing. After a 50 cc sample was collected, the needle was capped, and the tubing melted, thus resealing it.

Gas samples were collected from the air layer between the soil surface and the mulch, at 3-hour intervals over one 24-hour period, on September 11-12. The needle on a 50 cc syringe was punched through the mulch paper, midway between 2 plants, and a sample was drawn. Similar samples were collected over the bare soil, between plants from the unmulched rows.

Gas Analysis

Analysis of gas samples for CO_2 content may be accomplished in either of two ways. One involves drawing a continuous flow of air from the atmosphere being sampled. The stream of gas is then analyzed with an infrared gas analyzer. This method has been used by Brown and Rosenberg (6), and Monteith (24) to monitor CO_2 content of field air. This continuous flow infrared gas analysis method is accurate for measuring CO_2 levels near ambient concentration but requires the removal of large volumes of gas from the atmosphere being sampled.

Discontinuous sampling is another method and it involves collection of samples in containers for individual analysis. This method has also been used for analysis of field air (17, 20). The collection containers must be airtight to prevent leakage and contamination of the sample. Glass flasks (20), and polyethylene-aluminum-mylar bags (17) have been used successfully for this purpose. These individual samples can be analyzed with an infrared gas analyzer as described by Hopen (19), or be absorbed in a solution, precipitated, and titrated as described by Sharp (28).

Another discontinuous sampling method which was used by Sheldrake (29) in the field involves drawing a sample of gas through commercially prepared tubes of fine grain silica gel impregnated with a chemical that is sensitive to CO_2 . The crystals in the tube change color and the length of the stain indicates the CO_2 concentration in the gas sample (29). This method has the advantage of requiring small sample size, but is less accurate at low CO_2 concentrations.

Gas chromatography is designed for analysis of discontinuous samples. This method was chosen for the present study because it provided the greatest accuracy with the small volume samples being drawn from the plant canopy.

The gas samples were analyzed for CO_2 content with a Fisher-Hamilton Gas Partitioner #11-127, connected to a Hewlett-Packard 680 strip chart recorder. This gas partitioner was designed to

measure large concentrations of CO_2 in small volume (maximum 5 cc) samples. It was impossible to detect real differences as small as 5 ppm in a sample of 5 cc size. A sample loop was constructed in which the CO_2 from a larger sample could be condensed, and then analyzed. Using this method, the detection of small differences was accurate to ± 3 ppm. However, sampling variability in the field was ± 22 ppm.

The loop consisted of two 20 cm lengths and one 36 cm length of 2 mm I. D. stainless steel tubing. The long section was filled with crushed firebrick, and glass wool was inserted in both ends. It was then bent into a U-shape, with both sides even in length, and each end was connected to one of the shorter sections of tubing with Swagelock^R fittings.

The procedure for sample analysis required that the loop be partially immersed in a thermos of liquid oxygen (-183°C), [liquid nitrogen (-196°C) is not satisfactory] while the sample was passed through the loop. This condensed the CO_2 in the sample on the crushed firebrick inside the loop while most of the other gases in the air sample passed through. The liquid oxygen was then replaced by water containing ice, which caused the sample to vaporize. Simultaneously the sample was moved into the partitioner by activating a button on the control panel.

Samples should not be collected when the relative humidity is high, since water vapor condenses in the loop and interferes with CO₂ analysis. If this does happen, the loop must be dismantled and re-packed with dry firebrick.

The gas partitioner was set at an attenuation of 2 for the 100 cc samples from the plant canopy, and at 4 for the 50 cc samples from the soil-mulch interface, and from the soil. The flow rate of the helium carrier gas remained constant at 30 cc min⁻¹. The recorder was set at 1 millivolt input and a speed of 1 inch per minute.

Environmental Parameters

Soil and air temperatures, solar radiation, and windspeed were monitored during all canopy gas sampling periods. Iron-constantan thermocouples were placed at 3 heights: 5 cm below and 1 cm and 30 cm above the soil surface at 2 locations each, in both mulched and unmulched plots. The thermocouples were placed midway between plants to prevent shading by the plant canopy. A Leeds and Northrup^R 24-point recorder monitored the temperatures. Mean temperatures during each gas sampling period were reported.

Solar radiation was measured with a Mark IV Sola-meter^R (27). Instantaneous readings were taken at the beginning and end of each gas sampling period and an average radiation value was determined for each sampling period.

A Thermo-Systems, Inc. 4100 Digital Airflow Meter attached to a Hewlett-Packard 680 strip chart recorder monitored windspeeds during gas sampling. The sensor was mounted at a 34 cm height and aimed directly into the wind, to measure maximum windspeeds at the top of the canopy.

Plant Dry Weights, Green and Ripe Fruit Yields

A randomized complete block design shown in Fig. 3, was used to obtain vine dry weight and marketable fruit yields. The field was divided into 4 blocks, 4.57 x 10.97 m, and each block contained 3 experimental units, 4.57 x 3.66 m. An experimental unit consisted of a total of 10 plants; 5 mulched and 5 unmulched.

Eight weeks after transplanting, on August 8, 24 plants were removed from the field for dry weight measurements. One mulched and one unmulched plant from each experimental unit was included. All fruits were removed from the plants and placed in coded paper bags. The plants were then severed at the soil line. Plant tissue was dried in an oven at 65° C for 48 hours, and weighed on an 800 g capacity Mettler K-8 balance. The green and marketable fruit from these plants were counted and weighed separately. This procedure was repeated with the same design and number of plants on August 22.

A total of 24 plants, one mulched and one unmulched, from each of 12 experimental units, was selected prior to planting for marketable fruit harvests. Beginning on August 9 and continuing through

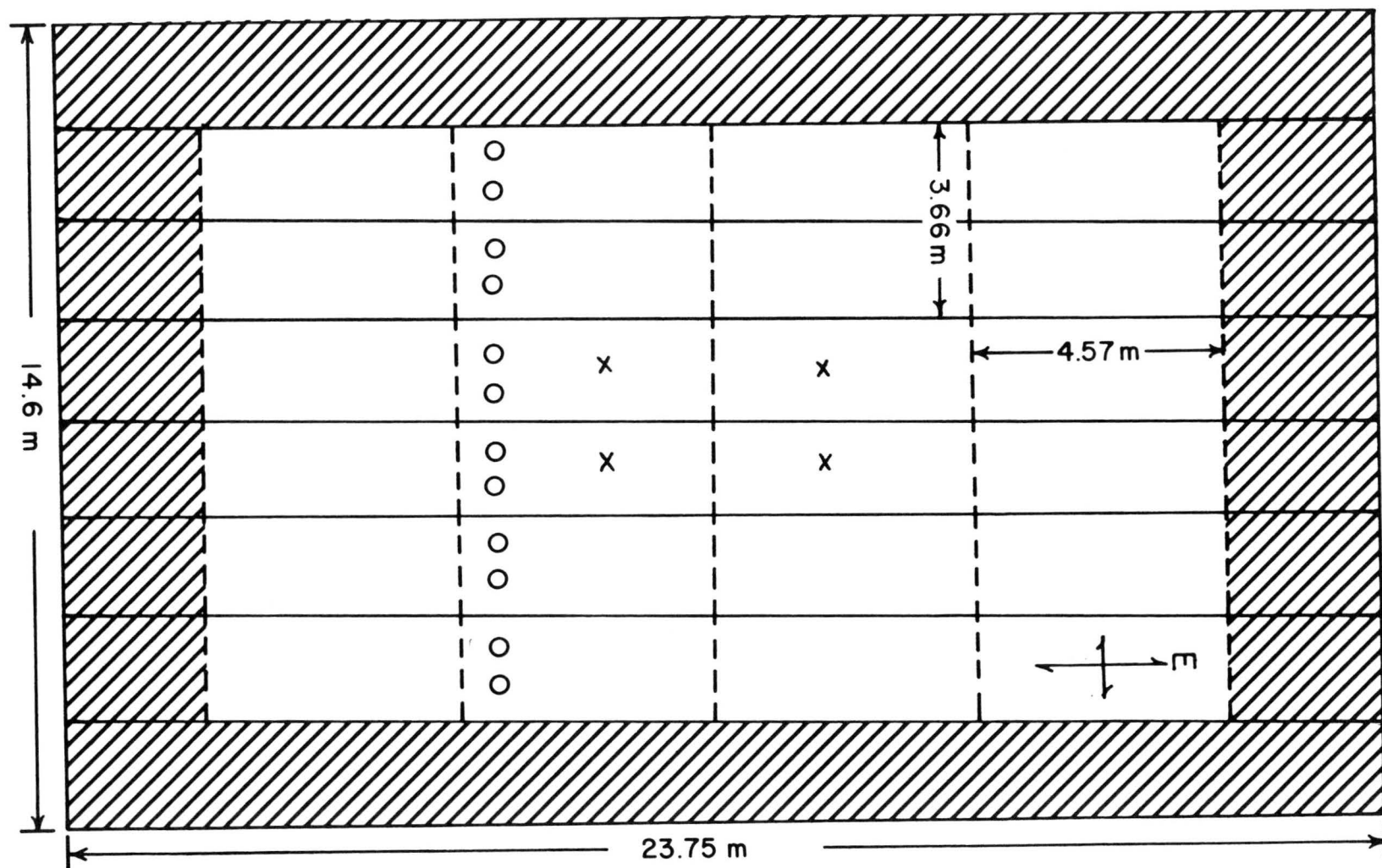





Figure 3. Field plot design with 3.66 m x 4.57 m experimental units.  - mulched areas;  - bare soil;  - guard rows and plants; 0 - tensiometers; X - thermocouples.

September 26, ripe tomatoes were harvested once a week from these 24 plants. The fruits from each individual plant were counted and weighed after each harvest.

RESULTS AND DISCUSSION

Corresponding CO_2 measurements with regard to 3 hour time intervals were not significantly different between sampling dates and were therefore combined. The only division of this data remained between the light and dark periods. The arithmetic means of the CO_2 concentrations at each height in the plant canopy are presented as profiles in Fig. 4, with 95% confidence limits. The CO_2 concentration at the base of the plants was significantly greater in the mulched plots, in both the light and dark periods. This represents an increase in CO_2 of approximately 21% during the light period and 10% in the dark, at the base of the plants. The relative difference in CO_2 levels between the mulched and unmulched plots was greater in the daytime due to warmer temperatures which would cause more CO_2 to be produced by the soil. The CO_2 levels in the canopy were greater in the dark, when both soil and above ground tissue respiration act as sources of CO_2 with no photosynthetic sink. The profiles above the bare soil appear as almost vertical lines, indicating no change in CO_2 concentration with increasing height. Profiles above the mulch show relatively high CO_2 concentrations near the base of the plants, which decrease with increasing height. The profiles over the mulch are similar in shape in the light and dark, but the decline in CO_2 with height is greater in the light. At night the decrease in CO_2 is due

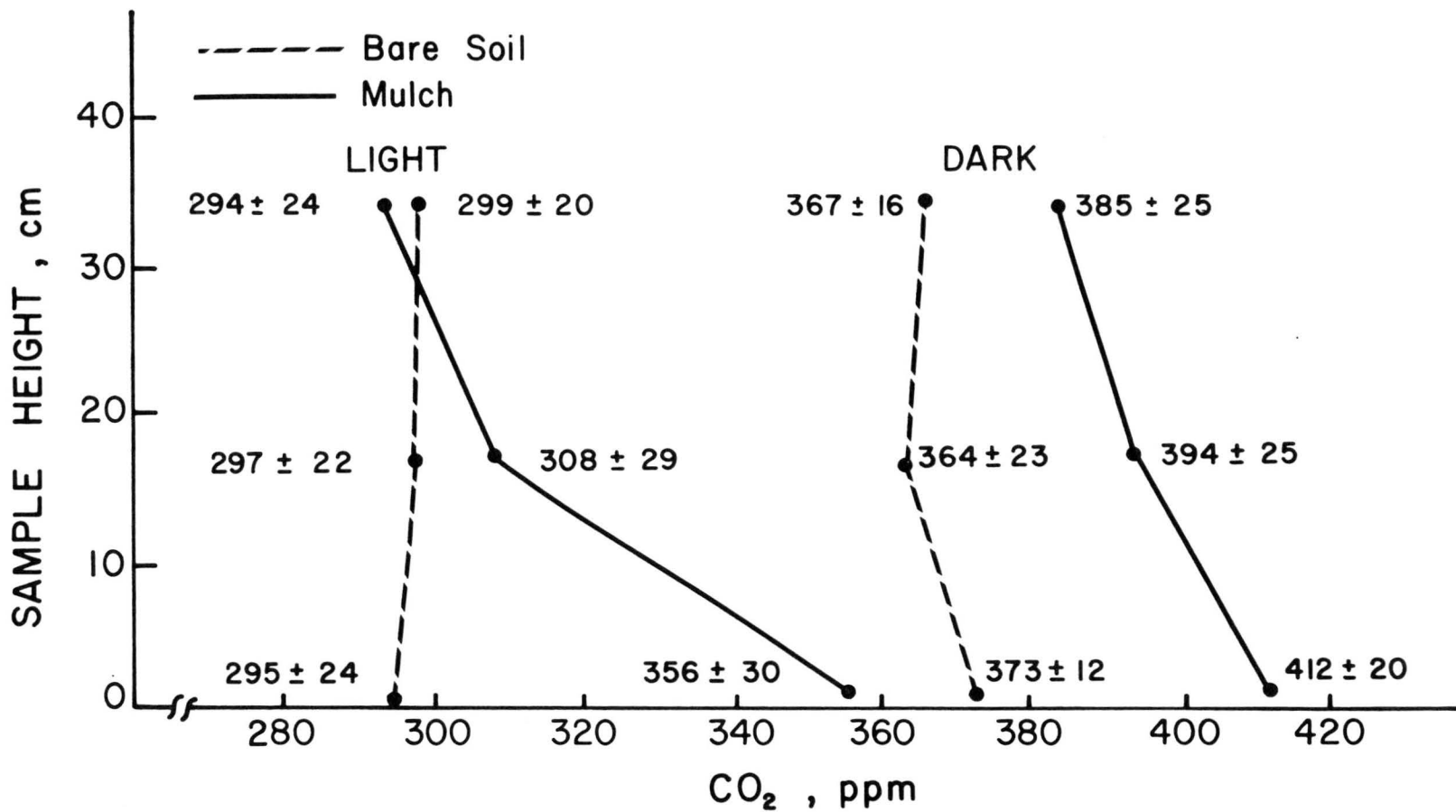


Figure 4. CO₂ profiles - mean CO₂ concentrations with 95% confidence intervals at 3 heights within plant canopy. Each mean represents 24 measurements, made on July 17-18 and September 11-12. Significant differences occurred between mulch and bare soil at the base during both light and dark periods.

only to mixing of the higher CO_2 concentrations, escaping from the hole in the mulch, with air outside of the canopy. However, in the light, photosynthesis, in addition to mixing, is responsible for the decrease in CO_2 with height.

The average CO_2 concentration for the entire profile in the dark was 369 ppm above the bare soil and 397 ppm above the mulch. The difference between these means is significant at the 1% level, indicating that there is a real increase in CO_2 above the mulch, especially in the dark when there is no CO_2 sink.

The CO_2 enrichment potential of the mulch was determined using mean CO_2 values presented in Fig. 4. The mulch caused a 5% increase in CO_2 at the top of the canopy (34 cm) in the dark, and a 21% increase at the base of the plants (1 cm) in the light. The 5% increase in CO_2 was measured when there was no photosynthetic sink, and without the warmer temperatures that would increase the rate of CO_2 production in the soil. This measurement, made at the top of the canopy to allow for dissipation of CO_2 with height above the soil, represents the minimum potential CO_2 enrichment for mature plants. The 21% increase in CO_2 was measured at the base of the plants where only a small photosynthetic sink exists. The warm daytime temperatures would increase CO_2 production in the soil. Thus, the 21% value represents the maximum potential enrichment due to the mulch during seedling growth when plants benefit most from added

CO₂ (39). The 5 to 21% increases in CO₂ concentration above the mulch provide an approximate range of the CO₂ enrichment potential of a mulch which is relatively impermeable to CO₂.

Mean CO₂ concentrations at the top of the canopy, shown in Fig. 5, reached a maximum of 385 ppm at 3 a.m., and dropped to a minimum of 285 ppm at 3 p.m. MDT. One hour should be subtracted from all times mentioned from this study to convert to apparent solar time. Brown and Rosenberg (6) measured similar maximum CO₂ values between 4 and 5 a.m., and minimums between 12 a.m. and 3 p.m.

Temperatures at a 30 cm height in the plant canopy are also shown in Fig. 5 as they were measured during two 24-hour sampling periods. The temperatures were the same in both mulched and unmulched canopies at this height and were within the 20° to 30°C range considered optimum for photosynthesis. Solar radiation measurements made on these same 2 days also appear in Fig. 5. The minimum light intensity measured between 9 a.m. and 3 p.m. was 0.5 langley's minute⁻¹.

Bohning and Burnside (4) found that tomato plant leaves became light saturated between 2000 and 2500 ft. c. [approximately 0.29 to 0.37 langley's min⁻¹ (12)] at CO₂ concentrations of 270 ± 30 ppm. In the present study, for a period of at least 6 hours the irradiance was greater than the light saturation value for tomato plant leaves when

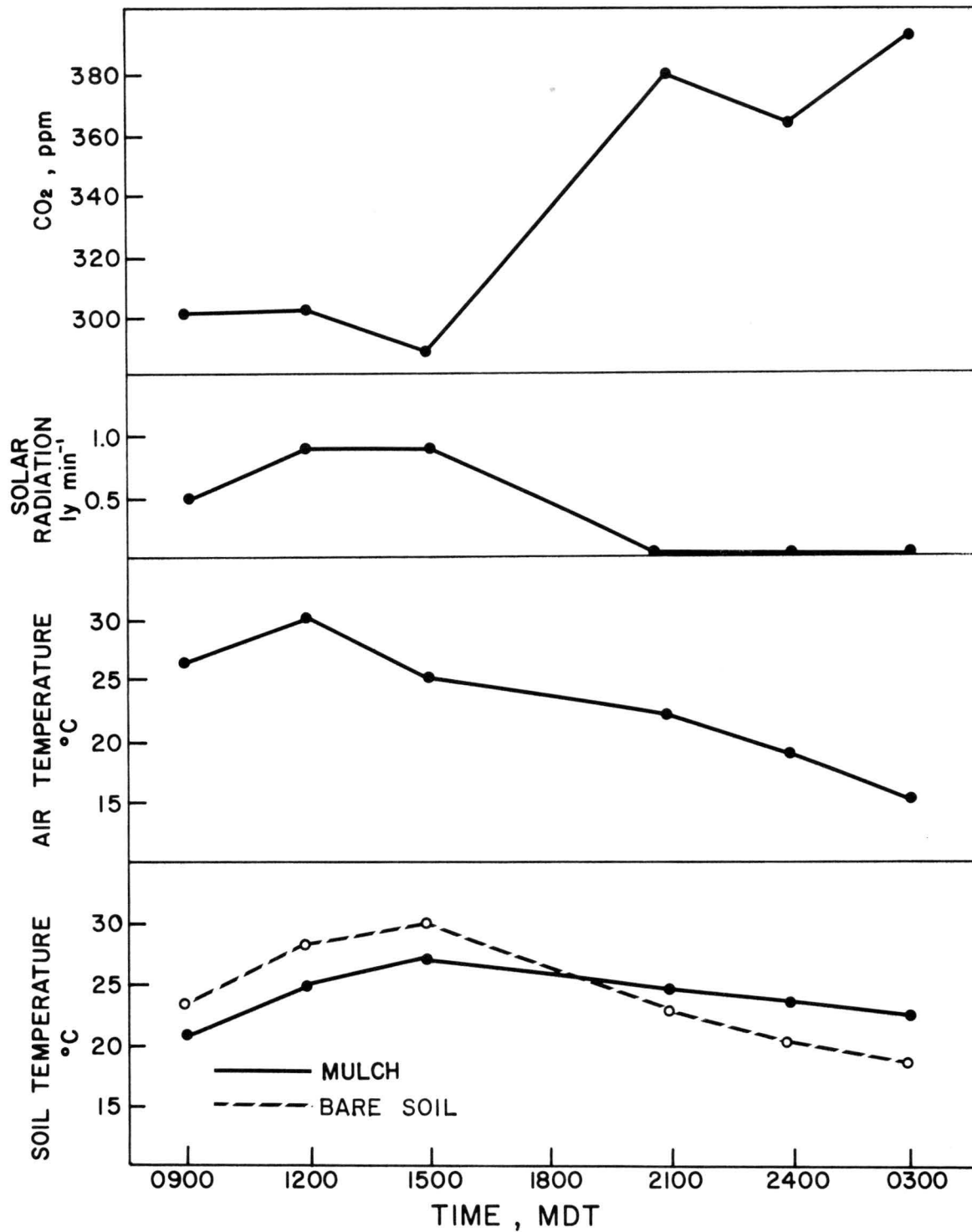


Figure 5. Mean CO₂ concentration, radiation, air, and soil temperatures - measured at 3-hour intervals on July 17-18 and September 11-12. Air temperatures were measured at 30 cm height and soil temperatures were measured at 5 cm depth.

the mean CO_2 concentration ranged from 285 to 300 ppm, as shown in Fig. 5. This supports Bonner (5) and Wittwer's (38) conclusions that light saturation of the plants occurs at a fraction of full sunlight at ambient CO_2 levels. Thus, CO_2 levels in the field are limiting to photosynthesis under normal sunlight. This indicates that tomato plants would benefit from increased levels of CO_2 if a system of field enrichment could be developed. Enrichment of a greenhouse atmosphere to 1000 ppm CO_2 increased tomato plant dry weights under low ($0.07 \text{ langleys min}^{-1}$) light conditions (39). With the same level of CO_2 enrichment, plant growth was increased even more at a higher light intensity [$0.22 \text{ langleys min}^{-1}$ (12)] (39), which is still only a fraction of the irradiance levels usually occurring in the field.

The CO_2 measurements made in the air layer between the soil and the paper mulch were compared to measurements made at the bare soil surface. The mean CO_2 concentration in 24 samples collected under the paper was 532 ppm, compared to 353 ppm above the bare soil. Thus, the CO_2 concentration under the mulch was significantly greater at the 5% level. Similar CO_2 values (514 ppm) have been measured under poly-coated black paper by Hopen and Oebker (20). Higher CO_2 concentrations (670 ppm) were found under black polyethylene film. Those values were probably higher because polyethylene film is less permeable to CO_2 than the poly-coated paper

(20). In all cases, this indicates a buildup of CO_2 under the mulch as it diffused out of the soil.

Carbon dioxide concentrations were measured at a depth of 5 cm in the soil. The mean of 12 measurements taken from the soil under the mulch was 1033 ppm, and from the bare soil was 603 ppm.

Carbon dioxide levels in the soil range from 0.1% to 5% (32). Carbon dioxide concentrations are often lower in the topsoil due to diffusion into the atmosphere (32). The measurements taken in this test were made very near the soil surface, at a 5 cm depth, and this could account for the relatively low CO_2 concentrations. The CO_2 concentrations in the mulched soil were significantly greater at the 5% level, even at the 5 cm depth, indicating that the mulch decreases the diffusion of CO_2 from the soil into the atmosphere, concentrating it in the upper soil strata.

Lundegardh (23) and Stolwijk and Thimann (31) indicate that 1% CO_2 (10,000 ppm) is the minimum concentration in the soil that may have an adverse effect on plant growth. However, insufficient oxygen levels seem to be more harmful than the buildup of CO_2 since it has been suggested that plant roots can tolerate much higher concentrations of CO_2 if the O_2 level in the soil is sufficient (32). Oxygen concentrations less than 15% in the soil constitute a deficiency for plant growth if the remainder of the gas composition is nitrogen (32).

Soil temperatures measured on July 17-18, and September 11-12 are plotted in Fig. 5. On both dates the temperature was lower in the mulched soil during the light period, and slightly higher than the bare soil in the dark. This effect of paper mulch on soil temperatures is similar to that of black plastic for which the following explanation has been given (7, 26, 39). The black surface is opaque to incoming radiation and absorbs it rather than transmitting it to the soil underneath. The mulch itself becomes warm and loses some of the heat by thermal radiation to the atmosphere. Heat transfer from the warm mulch surface to the soil is inhibited by the air layer between the mulch and the soil, which has a much lower heat conductivity than the mulch. Thus, while the mulch becomes heated, the soil beneath does not. Also, if the soil beneath the mulch is wetter than the bare soil, as is common since mulch decreases evaporation, more energy is required to heat wet soil due to the high specific heat of water. The mulched soil remains warm at night because the air layer between mulch and soil prevents the transfer of the soil heat to the atmosphere. Courter and Oebker (11) found that maximum soil temperatures under black paper mulch were most often lower than in bare soil, while minimum soil temperatures were higher under mulch than in bare soil. This is evidence that the mulch decreases the fluctuation of soil temperatures.

With regard to soil temperature differences on plant growth responses; the mulched soil was warmer only at night, when respiration takes place. The higher temperatures under the mulch would increase root respiration, having a negative effect on plant growth. Therefore, soil temperatures should not be responsible for the increased growth of the mulched plants.

Windspeed has an important effect on CO_2 concentrations in and around the plant canopy. Figure 6 shows the relationships between windspeed and CO_2 concentration at the top of the plant canopy at night, when CO_2 depletion due to photosynthesis is eliminated. Brown and Rosenberg (6) recognized a strong negative correlation between windspeed and nocturnal CO_2 concentration. A similar relationship was observed in the present experiment. The CO_2 concentration decreased toward ambient level in a linear fashion as the windspeed increased up to 134 cm/sec. At windspeeds above 134 cm/sec, the increase in CO_2 resulting from plant and soil respiration is eliminated, since the CO_2 is more rapidly mixed with the atmosphere. Harper et al. (17, 18) in their field CO_2 enrichment study with an average windspeed of 134 cm/sec, measured a CO_2 concentration of 450 ppm, at solar noon, at three-fourths plant height. This indicates that with a higher source level of CO_2 , windspeeds greater than 134 cm/sec would be needed to decrease the CO_2 concentration to ambient levels.

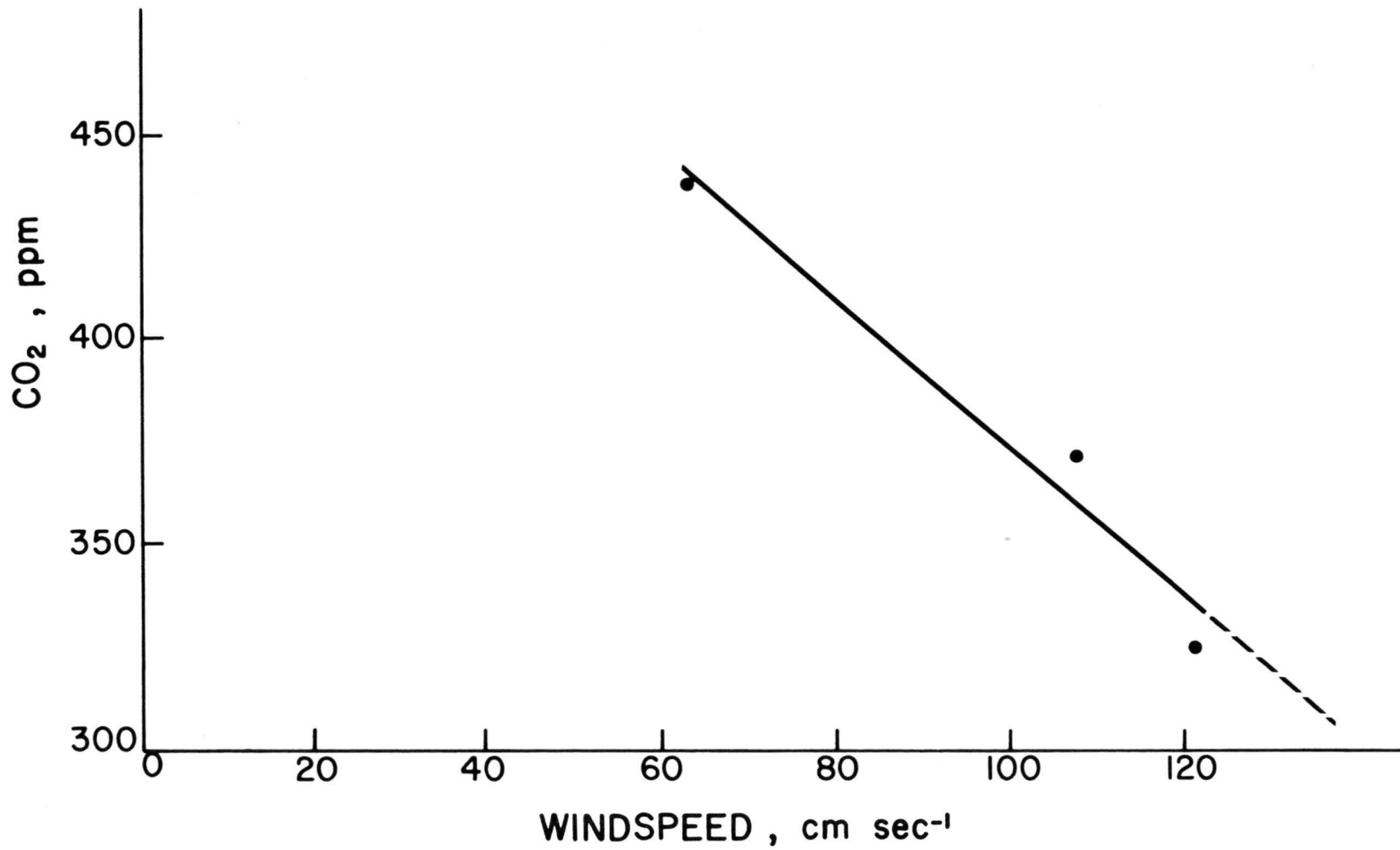


Figure 6. Mean nocturnal CO₂ concentration as a function of mean windspeed. Each CO₂ value represents 8 measurements made at the top of the canopy between 9 p.m. and 2 a.m. on July 17-18.

The plant dry weight data collected on August 9 and 22 are shown in Fig. 7. The mean dry weight of the mulched plants reflects an 18% increase over the unmulched plants. This is an indication that the mulched plants had a higher net CO_2 assimilation during the same growing period. The increase in plant tissue in the mulched plots could provide a greater sink for CO_2 in the light, and a greater source of CO_2 in the dark relative to the bare soil plots. Solar radiation was the same for all plants and soil nutrient levels were identical. Similar soil-water relations were maintained through separate irrigation systems. Temperatures were similar in the canopy and warmer in the mulched soil only at night. This suggests that differences in plant growth reflected in the plant dry weights are due not to light, temperature, water, or soil nutrients, but mainly to CO_2 concentrations which were found to be greater over the mulch.

Green fruit removed from the dry weight plants were counted and weighed, and this data appears in Fig. 8. There were significantly greater numbers of fruit and fruit weights with respect to the mulched plots on both dates. The weight per fruit was not significantly greater on either date. This indicates that a greater number of green fruit per plant was principally responsible for the increased yield of the mulched plots. This agrees with Vandenberg and Tiessen's observation (35) that mulch increases the number of flowers and fruit set on tomato plants; however, these results differ from the marketable fruit data collected from the same plots on later dates.

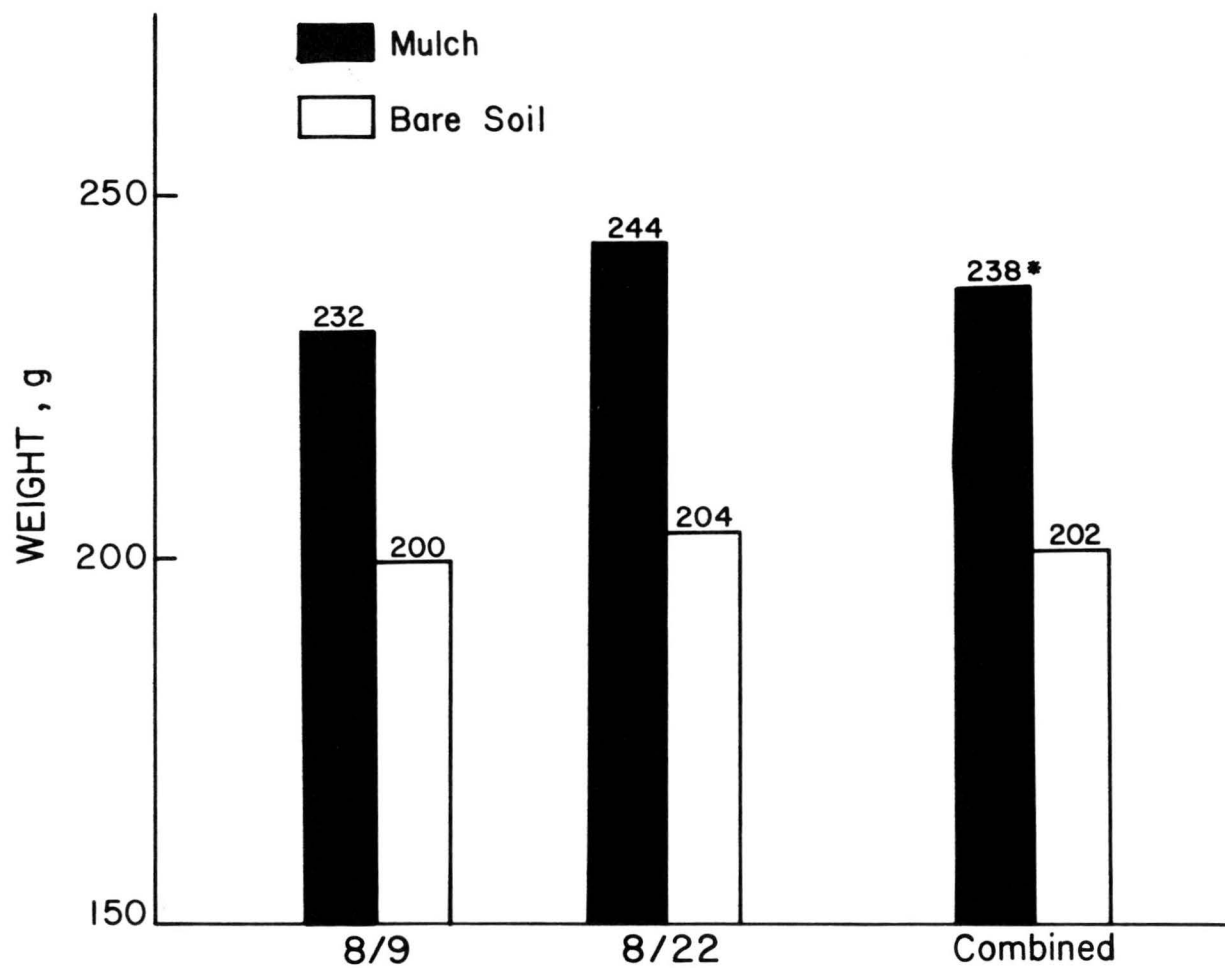


Figure 7. Mean plant dry weight data excluding fruit, collected on 2 dates. Means for individual dates represent 12 measurements. * Indicates a significant increase in the mulched plots at the 5% level.

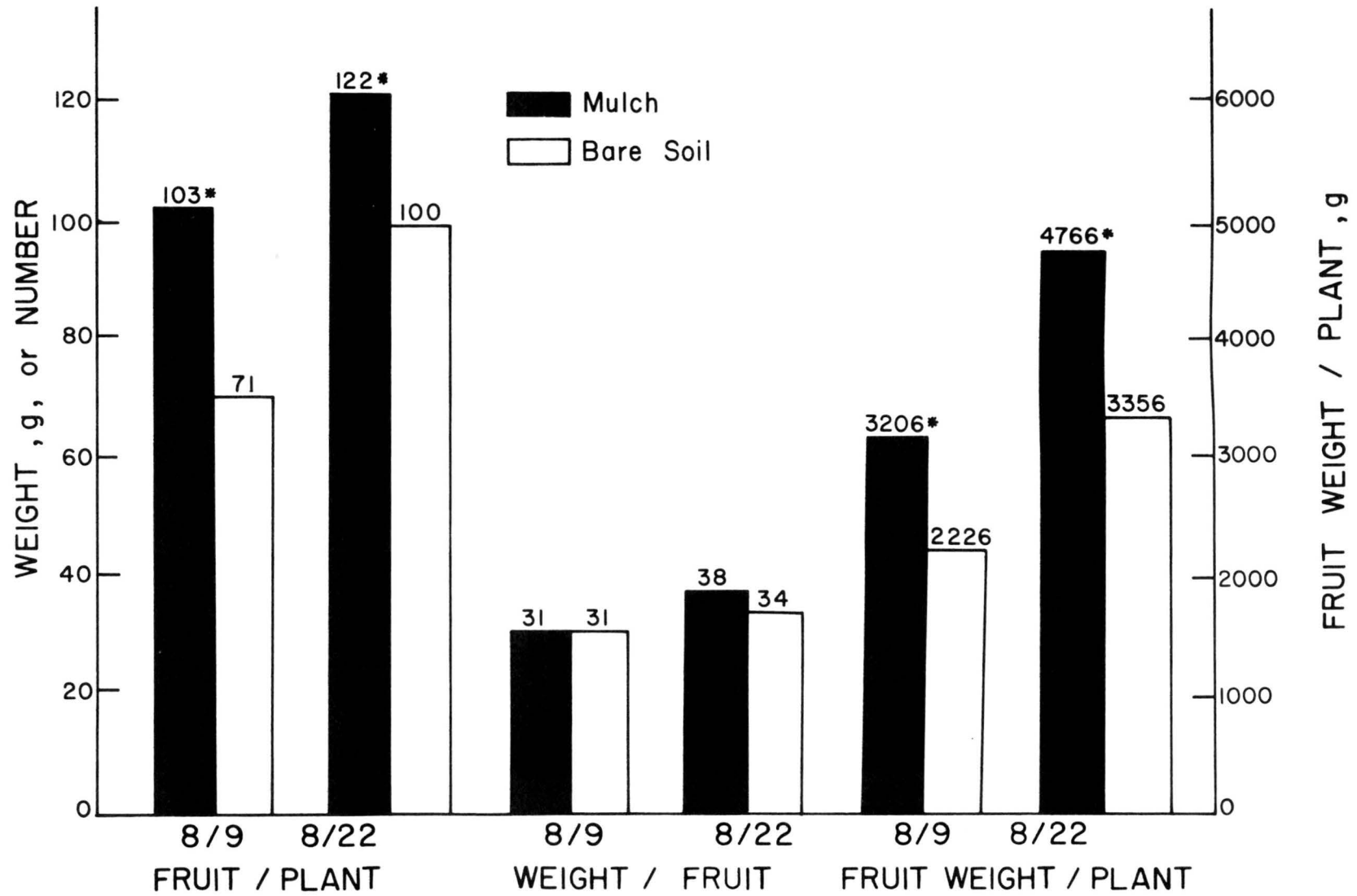


Figure 8. Green fruit data including numbers and weights. Each mean represents 12 measurements. * Indicates significant increase at 5% level.

Marketable tomatoes were harvested over an 8-week period, and these data appear in Figs. 9, 10, 11, and 12. The number of fruit per plant was not significantly greater in the mulched plants over the entire harvest period. However, more fruit were harvested from the mulched plants every week except the 5th and 6th weeks. The total weight of fruit harvested per plant was greater in the mulched plots by 36%. The mulched plants show a significant increase in mean weight per fruit, producing fruit that averaged 23% heavier. This indicates that the increased yield was due in large part to increased fruit size. However, an increased number of fruit shown in Fig. 11 may be partly responsible for the larger yields.

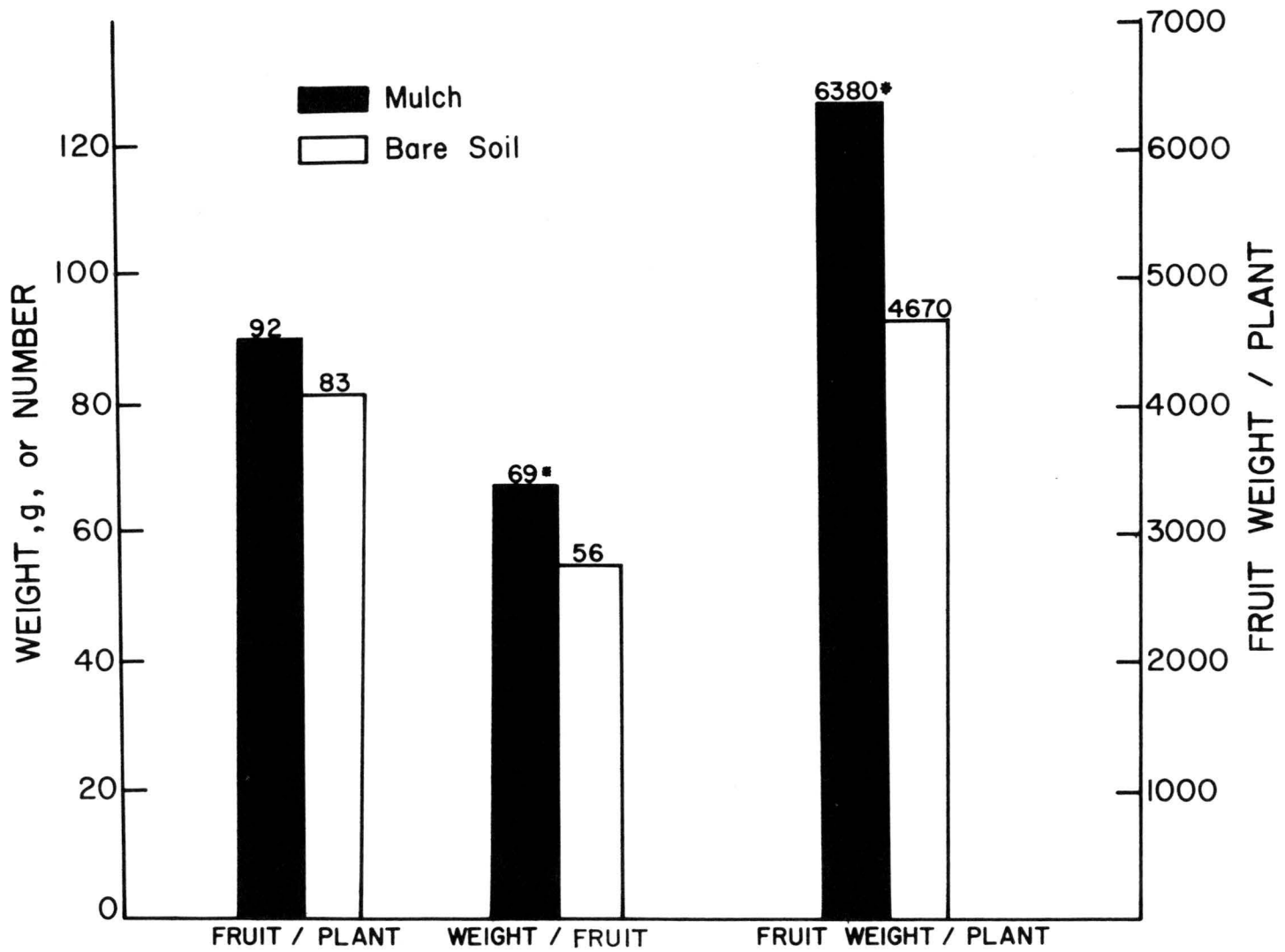


Figure 9. Mean totals of marketable fruit harvested between August 8 and September 26. Each mean represents 96 measurements. * Indicates a significant increase at the 5% level.

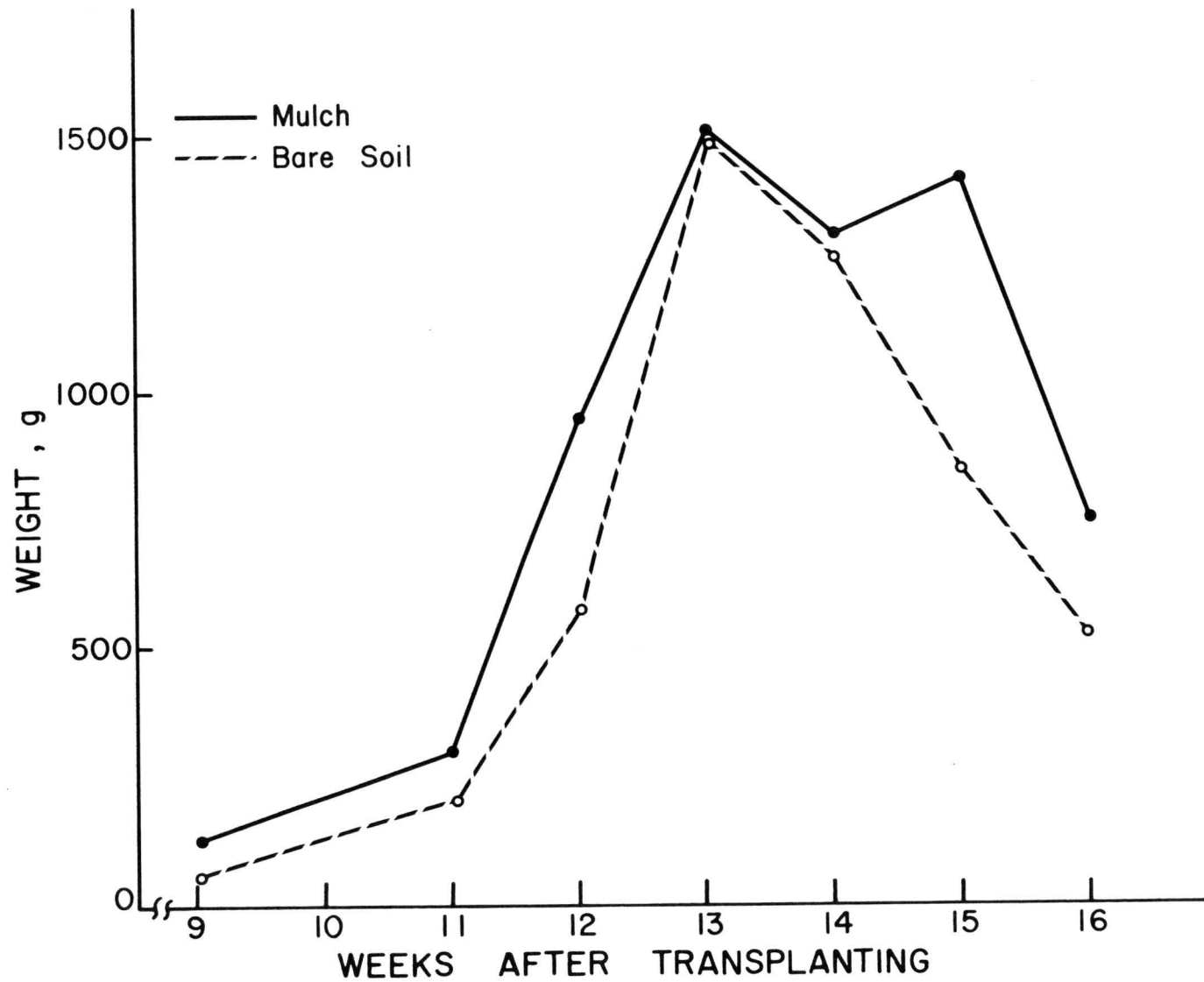


Figure 10. Mean weights of marketable fruit per plant on a weekly basis. Each mean represents 12 measurements.

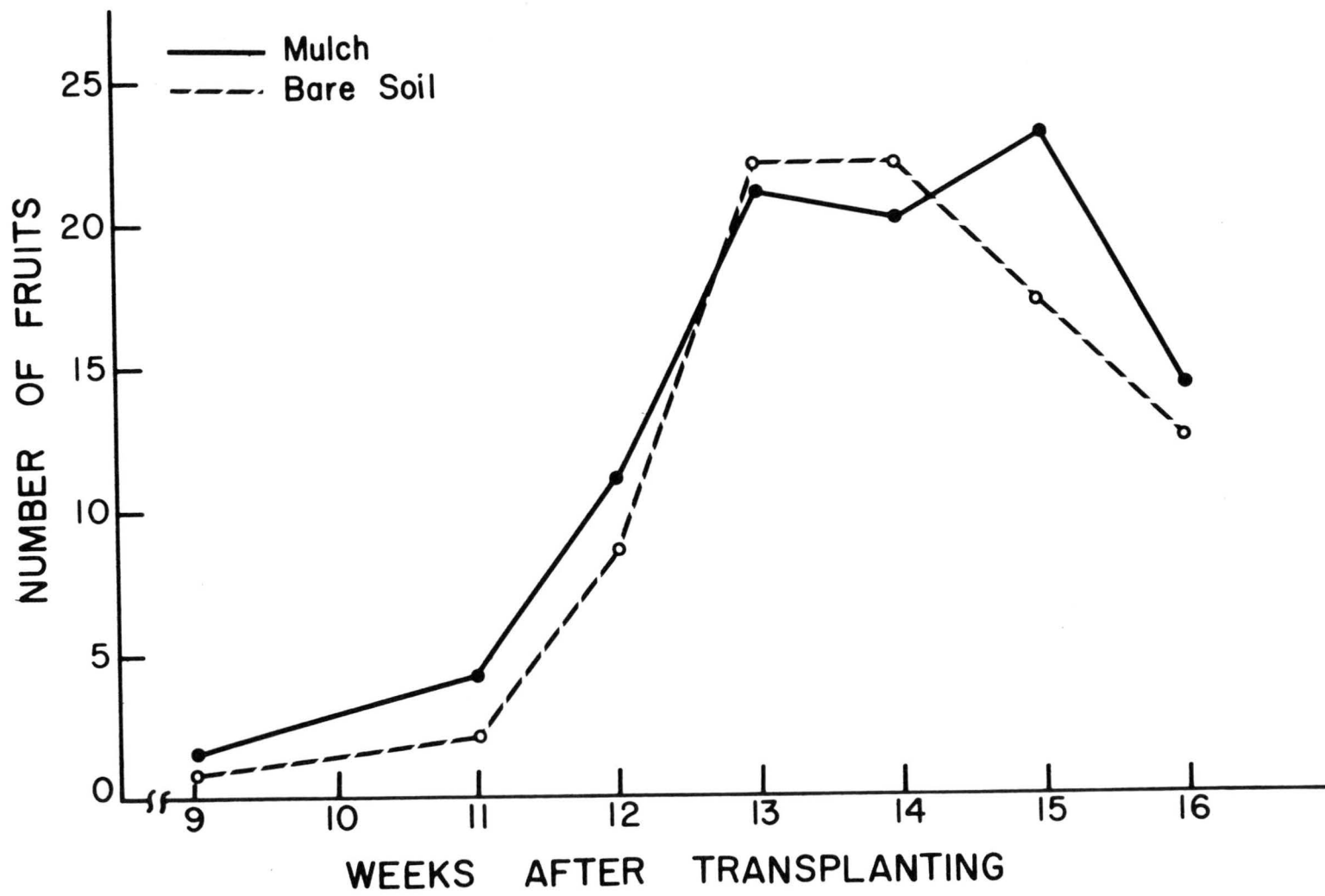


Figure 11. Mean numbers of marketable fruit per plant on a weekly basis. Each mean represents 12 measurements.

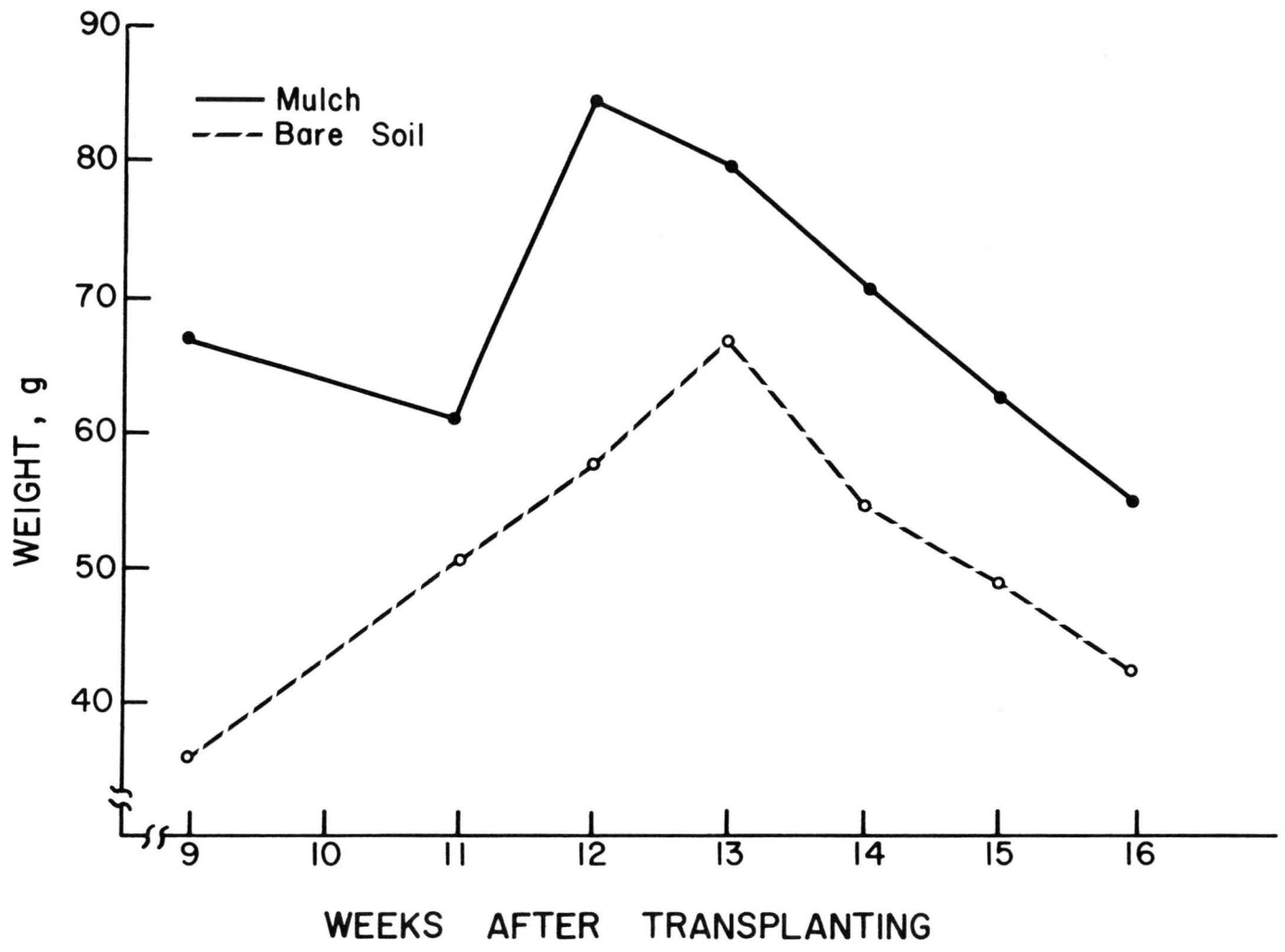


Figure 12. Mean weight per fruit on a weekly basis. Each mean represents 12 measurements.

SUMMARY AND CONCLUSIONS

Mulching with poly-coated black paper did increase tomato plant growth as shown by greater plant tissue dry weights. Mulching also increased the marketable fruit yield 36% by weight. The fruits from the mulched plants were larger and, in some cases, there were more fruit per plant.

Temperatures measured at a 5 cm depth in the soil under the mulch were slightly lower during the day and higher at night than in the bare soils; however, these differences were not significant. Temperatures near the top of the canopy were the same for the mulched and unmulched plots.

Carbon dioxide levels measured at the base of the plants were significantly greater over the mulch. This resulted from CO₂ accumulation in the soil under the mulch and between the soil surface and the mulch. Carbon dioxide levels in the plant canopies were greater at night when no photosynthesis occurred. The nocturnal buildup of CO₂ was dissipated by windspeeds greater than 134 cm/sec.

Carbon dioxide enrichment ranged from 5% to 21% in the micro-environment of the plant canopy. The mean CO₂ concentrations for the entire canopy profile at night showed a 7% increase due to the mulch. This was significant at the 1% level of probability.

Considering the supraoptimal insolation levels and the sub-optimal CO₂ concentrations measured in this experiment, the mulch, which is relatively impermeable to CO₂, caused a substantial increase in plant growth and development. Since mineral nutrition, soil moisture, and soil temperature were eliminated as variables affecting plant growth, it was concluded that the accumulation of CO₂ under the mulch, and its subsequent release at the base of the plants was largely responsible for the observed increased growth and yield of mulched tomato plants.

Previous research involving "compressed" CO₂ sources and relatively low value agronomic species points out that yields can in fact be increased. However, the implied dollar return does not appear favorable. Considering the CO₂ enrichment potential of mulch, which takes advantage of the natural respiratory supply of CO₂, and the resulting yield increase; the possibility of employing additional below mulch sources of CO₂ becomes attractive. Carbon dioxide impermeable mulch over incorporated plant residue would warrant investigation. Also, the possibility exists for utilizing established drip irrigation systems for CO₂ release under mulch. If CO₂ were released along the entire length of the tubing and a relatively impermeable mulch was used in conjunction with the release system, it would provide wider "chimneys" or columns of concentrated CO₂ than from a point source. This might result in greater

recovery of the added CO₂ by the plants, increasing the efficiency of a field CO₂ enrichment system.

These approaches might provide the best economic climate when applied to relatively high value horticultural food crops and/or species requiring accelerated growth and development in short season but high insolation areas such as the high elevation vegetable producing areas of the west.

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