Measurements of Soil CO_2 Flux

R.L. Garcia, T.H. Demetriades-Shah, J.M. Welles, D.K. McDermitt, and J.M. Norman[1]

LI-COR, inc., Environmental Division, 4421 Superior Street, Lincoln, NE 68504, and [1]Dept. of Soil Science, University of Wisconsin, Madison, WI 53706 USA

Introduction

The predominant processes that produce carbon dioxide in soil are respiration of roots and soil organisms and the decomposition of organic matter. In calcareous soils significant amounts of CO_2 can also be produced from the action of acidic rain on soil carbonate. The production of CO_2 in the soil is strongly correlated with soil temperature and moisture. (Norman, et. al. 1992). Therefore, soil temperature and moisture data can be useful when interpreting soil CO_2 flux measurements. One should also recognize that any experimental protocol that perturbs the soil temperature and/or moisture (eg., long term chamber enclosure) will most likely change the soil CO_2 flux.

Although the primary mechanism for transport of CO_2 from the soil to the atmosphere is diffusion, transport may also be influenced by fluctuations in pressure, wind, temperature, and displacement by precipitation. There is a great deal of spatial variability in soil CO_2 flux due to its dependence on environmental conditions and the heterogeneity of soil.

It may be more difficult for a researcher to recognize when measurements have been compromised by problems in technique or methodology when the process being measured has a high degree of variability. This makes it particularly important to rigorously evaluate techniques used for such measurements.

Chamber techniques are probably the most widely used means of measuring gas exchange between the soil and the atmosphere. In this paper we evaluate a new closed-dynamic chamber system.

Materials and Methods

An LI-6400 portable photosynthesis system (LI-COR Inc., Lincoln, Nebraska) was fitted with a 6400-09 soil CO_2 flux chamber (Figure 1). The system volume (including gas analyzer optical bench) is 991 cm^3 and the measured soil area is 71.6 cm^2. The CO_2 and water vapor analyzers are attached directly to the chamber and mixing in the chamber headspace is achieved with the gas analyzer mixing fan and the associated manifold (Figure 2). During a measurement, chamber air is withdrawn at the top of the chamber through the analyzer inlet duct and enters the optical path of the gas analyzer. Air is returned from the gas analyzer through the analyzer outlet ducts to the manifold near the soil surface. Soil CO_2 flux measurements were made using a soil collar inserted 3 to 4 cm into the soil as an interface between the soil and the chamber.

A high resolution pressure sensor (Datametrics Barocel type 590, Wilmington, MA) was used to monitor the pressure inside the chamber across a range of operating conditions in order to evaluate how operation of the system may influence pressure over the soil during a typical measurement.

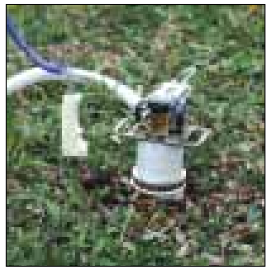

Figure 1. The CO_2 and H_2O analyzers in the LI-6400 sensor head are attached directly to the soil chamber.

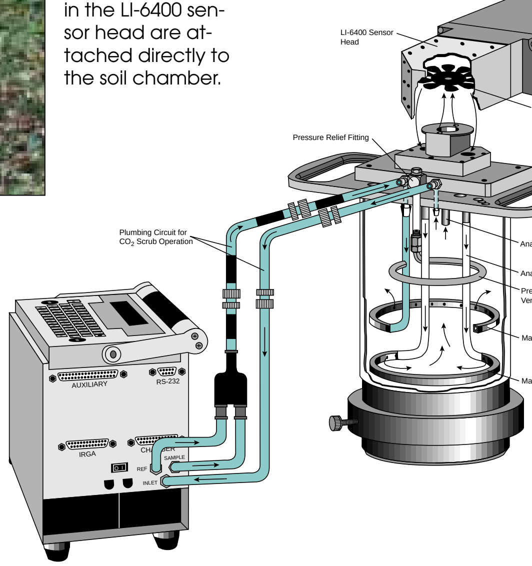

Figure 2. LI-6400 soil CO_2 flux system setup. The plumbing circuit highlighted in color is for CO_2 scrub operations; *it is only used during the draw down portion of a measurement cycle.* During the measurement, mixing in the chamber headspace is achieved with the gas analyzer mixing fan and manifold.

Chamber CO_2 Concentration and Soil CO_2 Flux

Soil CO_2 flux was measured while chamber headspace CO_2 concentration was allowed to rise (Figure 3). The soil CO_2 flux dropped from about 8 $\mu mol\ m^{-2}\ s^{-1}$ to about 4 $\mu mol\ m^{-2}\ s^{-1}$ as chamber headspace CO_2 concentration rose from 250 $\mu mol\ mol^{-1}$ to 1500 $\mu mol\ mol^{-1}$.

These measurements demonstrate the dependence of soil gas exchange measurements on the chamber CO_2 concentration and confirm Healy et. al. (1996) predictions in which analytical and numerical models of gas diffusion were used to evaluate the influence of chamber headspace concentration on estimates of soil CO_2 flux. They predicted that chamber-induced perturbations of the concentration gradient between the soil atmosphere and the free atmosphere above the soil could cause substantial underestimates of soil CO_2 flux, and that errors would be larger with increased chamber deployment time and air filled porosity of the soil.

The LI-6400 soil CO_2 flux measurement system has been designed to minimize perturbations in the soil-atmosphere CO_2 concentration gradient. Before starting the measurement, the ambient CO_2 concentration at the soil surface is measured. Once the chamber is installed, the CO_2 scrubber is used to draw the CO_2 concentration in the chamber headspace down below the ambient CO_2 concentration. The scrubber is turned off, and soil CO_2 flux causes the CO_2 concentration in the chamber headspace to rise (Figure 4). Data are logged while the CO_2 concentration rises through the ambient level. The software then computes the flux appropriate for the ambient concentration (Figure 5). The LI-6400 performs this measurement cycle automatically for as many iterations as desired.

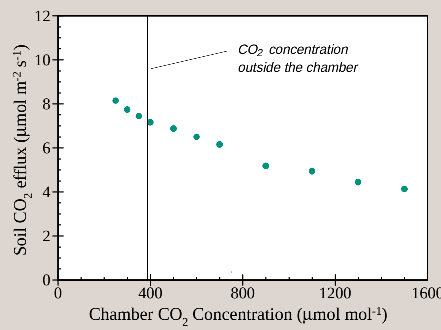

Figure 3. The dependence of soil CO_2 flux on chamber headspace CO_2 concentration.

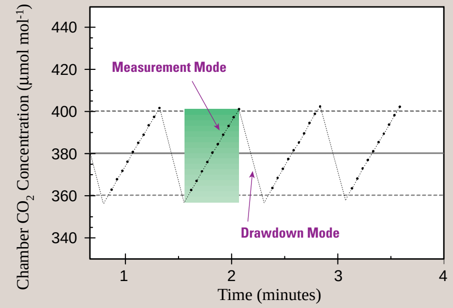

Figure 4. Data from four measurement cycles using a protocol which results in the soil CO_2 flux measurement being made with the chamber headspace CO_2 concentration at the outside ambient concentration of 380 $\mu mol\ mol^{-1}$.

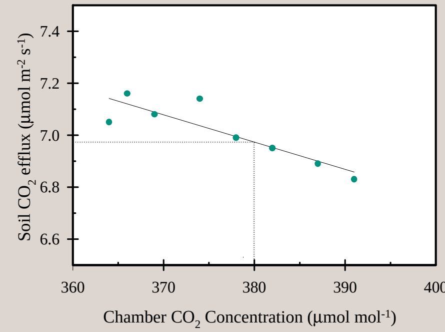

Figure 5. Intermediate flux values were used to calculate efflux at ambient conditions (380 $\mu mol\ mol^{-1}$ in this measurement). Data for Figures 3-5 were collected on a Steiner clay loam soil amended with garden humus.

Chamber Pressure Tests

Pressure tests on the system are summarized in Table 1. The pressure difference between inside the chamber and outside the chamber was measured with the system operating in measurement mode (pump off). Chamber headspace pressure was not significantly different from ambient atmospheric pressure when the mixing fan was turned on and set to the fast mixing rate.

Table 1. A summary of measurements of the difference between atmospheric pressure outside the chamber and pressure in the soil CO_2 flux chamber headspace induced by various modes of operation.

System Operation Mode	Pressure Difference Inside to Outside of Chamber (Pa)	Std. Dev. (# of samples)
In Measurement Mode Fan On vs Fan Off	+ 0.02 (NS)	0.06 (n=7)
In Scrub Mode Pump On vs Pump Off	+ 0.17 (P<0.01)	0.06 (n=5)

CO_2 **Drawdown Mode** is initiated by turning on the pump. This causes a positive pressure transient with a maximum of 2.5 Pa above ambient and duration of 0.25s (FWHM). The pressure then settles down to a steady state value about 0.17 Pa above ambient while in Drawdown Mode. Turning off the pump initiates **Measurement Mode**. This causes a negative pressure transient with a minimum about -2.0 Pa below ambient and duration of 0.37s (FWHM). In Measurement Mode, a steady state pressure about 0.02 Pa above ambient (NS) is reached within 1s of turning off the pump.

A systematic bias in pressure over the soil surface can cause significant perturbations of gas exchange. Flow-through or "open" systems are problematic because the pressure differentials necessary to provide flow can suppress or enhance CO_2 emissions. Kanemasu et. al. (1974) measured 10-fold changes in soil CO_2 flux with steady state pressure changes of 2 to 3 Pa in a flow through system. Air turbulence can also cause pressure gradients (Kimball and Lemon, 1971), and Hanson et. al. (1993) found a strong dependence of soil CO_2 flux on the mixing-fan speed inside a chamber. In the closed system reported here, mixing in the chamber headspace is achieved with a manifold and pressure is maintained in dynamic equilibrium with ambient barometric pressure by venting the chamber through a 0.25 m length of 4 mm ID tubing.

The efficacy of these measures is demonstrated by the very small pressure changes measured as the system was used in various operation modes.

Conclusions

- Chamber headspace CO_2 concentration can substantially affect measured CO_2 flux rates.
- The soil chamber system reported here measures soil CO_2 flux at ambient CO_2 concentration.
- Pressure gradients as small as 1 Pa can have substantial effects on measured CO_2 flux rates.
- The soil chamber system reported here operates at or very near ambient barometric pressure during the measurement cycle and 0.17 Pa above ambient during the drawdown cycle. Very brief (≤ 0.37s FWHM) pressure transients occur when the pump is turned on or off.

References

Hanson, P.J., Wullschleger, S.D., Bohlman, S.A. & Todd, D.E. (1993) Seasonal and topographic patterns of forest floor CO_2 efflux from an upland oak forest. Tree Physiology 13:1-15.

Healy, R.W., Striegl, R.G., Russell, T.F., Hutchinson, G.L. & Livingston, G.P. (1996) Numerical evaluation of static-chamber measurements of soil-atmosphere gas exchange: Identification of physical processes. Soil Sci. Soc. Am. J. 60:740-747.

Kanemasu, E.T., Powers, W.L. & Sij, J.W. (1974) Field chamber measurements of CO_2 flux from soil surface. Soil Science 118(4): 233-237.

Kimball, B.A. & Lemon, E.R. (1971) Air turbulence effects upon soil gas exchange. Soil Sci. Soc. Amer. Proc. 35:16-21.

Kimball, B.A. (1983) Canopy gas exchange:gas exchange with soil. *In* Limitations to efficient water use in crop production. ASA-CSSA-SSSA, Madison,WI.

Norman, J.M., Garcia, R.L. & Verma, S.B. (1992) Soil surface CO_2 fluxes and the carbon budget of a grassland. Journal of Geophysical Research 97(D17): 18845-18853.

LI-COR®