

Carbon Dioxide Partial Pressure in Lysimeter Soils¹

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ABSTRACT

The carbonate chemistry portion of mechanistic salinity models is generally the weak link in describing salt reactions in soils. This is primarily due to a lack of available soil atmosphere CO₂ data. Carbon dioxide concentrations were measured at 0.25, 0.50, and 0.75 m depths in 0.30 m diam lysimeters containing 1.0 m of sodic soil. Four non-cropped treatments included a check, gypsum, fresh manure, and chopped alfalfa irrigated weekly with 70 mm (5.0 l) of tap water (EC=0.7 and SAR=1.7). Six cropped treatments included barley (*Hordeum vulgare*), alfalfa (*Medicago sativa* L.), Sordan [Sordan is a trade name for a sorghum (*Sorghum bicolor*), sudangrass (*Sorghum sudanese* hybrid)], Sordan + leaching, cotton (*Gossypium hirsutum* L.), and tall wheatgrass (*Agropyron elongatum*). The cropped lysimeters were irrigated at 1.25 times the consumptive use since the previous irrigation (0.20 leaching fraction). Soil P_{CO₂} values were decreased by the gypsum treatment and increased by all other treatments as compared to check. Cotton and barley had the lowest P_{CO₂} values for the cropped treatments and Sordan had the highest (frequently above 16 kPa). The P_{CO₂} levels were affected by applied organic matter source, crop, plant growth rate, irrigation water application and leaching.

Additional index words: Carbonate, Bicarbonate, Soil Aeration, Soil Air.

CARBON dioxide partial pressure (P_{CO₂}) is one of several factors that control soil solution pH and calcium ion activity (Ca²⁺) in calcareous and sodic soils. The reason is because CO₂ dissolves in water and forms carbonic acid (H₂CO₃) which, in turn, dissociates to form hydrogen (H⁺), bicarbonate (HCO₃⁻), and carbonate (CO₃²⁻) ions. The total concentration of HCO₃⁻ and CO₃²⁻ anions, the ratio between the two, and the sodium ion concentration to a great extent, controls the pH of arid and semiarid soils. The CO₃²⁻ ion activity also reacts with Ca²⁺ to control its activity (Robbins, 1985; Tanji and Doneen, 1966).

Soil salinity models designed to describe salt reactions in high pH soils require modeling carbonate chemistry, and consequently P_{CO₂} data for the soil atmosphere must be calculated or supplied (Oster and Rhoades, 1975; Robbins et al., 1980; Suarez, 1982). Considerable information is available on the effect of time, temperature, moisture, and organic matter on P_{CO₂} in laboratory soil samples (Enoch and Dasberg, 1971; Yamaguchi et al., 1967) and on soil surface flux of CO₂ under field conditions (de Jong et al., 1974). However, only limited soil atmosphere CO₂ data are available for soils containing growing crops.

The purpose of this study was to collect and compare the soil atmosphere CO₂ partial pressure data from four non-cropped and six crop treatments under greenhouse lysimeter conditions where water applications, temperatures and soil type would be similar for all treatments.

MATERIALS AND METHODS

The surface 0.15 m of a Freedom silt loam (fine-silty, mixed, mesic, Xerollic Calciorthids) soil was used in the lysimeter study. The soil was taken from an area that had not been irrigated or cultivated and was sodic in the surface. The exchangeable sodium percentage (ESP) was 33, the cation exchange capacity (CEC) was 210 mmoles of charge per kg,

the saturation paste pH was 8.6 and the saturation paste extract electrical conductivity was 2.4 dS m⁻¹.

The 1.18 m deep lysimeters were constructed from 0.30 m ID polyvinylchloride irrigation pipe. A 0.05 m layer of coarse sand was placed in the bottom of each lysimeter over a drain tube. The soil was then added and vibrated until a 1.0 m depth of soil was compacted to a bulk density of 1.35 Mg m⁻³. Heavy walled glass sampling tubes (13 mm ID by 0.20 m long) were then inserted 0.15 m into the side ports at 0.25, 0.50, and 0.75 m below the soil surface. The inside end of the tube was left open and the outside end was covered with a rubber septum for gas sampling. The lysimeters were on a hydraulic weighing system used to measure evapotranspiration, irrigation, and drainage (Robbins and Willardson, 1980). The study was conducted in a partly temperature-controlled greenhouse with supplemental lighting from 1 October to 1 April.

Each of 10 treatments was duplicated. The four non-crop treatments included a check, 5.0 kg gypsum m⁻², 5.0 kg chopped alfalfa (*Medicago sativa* L.) m⁻², and 5.0 kg fresh manure m⁻². Gypsum, chopped alfalfa, and manure were completely mixed with the surface 0.20 m of soil. The gypsum rate was equal to 1.25 times the exchangeable sodium in the upper 0.50 m on an equivalent basis. The alfalfa and manure were applied on an air dry basis (oven dried at 55°C). These four treatments were irrigated every 7 days with 70 mm (5.0 L) of tap water (EC = 0.7 ds m⁻¹ and SAR = 1.7) until the infiltration rate decreased to below 70 mm in 5 days. The six cropped treatments were barley (*Hordeum vulgare*), alfalfa, Sordan [Sordan is a trade name for a sorghum (*Sorghum bicolor*), sudangrass (*Sorghum sudanese*) hybrid], Sordan + leaching, cotton (*Gossypium hirsutum* L.), and tall wheatgrass (*Agropyron elongatum*). Two lysimeters were irrigated the same as the check until it took more than 5 days for 70 mm of water to enter the soil. Sordan was then planted and this treatment was designated as the leached + Sordan treatment. The rest of the crops were planted three days after a 140 mm (10 L) tap water irrigation and then covered for 4 days with aluminum foil. By that time the crops had emerged. All crops were then irrigated at 1.25 times the consumptive use (0.20 leaching fraction) since the last irrigation on a semiweekly, weekly, or biweekly schedule, depending on water use rate of a particular crop. The leachate water was collected and the volume measured and subtracted from the irrigation water volume to calculate evapotranspiration.

The whole barley plants were harvested at maturity and then replanted to barley 2 weeks later. Three crops were grown. The second and third crops were fertilized with 2.1 g of ammonium nitrate (100 kg N ha⁻¹) at planting time. After the third barley crop was harvested, those two lysimeters were irrigated with 1.25 times the volume of water used since the last irrigation and were then planted to tall wheatgrass. The tall wheatgrass was planted 14 days after the third barley crop was harvested and three days after the lysimeters had been irrigated. The grass was harvested four times when it was 0.5 m tall. Four alfalfa crops were grown and harvested at full bloom. The Sordan was cut four times when most of the seed heads were at hard dough stage and were also fertilized with 2.1 g of ammonium nitrate (100 kg

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N ha^{-1}) after each cutting. The cotton was allowed to grow until all bolls were ripe and the leaves had started to drop and new leaf buds started to form.

Duplicate carbon dioxide samples were initially taken at the three depths with a 20 mL syringe and needle through the septum covered glass port. A 15 mL sample was stored in 10 mL evacuated vials coated with paraffin to reduce sample leakage. The gas samples were then analyzed with a Hewlett Packard 5730A Gas Chromatograph³. Later, 5 mL samples taken directly from the glass sampling tubes were analyzed with a Microtechnology 500³ portable gas microchromatography unit.

³ The use of brand names is for the reader's convenience and does not imply endorsement of these instruments over any other by the authors or sponsoring institution.

Initially the samples were taken daily. When it became evident that the CO_2 levels in the soil air followed a cyclic pattern following each irrigation, after 2 months, samples were not taken on weekends. Samples taken on irrigation days were always taken before the water was applied. Samples were not taken for several days on some treatments due to problems with analytical equipment.

RESULTS

Carbon dioxide partial pressure values agreed very well between duplicate treatments (± 5 to $\pm 15\%$) for a given time and depth, except for the first Sordan grass crop. One Sordan lysimeter went anaerobic for a short period due to a plugged drain tube, thus causing

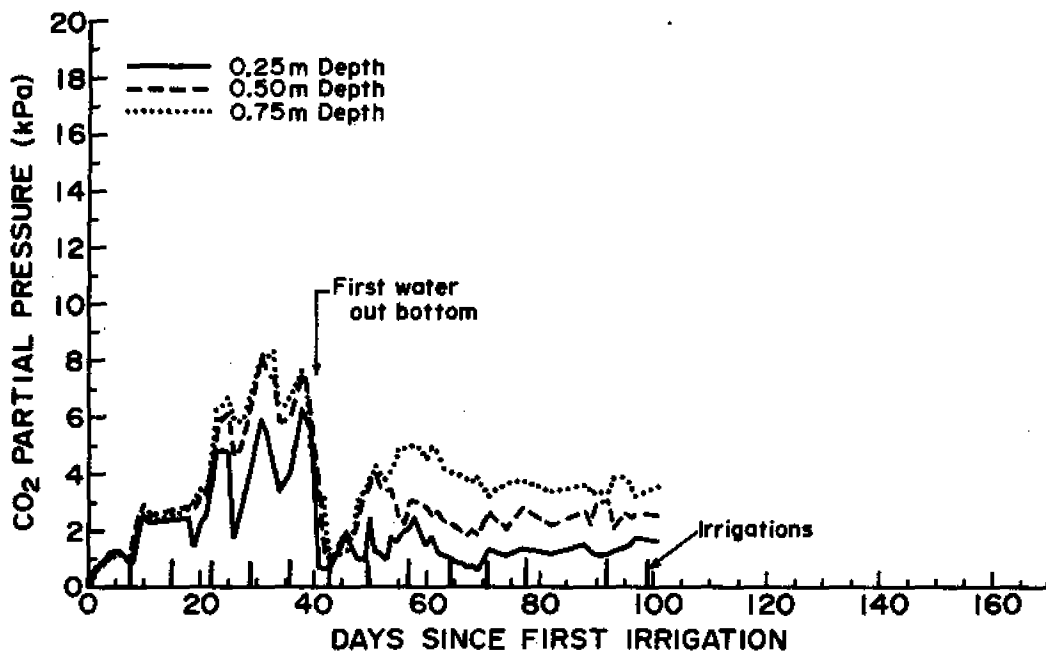


Fig. 1. Carbon dioxide partial pressure at three depths for the check treatment. Irrigation frequencies are shown by the longest vertical lines.

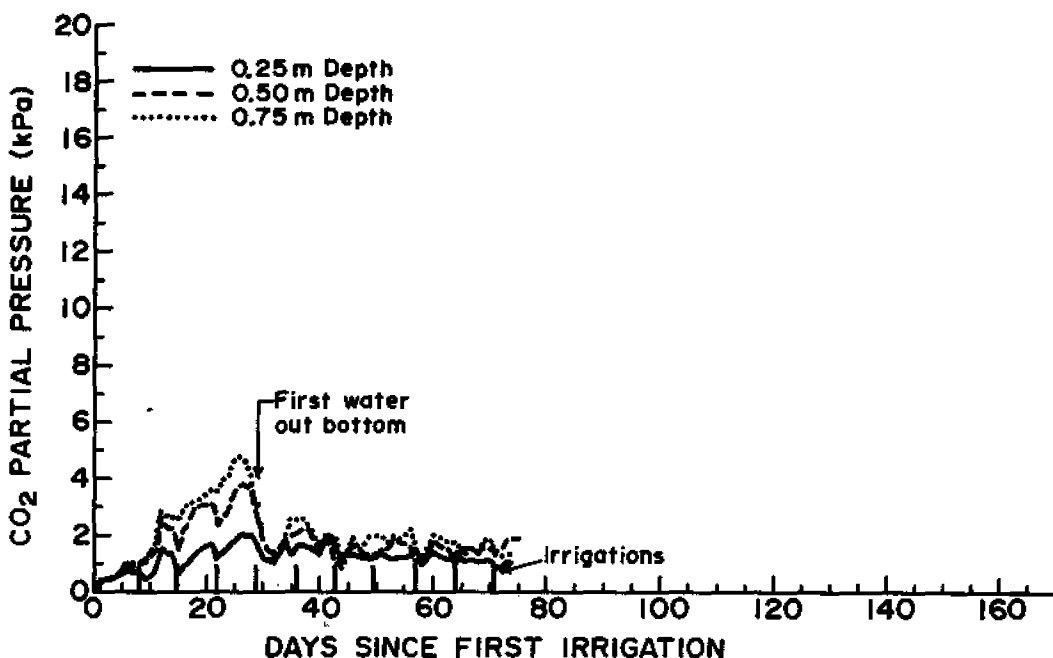


Fig. 2. Carbon dioxide partial pressures at three depths for the gypsum treatment (1.0 kPa is equal to 1.0%).

reduced plant growth. Because of the close agreement between duplicate samples, the large data volume, and the exploratory nature of the study, only P_{CO_2} data from one lysimeter for each treatment is shown. All four of the noncropped treatment soils eventually sealed up and the infiltration rates slowed to the point that it took over 5 days for the 70 mm irrigation to enter the soil. At that point irrigation was terminated. The end of the CO_2 data lines in Fig. 1 through 10 represent the time when irrigation was stopped for each treatment.

Check. The soil P_{CO_2} increased at all check treatment

depths until the soil columns became saturated and water drained from the lysimeters. The P_{CO_2} was in excess of 7 kPa for several samplings at 0.50 and 0.75 m and slightly lower at 0.25 m. Following water drainage from the lysimeters, a sharp decrease in P_{CO_2} was measured, followed by a smaller increase that peaked somewhat lower than the maximum prior to the first drainage water outflow. Beyond this second peak the P_{CO_2} leveled off at about 1.5, 3.0 and 3.5 kPa for the 0.25, 0.50 and 0.75 m depths (Fig. 1).

Gypsum. The P_{CO_2} values for the gypsum treatment followed the same pattern as the check except that the

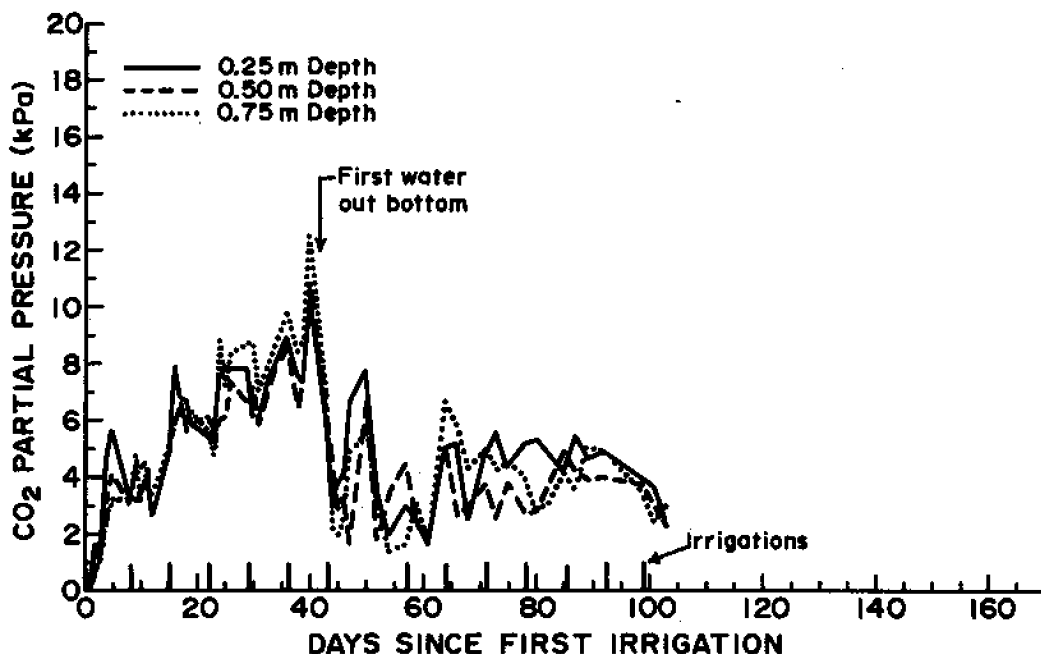


Fig. 3. Carbon dioxide partial pressures at three depths for the manure treatment.

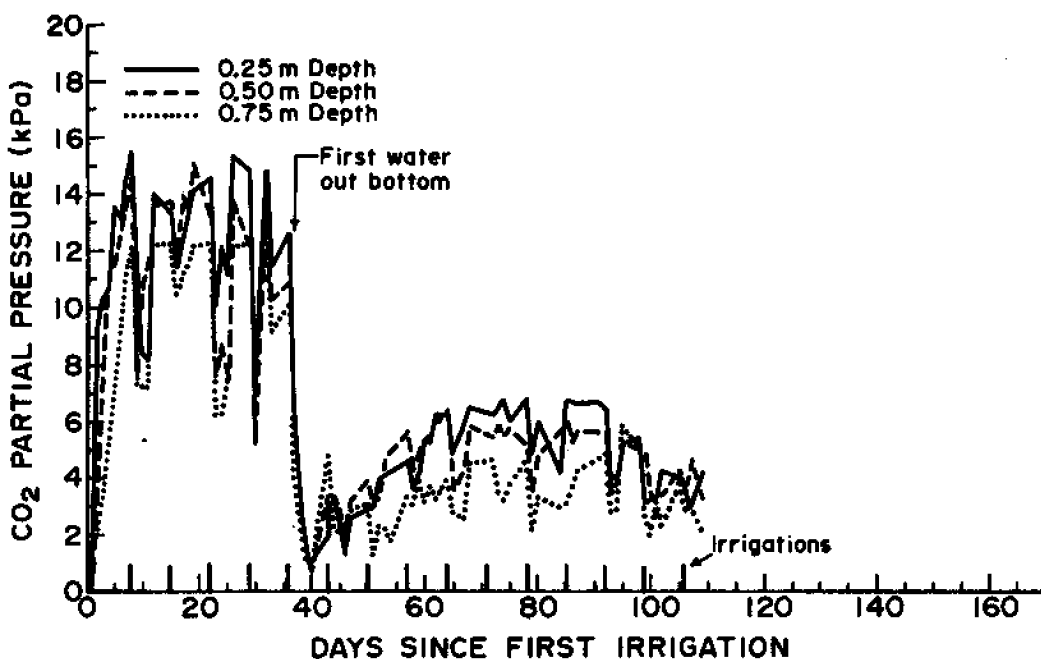


Fig. 4. Carbon dioxide partial pressures at three depths for the chopped alfalfa treatment.

values were about 50 to 60% that of the check. For the first five irrigations the 0.25 m depth was lower than the other two, but after the first drainage water outflow the P_{CO_2} values for the three depths leveled off between 1 and 2 kPa (Fig. 2).

Manure. The manure treatment P_{CO_2} values had the same general pattern as the check, but the values were higher than the check. The P_{CO_2} values were more uniform with depth for most of the sampling period than were the check P_{CO_2} values (Fig. 3).

Chopped Alfalfa. By the second irrigation all chopped alfalfa treatment sample depths had reached their maximum P_{CO_2} values and remained high until the first water drained from the lysimeters. The P_{CO_2} nearly always decreased at all depths shortly following each irrigation. For the period during which water was draining from each irrigation the P_{CO_2} values were generally higher than for the other three non-cropped treatments. The P_{CO_2} gradient with depth was reversed for the manure and chopped alfalfa compared to that of the other two non-cropped treatments (Fig. 4).

Barley. While the first crop of barley was in the early growth stage the P_{CO_2} values increased slowly. Once the crop began vigorous vegetation growth the P_{CO_2} rapidly increased until the first water drained from the lysimeters. After a sharp decrease the P_{CO_2} again increased slightly and then dropped off as the crop matured. The deeper soil depths had higher P_{CO_2} values during the second barley crop, but the third crop did not sustain as high P_{CO_2} levels. There was usually a drop in the P_{CO_2} values after each irrigation. The P_{CO_2} was above 10 kPa in only a few samples taken during the first and second crops (Fig. 5).

Alfalfa. The first alfalfa crop had the highest P_{CO_2} values with sharp decreases after the first leachate drained from the lysimeters and after each of the four cuttings. There were also P_{CO_2} drops after most irrigations. The P_{CO_2} exceeded 12 kPa in the first crop

and 10 kPa in the subsequent crops, several times. The P_{CO_2} pattern was similar to that for barley but was slightly higher (Fig. 6).

Sordan. A sharp P_{CO_2} decrease was not observed after the first leachate drainage from the Sordan lysimeters, but there were sharp P_{CO_2} decreases after each of the four harvests. Irrigation water applications were usually followed by slight P_{CO_2} decreases. No single depth was constantly lower or higher in CO_2 than the other two. The presence of actively growing Sordan plants produced the highest P_{CO_2} values of the 10 treatments studied. Values in excess of 14 kPa were not uncommon and values in excess of 18 kPa were recorded on several occasions (Fig. 7). The Sordan also produced the largest mass of top growth and this appears to be associated with the higher P_{CO_2} values.

Leached and Sordan. This treatment was the same as the check for the first 11 irrigations in that it was irrigated weekly. Then following the 11th irrigation it was planted to Sordan. Irrigation was then applied at 1.25 times consumptive use once the grass was 0.40 m tall. The P_{CO_2} values were similar to the check until the Sordan started vigorous growth and water use. There were P_{CO_2} drops after each harvesting as in the Sordan treatment, but the leached + Sordan treatment did not produce quite as high P_{CO_2} values as the Sordan treatment planted at the time of the first irrigation. During the second and fourth crop, values in excess of 13 kPa were recorded several times and during the third crop and fourth crop, values in excess of 15 kPa were measured (Fig. 8).

Tall wheatgrass. Tall wheatgrass was planted after the third barley crop. During the first crop while the grass was becoming established, the P_{CO_2} decreased until the grass was cut and fertilized, and regrowth became vigorous. The second through fourth crops had quite similar P_{CO_2} patterns. The 0.25 m depth had lower P_{CO_2} values than the other two and the 0.75 m

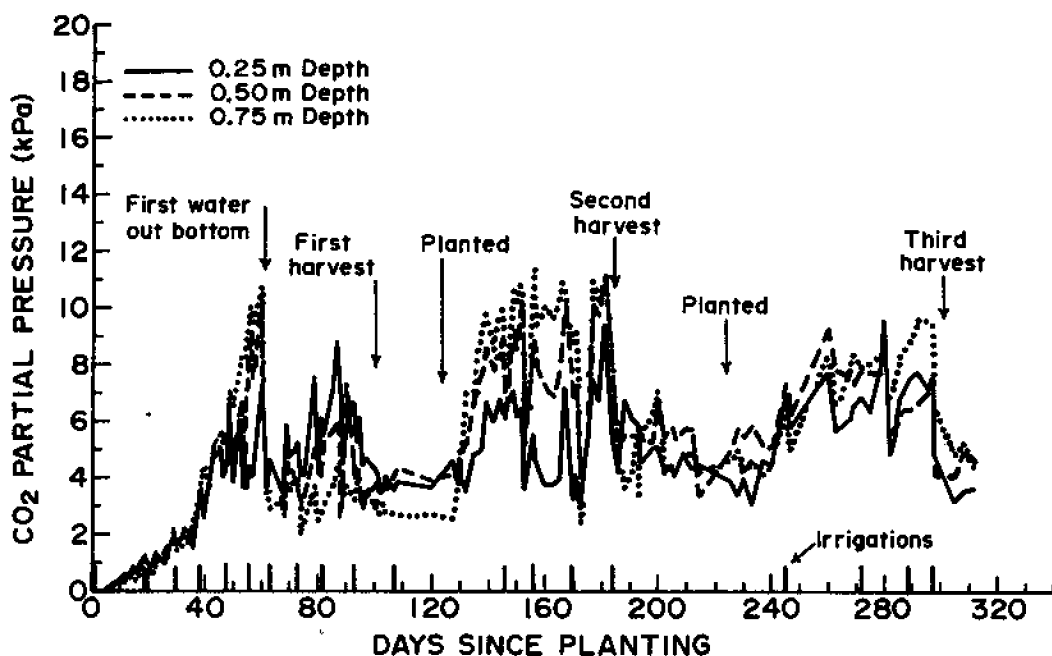


Fig. 5. Carbon dioxide partial pressures at three depths for the barley treatment. Plantings and harvests are also shown.

depth was usually highest. Values in excess of 12 kPa were measured at 0.75 m and 8 kPa occasionally occurred at 0.50 m. The P_{CO_2} nearly always rose sharply the day after irrigation of wheatgrass and then dropped the second day after irrigation whereas the rest of the treatments had an immediate drop in P_{CO_2} on the day following irrigation (Fig. 9).

Cotton. Cotton had a different soil P_{CO_2} pattern than the other crops. During the plant establishment stage, it increased gradually and then increased sharply to 6 kPa as vigorous foliage growth and water use took place. During the major blooming stage the P_{CO_2} decreased to around 3 to 4 kPa and then increased to as

high as 8 kPa while the bolls were filling. The P_{CO_2} then decreased to between 2 to 4 kPa as the bolls matured and leaf abscission began (Fig. 10).

DISCUSSION

Recognizing that the growing conditions in greenhouse lysimeters are different from those in the field and that care must be used in extrapolating these kinds of data to field conditions, this study was conducted to determine soil atmosphere P_{CO_2} values for four leaching treatments and five field crops grown under similar conditions.

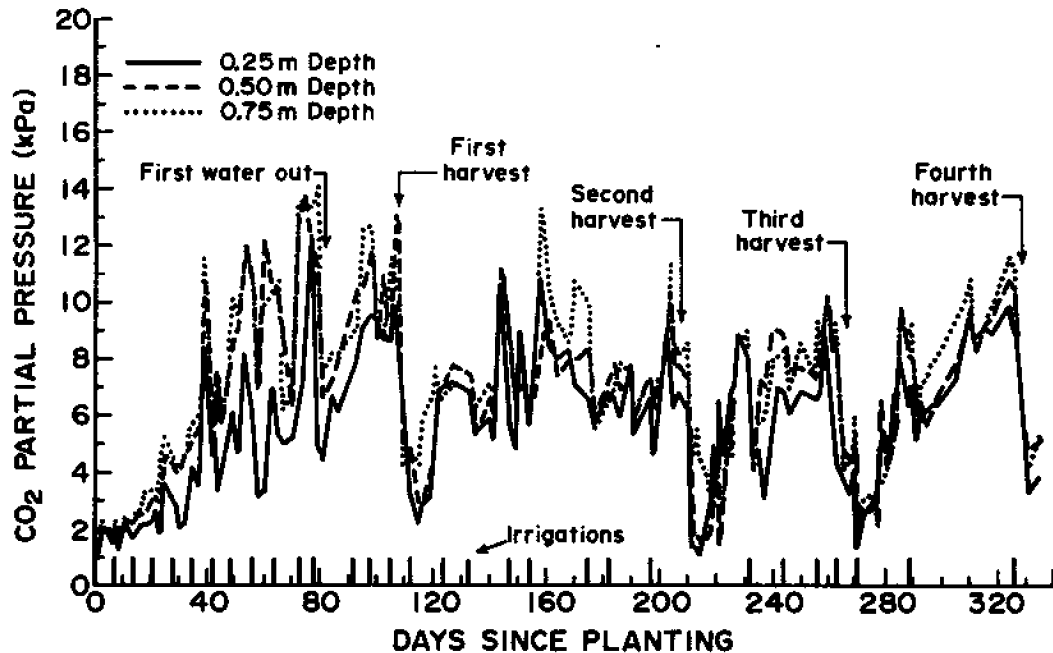


Fig. 6. Carbon dioxide partial pressures at three depths for the alfalfa treatment.

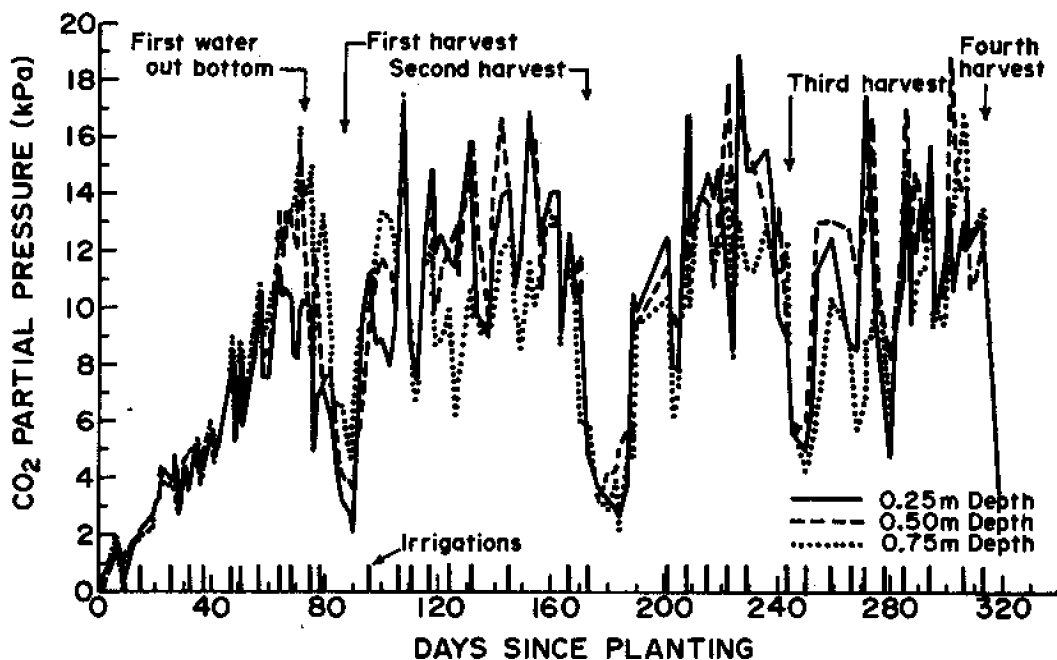


Fig. 7. Carbon dioxide partial pressures at three depths for the Sordan treatment.

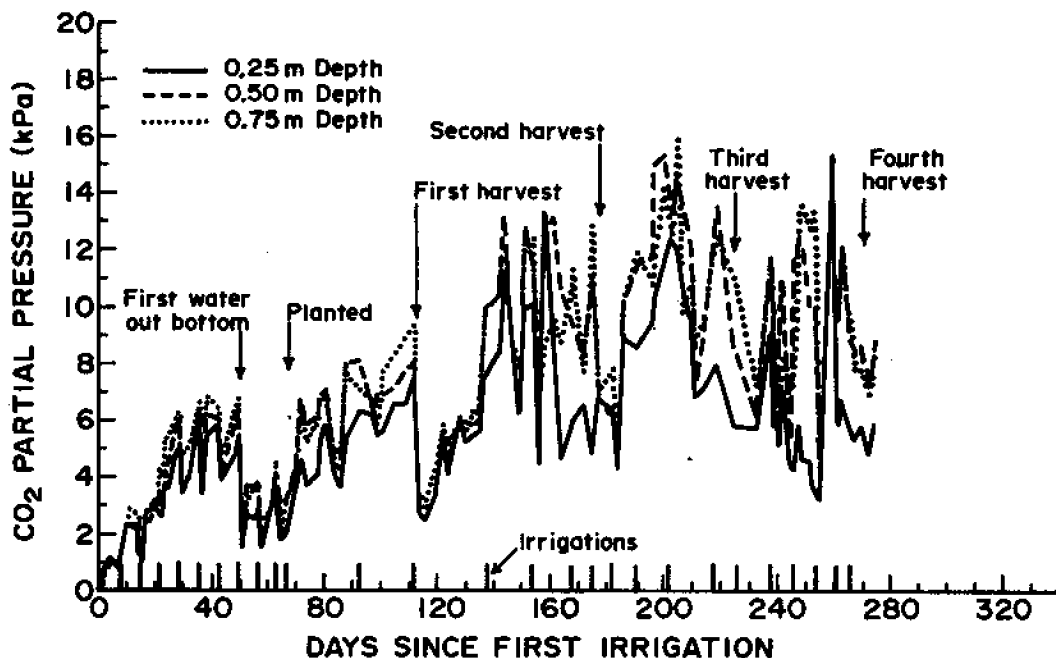


Fig. 8. Carbon dioxide partial pressures at three depths for the leached, then Sordan treatment. The crop was not planted until sufficient water had been applied for four leaching events to take place (about 0.5 pore volumes of leachate).

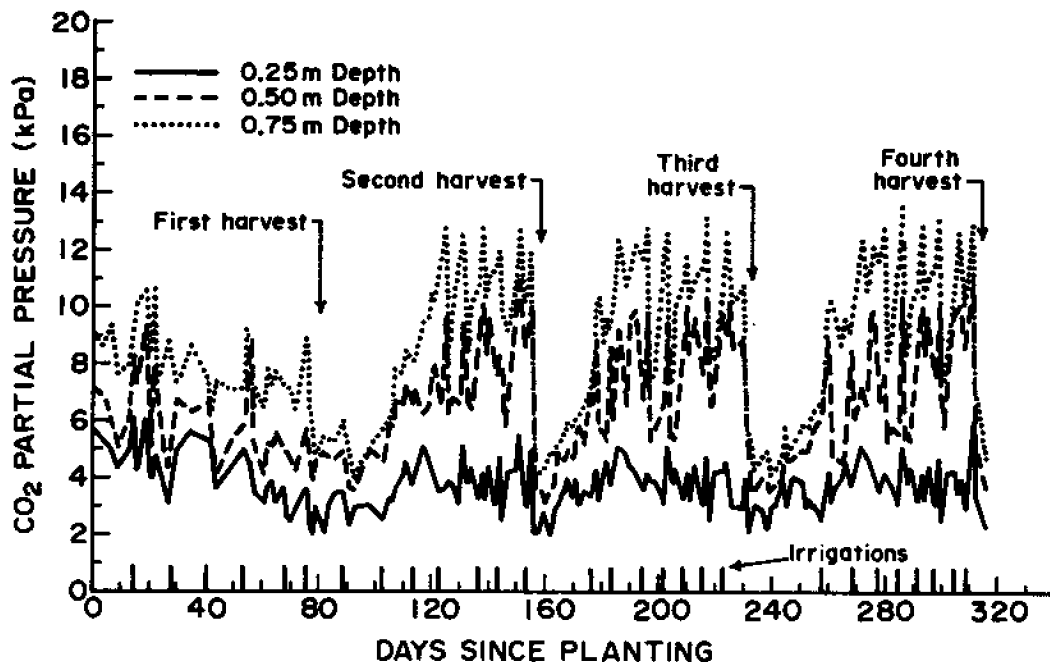


Fig. 9. Carbon dioxide partial pressures at three depths for the tall wheatgrass treatment.

The CO₂ produced in the check and gypsum treatments was due to native organic matter decomposition. Application of water to this artificial system caused an initial rapid organic matter decomposition and a flush of CO₂, and then the P_{CO₂} partial pressure leveled off at around 1 to 3 kPa. The check P_{CO₂} values in this study agreed with those measured by Yamaguchi et al. (1967), at three depths and 20°C in 80 cm columns with a low organic matter soil and a pH of 6.9. The values reported here are generally lower than those reported by Enoch and Dasberg (1971) for five low organic matter laboratory soils treated with 3 g of powdered milk per kg of soil.

The P_{CO₂} in the gypsum treatment was lower than the check as would be expected since as the Ca²⁺ activity increases, the CO₃²⁻ activity must decrease due to CaCO₃ precipitation which in turn decreases HCO₃⁻, H₂CO₃, and finally soil air CO₂ (Robbins, 1985). During the drying cycles, the check treatment developed large cracks that probably caused the P_{CO₂} gradient with depth. The gypsum treatment did not exhibit the cracking nor the P_{CO₂} gradient after the first drainage event.

The manure P_{CO₂} values seemed to follow the same trend with time as the check but at a higher value which would suggest the same decomposition rate as

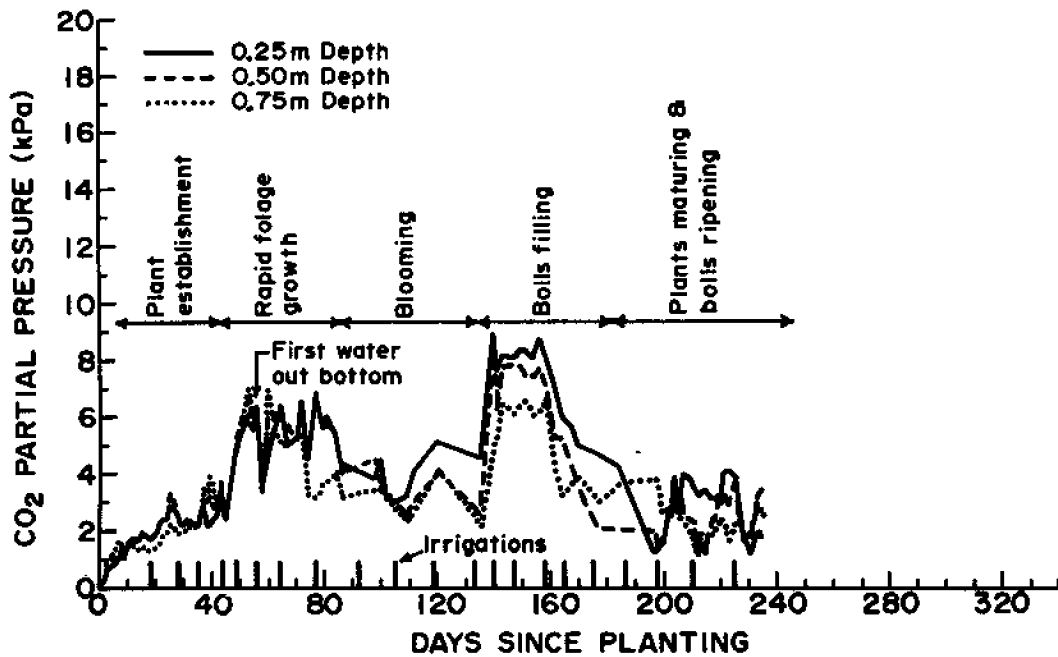


Fig. 10 Carbon dioxide partial pressures at three depths for the cotton treatment. Growth stages are also shown.

the original soil organic matter, but reflecting the higher total organic matter content. As a contrast, the chopped alfalfa had a much more rapid P_{CO_2} production rate and level that would suggest that alfalfa was more easily decomposed by soil organisms than manure. The P_{CO_2} gradient reversal with depth of the alfalfa and manure from that of the check is due primarily to the location of the decomposing material in the surface 0.20 m.

The barley, alfalfa, tall wheatgrass, and two Sordan treatments all produced similar P_{CO_2} patterns. The P_{CO_2} always decreased shortly after the crops were harvested, regardless of whether it was the killing of the plant as with the barley, or foliage removal as with the other three crops. There was a 3 to 4 kPa rise in the P_{CO_2} on the day following irrigation in the tall wheatgrass treatments, suggesting a respiration activity increase in excess of the CO_2 diffusion and water adsorption from the soil air. This result would indicate a flush of growth after irrigation and may be associated with the wheatgrass tending to come out of dormancy after irrigation following a dry period. The CO_2 production by the roots appeared to be associated with the rate of top growth. This event could have implications on such things as soil solution pH and its effect on trace mineral solubility near the root at various stages of plant growth, particularly iron uptake by some pH sensitive grasses. Time of leaching for Na removal from soils also might well be planned for periods of vigorous plant growth to take advantage of increased lime solubility due to increased H_2CO_3 which lowers the soil solution pH.

The P_{CO_2} pattern for the cotton crop changed with stages of plant development. The rapid foliage growth and the boll filling stages were accompanied by the increased soil P_{CO_2} values. Cotton also had the lowest P_{CO_2} values of the crops growth. The shallower depth often had the highest P_{CO_2} values, suggesting that cotton has a shallow root respiration pattern.

For all treatments, irrigation water applications caused short-term fluctuations while plant growth rate and ease of organic matter decomposition were the controlling factors over long time periods. The P_{CO_2} decreases following irrigation is the result of CO_2 dissolving in the water from the high CO_2 soil atmosphere. The CO_2 is approximately 30 times as soluble as O_2 and 50 times as soluble as N_2 in water at $15^\circ C$.

Recognizing that soil atmosphere data taken from lysimeters may not represent field soils because of temperature and other differences, these data provide an insight into P_{CO_2} data for the conditions considered. These data show considerable CO_2 production differences by the presence of different crops, and differences between plant growth stages. It also gives relative value differences caused by removing the aboveground portions of crops.

Because of interaction between P_{CO_2} , pH, and Ca^{+2} activity in calcareous soils, P_{CO_2} data are necessary to adequately model Na^+ and Ca^{2+} exchange and leaching. In the past only limited P_{CO_2} data have been available for these models and no data are available that compare different crops grown under similar conditions. If the differences in CO_2 production by different crops and crop management are known, it may very well be possible to select crops and management programs that will enhance Na removal from the exchange complex more efficiently than has been done in the past, especially in areas where gypsum and other applied Ca sources are not available or are too expensive.

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