CORN ROOT INFLUENCE ON AUTOMATED MEASUREMENT OF SOIL CARBON DIOXIDE CONCENTRATIONS

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Carbon dioxide (CO_2) production is a more desirable indicator of soil carbon (C) dynamics than CO_2 flux at the soil-air interface, which is significantly influenced by the gas-transport condition of the soil. Production of CO_2 can be computed from CO_2 concentrations if high-temporal measurements are made. Our objective was to design, implement, and test an automated CO_2 measurement system that requires low maintenance but provides high-temporal resolution of CO_2 concentrations in soil. The CO_2 sensors were located at different soil depths from 10 to 60 cm, with and without roots, to measure the effect of corn (*Zea mays*, L.) root activities on CO_2 concentrations over time. A direct comparison indicates that soil CO_2 measured with the automated measurement system represents CO_2 of soil surrounding the sensor. Computed CO_2 production was highest in the soils above 20 cm. A peak of soil CO_2 concentration occurred after each of the major rain events. The amplitude of the peaks decreased with depth. Differences between the CO_2 concentrations in the root and root-excluded soils were small between rainfall events and large at and after rain. Soil CO_2 concentration showed diurnal variations at the 10-, 20-, and 40-cm depths, whereas it was hardly detectable at the 60-cm depth. The automated CO_2 measurement system is a useful tool for gaining knowledge of CO_2 production in soils over time and across depth and of contributions from roots and bulk soil to total CO_2 production in soils. (Soil Science 2005;170:779–787)

Key words: CO_2 sensor, soil CO_2 respiration, corn root rhizosphere, CO_2 production.

S OIL respiration, which is estimated to be one order of magnitude higher than fossil fuel emission, is a significant component of the global C balance (Raich and Schlesinger, 1992). Several researchers have recognized that CO_2 production is a more desirable indicator of soil C dynamics than CO_2 flux at the soil-air interface, which is significantly influenced by soil gas-

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transport conditions. Methods have been developed to compute CO_2 production using concentrations at various depths of soil (Davidson and Trumbore, 1995; De Jong and Schappert, 1972; Risk et al., 2002). One problem causing concern, however, is the introduction of computed negative CO_2 production, probably caused by the low-temporal resolution of the data (De Jong and Schappert, 1972; Risk et al., 2002).

Most researchers have determined CO_2 concentration in soil air by extracting soil gas samples and analyzing them by gas chromatography (GC) or other instruments (Burton and Beauchamp, 1994; Buyanovsky and Wagner, 1983; Davidson and Trumbore, 1995; De Jong and Schappert, 1972; Risk et al., 2002). Soil gas sampling is a difficult and cumbersome procedure that limits the frequency of CO_2 measurements. Gas sampling may also cause artificial

airflow within the soil, depending on how much and how often sampling is carried out. Soil CO_2 concentrations can change rapidly with events such as rainfall or tillage, and are subject to both diurnal and seasonal variations. Data collected weekly or even biweekly may not provide an accurate and dynamic measure of soil CO_2 concentration. Recently, however, newer *in situ* measurements of soil CO_2 have been reported. Hirano et al., (2003), Tang et al., (2003), and Jassal et al. (2004) used buried infrared gas analyzers and solid-state CO_2 sensors to measure CO_2 concentration every 30 minutes, 30 seconds, and hourly, respectively, and provided detailed variations of soil CO_2 concentration at multiple depths.

Carbon dioxide production should be highest in the upper soil layers where organic matter accumulates and most of the metabolic activity is located. Yet, studies have shown that CO_2 concentration generally increases with depth (e.g., Davidson and Trumbore, 1995; De Jong and Schappert, 1972; Reardon et al., 1979). However, not all studies agreed on the origin of the CO_2 in the deeper soil. Some studies suggest that the origin is surface soils (Reardon et al., 1979; Risk et al., 2002) and others imply deeper soils (Davidson and Trumbore, 1995; De Jong and Schappert, 1972; Goulden et al., 1998). Seasonal variations of CO_2 concentration can penetrate into the deep soils and may also involve exchanging CO_2 between the vadose zone and groundwater (Reardon et al., 1979). It is also known that soil CO_2 concentrations undergo large changes after rains (Buyanovsky and Wagner, 1983).

Carbon dioxide is generated due to both live root activities and microbial activities. As roots penetrate the soil, they produce large amounts of organic C which could be another source of CO_2 production due to root activities in the rhizosphere, in addition to live root respiration (Bolinder et al., 1999). The contribution of root respiration to total soil respiration, estimated with various methods, varies from below 10% to more than 90% (Hanson et al., 2000). CO_2 production increased faster with increase of soil temperature in rooted soil than in root-excluded soil (Boone et al., 1998).

Our objective was to design, implement, and test an automated CO_2 measurement system that requires low maintenance but provides high-temporal resolution of CO_2 concentrations in soil. Several goals were kept in mind in designing the system. One was to minimize soil

disturbance during installation of the system in the field. Another was to allow for an easy and rapid replacement of the sensors in case of malfunction. The sensors were installed at different depths, in soils with and without roots, to document the effect of corn (*Zea mays* L.) root activity on CO_2 concentrations.

MATERIALS AND METHODS

Experimental Site

All experiments were carried out in two 6 × 9 m corn plots, plots III-7 and IV-5, of a long-term continuous corn field study started in 1980 at the University of Minnesota Research and Outreach Center, Rosemount, Minnesota (44 degrees 45′ N, 93 degrees 04′ W) (Clapp et al., 2000; Clay et al., 1990; Clay et al., 1985; Layese et al., 2002). The soil is a Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludoll) with an underlying layer of gravel at about 90 cm below the soil surface. The climate of the region is subhumid. The weather station located at the Research Center provides air temperature and precipitation data. Thermistors (107 Temperature Probe, Campbell Scientific, Inc., Logan, UT) buried at 10, 20, 40, and 60 cm depth provide soil temperature every 30 minutes. Corn was planted on day of the year (DOY) 136. Ammonium sulfate was broadcast at a rate of 150 kg N ha^{-1} one week after planting. Row-spacing was 75 cm and planting density was 80,000 ha^{-1}. At the end of the growing season, corn grain and stover were harvested and removed from the plots; the soil was then rototilled to a depth of about 15 cm.

CO_2 Probes

Carbon dioxide concentrations were measured with CO_2 transmitters (model GMT220, Vaisala, Inc., Woburn, MA), consisting of a sensor, a box containing voltage output terminals, and a cable connecting the sensor to the box. The voltage output terminals were connected to a datalogger (model CR10X, Campbell Scientific, Inc., Logan, UT), which was programmed to read and record the voltage every 30 minutes. The sensor is a cylinder 1.85 cm in diameter and 10.9 cm in length (Fig. 1). Each sensor was placed at the bottom of a PVC pipe (3.7 cm i.d.), which was pushed into the void space left by removal of a soil core 8 months before CO_2 concentration measurements were started on DOY 183. The pipe
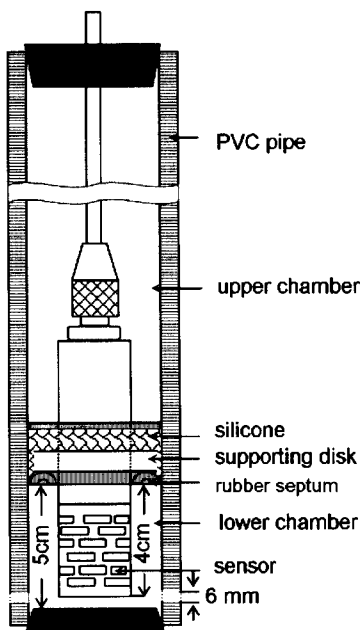
Fig. 1. Diagram of the CO_2 sensor unit in the PVC pipe.

was sealed at both ends with rubber stoppers. The pipe was further divided into upper and lower chambers by a donut-shaped rubber septum and its supporting plastic disk. Silicone sealant was added on top of the supporting disk to ensure no leaks between the upper and lower chamber. Only the tip of the sensor, where CO_2 was actually measured, was enclosed in the lower chamber. The soil gas diffused into the lower chamber through holes drilled in the wall of the pipe. The holes were covered with waterproof breathable fabric to prevent liquid water from getting into the PVC pipe. The empty space of the lower chamber was kept as small as possible to minimize differences between the soil and chamber CO_2 concentrations. We confirmed no leakage between the upper and lower chambers by introducing a few pieces of dry ice into the upper chamber and found no increase in CO_2 in the lower chamber. When replacing a sensor is required, only the sensor, septum and supporting disk are pulled out, and the PVC pipe stays in the soil. It takes <20 minutes to replace a problem sensor without disturbing the soil and creating a gap in data collection.

The transmitters were installed both in root-active (RA) and between root-excluded (RE) corn rows at 10-, 20-, 40-, and 60-cm depths, for a total of 8 transmitters in each plot. The between-row sensors in their PVC pipes were

set inside larger PVC pipes (20.2 cm i.d.). The bottom edge of the large PVC pipe was sharpened and pushed into the ground with a tractor bucket loader. The upper rim of the larger PVC pipe was flush with the soil surface. The bottom of the larger PVC pipes were set 20 cm deeper than the bottom of the small PVC pipes. Care was taken to prevent weed growth within the large pipe.

To confirm that the air inside the sensor was representative of the surrounding soil, paired gas samples were taken from the lower chamber and from soil at the same depth as the sensor 5 to 15 cm from the pipe. Soil gas samples were taken through 0.16 cm i.d. Teflon tubing inserted in the soil. The same type of tubing had been inserted into the 3.7 cm i.d. PVC pipe when the CO_2 sensor was installed. The gas samples were taken weekly over a period of 5 weeks. These samples were analyzed for CO_2 by GC against standard concentrations. The GC is equipped with a thermal conductivity detector. How closely the CO_2 concentration in the bulk soil is represented by the CO_2 concentration measured inside the PVC pipe was assessed by the root mean square error (RMSE):

$$\text{RMSE} = \sqrt{\frac{1}{K}\sum_{i=1}^{K}(S_i - P_i)^2} \qquad (1)$$

where S_i and P_i are CO_2 concentrations in the soil and inside the PVC pipe, respectively, and K is the total pairs of measurements.

CO_2 Production

Production of CO_2 was computed in the RA soil of plot III-7 from DOY 222 to 228, during water redistribution after a rainfall on DOY 218. On DOYs 223 and 226, the decrease in water content during water distribution was determined gravimetrically in soil samples taken at 10 cm intervals from the soil surface to the 60-cm depth. Water contents between DOYs 222 and 228 were estimated by linear extrapolation.

Production of CO_2 in soil can be calculated by rearranging the one-dimensional CO_2 transport equation of Šimůnek and Suarez (1993):

$$S = \frac{\partial(\varepsilon C_G + \theta C_L)}{\partial t} - \frac{\partial}{\partial z} \qquad (2)$$

$$\left(D_G(\theta)\frac{\partial C_G}{\partial z} + D_L(\theta)\frac{\partial C_L}{\partial z} \right)$$

where S is the CO_2 source/sink term (g cm^{-3} h^{-1}), t is time (h), z is soil depth (cm), ε and θ are soil air and water contents (cm^3 cm^{-3}),

respectively, C_G and C_L are CO_2 concentrations in soil air and water (g cm^{-3}), respectively, and D_G and D_L are diffusivity of CO_2 in soil air and water (cm^2 h^{-1}), respectively. Convective fluxes are ignored in the above equation. C_L can be related to C_G through Henry's law, $C_L = K_H \cdot C_G$, where K_H is Henry's law constant in a CO_2 $-H_2O$ system (dimensionless) (Plummer and Busenberg, 1982). Substituting C_G for C_L in Eq.(2), and defining retardation factor $R = \varepsilon + \theta \cdot K_H$ and effective diffusivity $D = D_G + D_L \cdot K_H$, Eq.(2) becomes:

$$S = R\frac{\partial C_G}{\partial t} - \frac{\partial}{\partial z}\left(D\frac{\partial C_G}{\partial z}\right) \qquad (3)$$

In the calculation, time is divided into steps at times t^j ($j = 1, 2, 3, ...$) when C_G is measured and the soil depth is divided into layers at depths z_i, ($i = 1, 2, 3, ...$) where C_G is measured. C_G measured at depth z_i and time t^j is noted as $C_{G\,i}^{\,j}$. Other parameters, S, R, and D, are similarly noted. Carbon dioxide production in soil is then approximated:

$$S_i^j = \frac{R_i^{j+1} + R_i^j}{2}\frac{C_i^{j+1}-C_i^j}{t^{j+1}-t^j} - \frac{2}{z_{i+1}-z_{i-1}} \qquad (4)$$

$$\left(D_{i+1/2}^j \frac{C_{i+1}^j-C_i^j}{z_{i+1}-z_i} - D_{i-1/2}^j \frac{C_i^j-C_{i-1}^j}{z_i-z_{i-1}}\right)$$

where C_G is written as C for simplification.

Diffusivities of CO_2 in soil air and water are calculated using the Millington and Quirk (1961) equation:

$$\frac{D}{D_0} = \frac{\lambda^{10/3}}{\Phi^2} \qquad (5)$$

where Φ is soil porosity. When Eq.(5) is used to calculate CO_2 diffusivity in soil air, $D = D_G$, $\lambda = \varepsilon$, D_0 is CO_2 diffusivity in free air (no soil), and its values at different temperatures can be calculated with the equation of Fuller et al. (1966). For calculating diffusivity in soil water, $D = D_L$, $\lambda = \theta$, D_0 is CO_2 diffusivity in free water (no soil), and its values at different temperatures can be calculated with the equation of Bird et al. (1960) (p. 515).

To minimize noise of measured CO_2 concentrations being amplified in the calculation of CO_2 production, the original measured data were smoothed with a Savitzky-Golay digital filter, which smoothes noisy data but preserves peak height and widths (Press et al., 1992; Savitzky and Golay, 1964):

$$X_k = \left(\sum_{n=-m}^{n=m} B_n \cdot x_{k+n}\right)\Big/ N \qquad (6)$$

where x_{k+n} ($n = -m$ to m) are members of a subset of original series of values x_o ($o = 1,2,3,.......,M$, and M is total number of members in the original series. For our data, x_o is time series of measured soil CO_2 concentrations. X_k is the smoothed value. The coefficients of B_n ($n = -m$ to m) are convoluting integers, and the denominator N is a normalizing factor. B_n and N vary, depending on degrees of polynomial and total points ($2m + 1$) used in deriving Eq.(6). Savitzky and Golay (1964) had listed B_n and N for up to quintic polynomials and $m = 2$ to 12 points of original values. Applying Eq.(6) repeatedly for $k = m + 1$ to $M - m$, a new, or smoothed, series of values is constructed. We used the B_n of a cubic polynomial and $m = 8$ to smooth the measured CO_2 concentrations.

RESULTS

A comparison of CO_2 concentrations inside the lower chamber and in the surrounding soil showed no discernible bias at lower concentrations (Fig. 2). The root mean square error (RMSE) of CO_2 concentration between soil gas samples taken from the bulk soil and inside the PVC pipe is about 830 ppm. At higher CO_2 concentrations, gas samples taken from the soil tended to be lower than the concentration of samples taken inside the lower chamber, possibly due to the reduced gas diffusivity in deep and wet soil where the concentrations tended to be higher. Overall, the soil CO_2 concentrations in the lower chamber were very close to the concentrations in the adjacent soil.

The time series of CO_2 concentration from DOY 183 to 258 in RA soils and RE soils of plots III-7 and IV-5 are shown in Fig. 3. Soil CO_2 concentrations showed an increase with depth, surges after rains, and diurnal variations. A peak of soil CO_2 concentration occurred at each of the major rain events. The CO_2 surge began immediately after the rain at the 10- and 20-cm depths but was delayed for several hours at the 40- and 60-cm depths. The amplitude of the peaks decreased with depth. The overall soil CO_2 concentrations gradually declined over the entire study period. The downward trend may be caused by the gradual decline in soil water content during a dry summer. Differences between the CO_2 concentrations in RA and
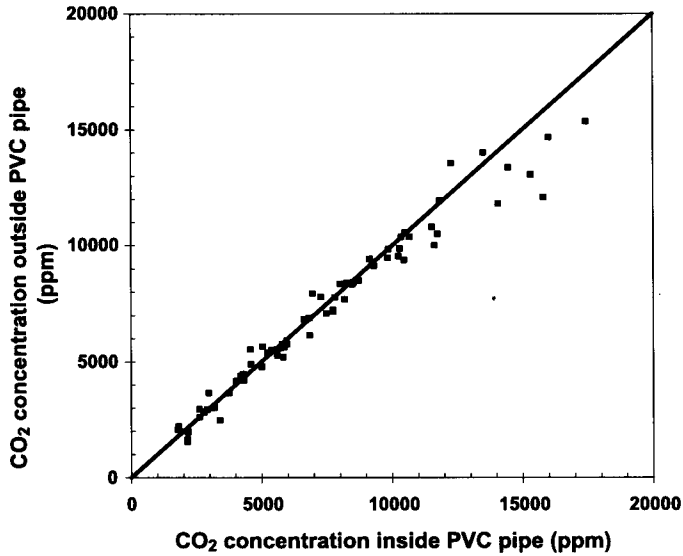
Fig. 2. Comparison of CO$_2$ concentrations by gas chromatography inside lower chamber and its surrounding soil.

RE soils were small between rain events and greater during and after rain. After a rain, CO$_2$ concentrations of RA soils at the 10 and 20 cm depths increased faster and to a higher peak concentration than those of the RE soils.

Soil CO$_2$ concentrations showed diurnal variations at the 10-, 20-, and 40-cm depths, whereas similar variations were hardly detectable at the 60-cm depth except for the early days of RE soil of plot IV-5 (Fig. 3 and 4). Soil CO$_2$ concentrations and temperature were in phase at the 10- and 20-cm depths and out of phase at 40-cm. Soil temperatures peaked a little earlier at the 10-cm depth than at the 20-cm depth, as did CO$_2$. At the 40-cm depth, CO$_2$ peaked several hours earlier than did temperature. The timings of maximum and minimum CO$_2$ concentration varied by about 2 hours on different days.

The computed CO$_2$ production in the RA soil of plot III-7 from DOY 222 to 228 during water redistribution was maximum at the 10-cm depth, and minimal at 40-cm, although higher CO$_2$ concentrations were found in the deeper soil (Fig. 5). Average CO$_2$ production rates were 2.2, 0.56, and 0.22 g m^{-3} hr^{-1} at depths of 10, 20, and 40 cm, respectively. Production of CO$_2$ also showed diurnal variations.

DISCUSSION

The peaks of CO$_2$ concentration were likely due to the sealing of surface soil by rain. The peaks were higher in the RA soil than in the RE soil. Rates of CO$_2$ respiration are usually higher in soils with plant roots (Boone et al., 1998). Corn roots feed the microbial population in the rhizosphere with exuded nutrients and sloughed-off material, which are rapidly decomposed with attendant production of CO$_2$ (Molina et al., 2005; Molina et al., 2001; Paterson, 2003). In addition, live roots respire and contribute to total CO$_2$ production. Thus, rates of CO$_2$ respiration in the RA soil should have been higher than in the RE soil. This increased activity coupled with a reduced CO$_2$ diffusion in the upper soil layers saturated with water caused the observed higher peaks of CO$_2$ concentrations in the RA soil. Subsequently, as the water was redistributed in the soil profile, gas diffusion increased and differences in the CO$_2$ concentrations between the RA and RE soils were less pronounced.

Jassal et al. (2004) had suggested that the large increase in CO$_2$ concentration at the 20-cm depth after rainfall in a Douglas fir stand was the result of a sudden flush in soil microbial activity with a small increase in soil water content in a dry soil. We suggest that this mechanism did not apply to our corn field because our data indicated that soil CO$_2$ concentration increased drastically whether soil was dry or wet before rain. Lee et al. (2004) reported that a sudden increase in moisture content in the litter layer in a mixed species forest

caused an instant increase in CO_2 release. This is unlikely the mechanism that caused the large increase of soil CO_2 concentration in our experiment because corn stover of previous years had been removed from the plots. The CO_2 production rate varies with change of soil moisture content, especially in the dry state (Lee et al., 2004). The CO_2 peaks observed in our plots may be the result of production rate increase and sealing of surface soil by rain, but the main cause is likely to be the sealing of surface soil by rain.

Computed CO_2 production in the RA soil was highest in the upper soil layers and was similar in magnitude to that observed in virgin prairie soil at 10 cm (De Jong and Schappert, 1972). Measured soil CO_2 concentration decreased over time due to the increase in soil gas diffusivity in the period in which soil moisture was continuously decreasing after rain-

fall; however, the computed CO_2 production held at a relatively steady rate except the diurnal variation (Fig. 5). Soil CO_2 concentration does not necessarily reflect the soil CO_2 production.

Diurnal variations of soil CO_2 concentrations have been reported by Makarov (1958) where maximum CO_2 output occurred at midday and 3 pm. Edwards and Riggs (2003) used an automated monitoring chamber system that showed detailed diurnal variations in CO_2 efflux at the soil surface. De Jong and Schappert (1972) reported a diurnal variation in CO_2 concentration at a 15-cm depth, but negligible change at a 30-cm depth. They suggested that the effect of diurnal variations on soil respiration can be accounted for by always sampling at the same time of day. Various correlations have also been established between the diurnal variations of CO_2 concentration and temperature. Tang et al. (2003) observed that soil CO_2 concentrations at
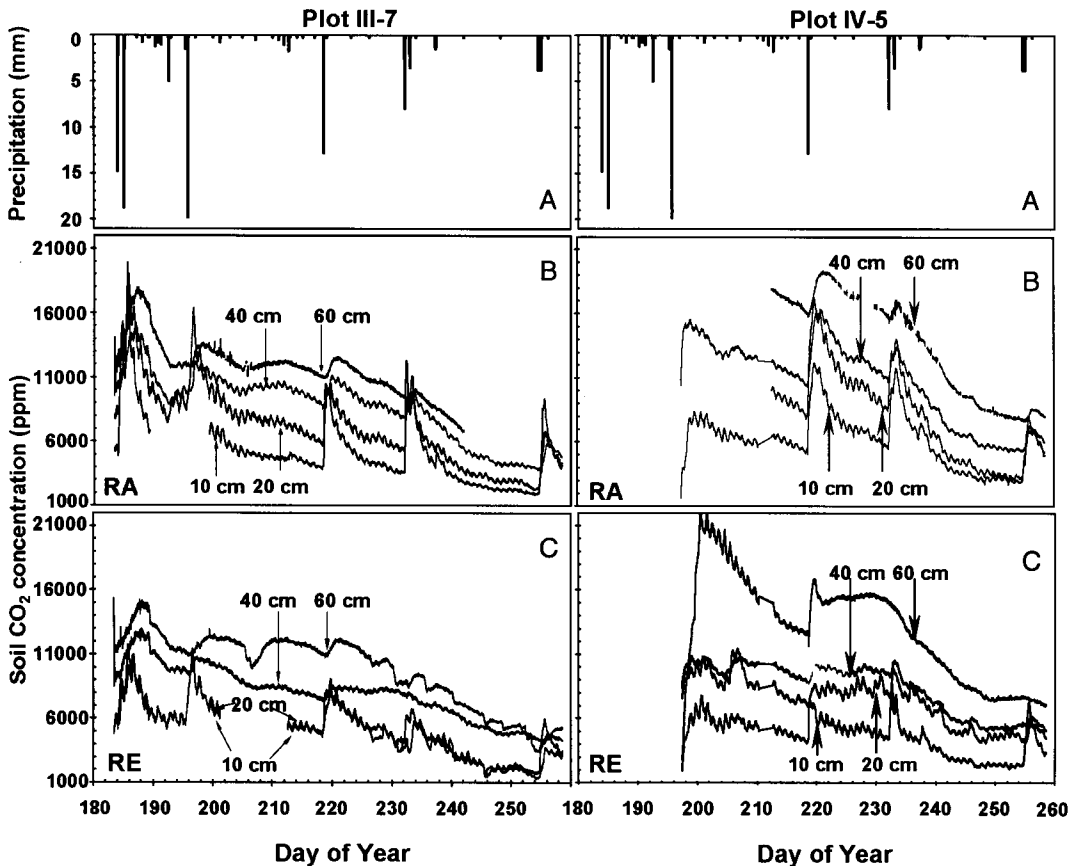

Fig. 3. Soil CO_2 concentrations at various depths, in root-active (RA) and root-excluded (RE) soils of plots III-7 and IV-5. A, Precipitation; B, CO_2 concentration in RA soils; C, CO_2 concentration in RE soils. Numbers in the graphs are soil depths.
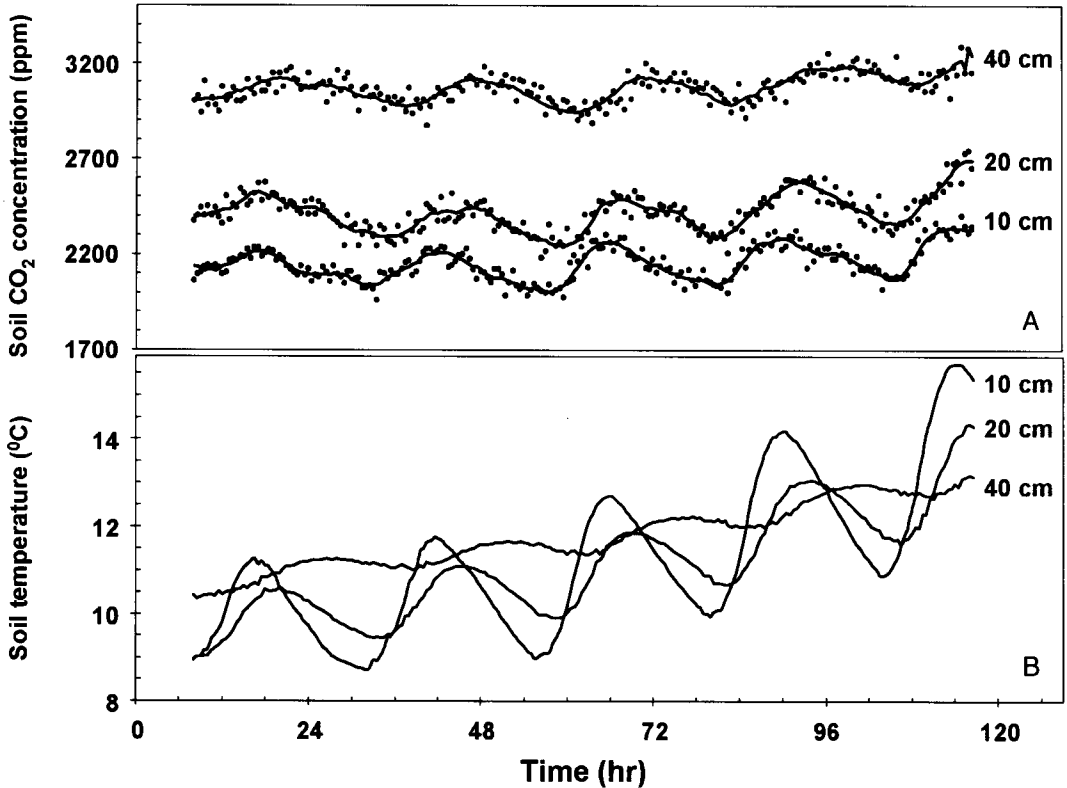
Fig. 4. Diurnal variations of the soil CO_2 concentration (A) and temperature (B). The numbers in the graphs are soil depths. In (A): the dots are measured values and lines are smoothed values using the Savitzky-Golay filter.

depths of 8 and 16 cm in oak-grass savanna peaked at a time around 14:30 to 16:30 when soil temperatures were highest. In a cool-temperate deciduous broadleaf forest, CO_2 concentrations reached a minimum in early afternoon (Hirano et al., 2003). In a boreal forest, soil CO_2 concentrations were out of phase with temperature (Hirsch et al., 2003). Jassal et al., (2004) reported that in a 54-year-old Douglas fir stand diurnal variation of CO_2 efflux followed variation of soil temperature at the 2-cm depth. The different timings suggest different driving forces behind the CO_2 diurnal variations. When CO_2 is in phase with temperature, the driving force is temperature (Tang et al., 2003), provided that variation in gas transport conditions during the day is small. When CO_2 is not in phase with temperature, different forces are involved. Hirano et al. (2003) suggest that CO_2 variation in the trunk space between a forest floor and canopy is the driving force. Hirsch et al. (2003) suggest that wind speed changes between morning and evening could be the driving force.

In our experiment, diurnal variations at 10 and 20 cm are in phase with diurnal variation of soil temperature; variation at 40 cm is out of phase with soil temperature. It can be seen from Fig. 4 that peaks and valleys of CO_2 concentration at 40 cm follow those at 20 cm, therefore, it was likely that CO_2 diurnal variation at the 40-cm depth is driven by CO_2 variation in soils above it.

In conclusion, CO_2 concentrations measured by the automated CO_2 measurement system represent those of adjacent soils. The high-temporal resolution of CO_2 concentration at multiple depths permits calculation of CO_2 production in soil. CO_2 production provides the information whereby CO_2 is generated in the soil and excludes the influence of gas-transport conditions. It will be advantageous, in predicting effects of temperature increase on soil respiration, to correlate soil temperature with CO_2 production instead of CO_2 flux at the soil-air interface which is also influenced by gas-transport conditions of the soil. CO_2 flux at the soil-air interface provides information of the
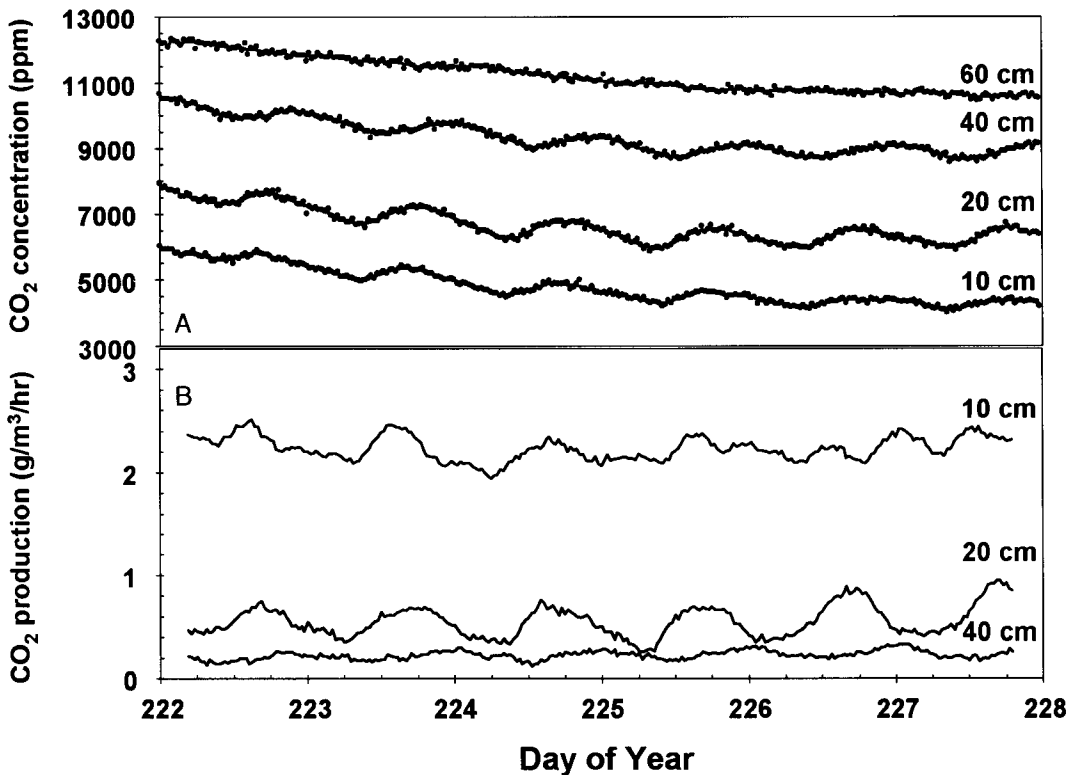
Fig. 5. Comparison of the CO_2 concentration (A) and production (B). The numbers in the graphs are soil depths. In (A): Dots are measured values and lines are smoothed values using the Savitzky-Golay filter.

interaction between soil and atmosphere, but less detailed information of CO_2 generation below ground. Combined measurements of both, flux and production, would provide a more complete understanding of CO_2 generation and transport in soil. Most of the CO_2 in our field was produced in the surface soil and the CO_2 production decreased with depth. Corn roots contributed significantly to CO_2 production in soil that is characterized by a faster increase and a higher peak of soil CO_2 concentration during and after rain events in RA soil than in RE soil. Soil CO_2 concentration changed dramatically during and after rain events. Carbon dioxide diurnal variation of surface soil in the field was caused by diurnal variation of soil temperature, whereas CO_2 variation at 40 cm was probably driven by CO_2 variation above it. For future work, non-destructive methods of determining soil water content, such as time domain reflectometry, could be used to provide long-term and frequent measurements of soil water content for both RA and RE soils. Comparison of CO_2

productions of RA and RE soils over the long-term can certainly be achieved.

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