Considerations for making chamber-based soil CO_2 flux measurements

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Abstract
Chamber-based method for making soil CO_2 flux (F_c) measurement has two basic system designs: closed-chamber systems (also called transient or non-steady-state systems), and open-chamber systems (also called steady-state systems). For closed systems, air is circulated from a chamber to an infrared gas analyzer (IRGA) and then returned to the chamber. F_c is estimated from the rate of CO_2 concentration increase inside a chamber that has been deployed on the soil surface for a short period of time. For an open system, fresh ambient air is pumped into or pulled from a chamber, and F_c is calculated using the air flow rate and the difference in CO_2 concentrations between the air entering and leaving the chamber after the air in the chamber headspace has reached a steady state. In this paper, we will discuss in detail those considerations and requirements in chamber design and in making soil CO_2 flux measurements. Due to the space limit, the discussion will be on the closed-chamber design only.

Key Words
Soil CO_2 flux, Closed-chamber based flux measurement, steady-state soil CO_2 flux system.

Introduction
Soil CO_2 production is the sum of the respiration from free-living microbes (heterotrophic) and plant roots (autotrophic), and it is strongly temperature dependent. On a seasonal scale, soil CO_2 production will also depend on the soil moisture, soil organic content, growth activity of plants etc. Due to the high resistance to gas transport in the soil, a strong CO_2 concentration gradient exists in the soil and across the soil surface. This gradient, among others, is a major driving force for soil CO_2 efflux. The fundamental requirement for an accurate F_c measurement is that the deployment of chambers and sensors must have no or minimal disturbance to environment conditions that have impact on soil CO_2 production (soil temperature, soil moisture, radiation, wind speed, plant growth, shading on soil etc.) and CO_2 transport (CO_2 diffusion gradient, chamber pressure equilibrium etc.) across the soil surface.

Methods for soil CO_2 flux measurement
The closed-chamber method is the most common approach used to estimate the fluxes of CO_2 (F_c, μmol/m^2/s) and other trace gases at the soil surface. It is widely used in carbon cycle research, soil sciences, agronomy, and other environmental research areas (*Norman et al.* 1992; *Davidson et al.* 2002). F_c can be estimated with Eq. 1 using the information of chamber volume (V), soil surface area (S), air temperature (T), atmospheric pressure (P), and the rate of CO_2 concentration increase inside the chamber (dC_c/dt, μmol/mol/s) which has been on the soil surface for a short period of time.

$$F_c = \frac{PV}{RTS}\frac{dC_c}{dt} \qquad (1)$$

Where R is the gas constant (8.314 Pa m^3/°K/ mol).
Many custom-made closed systems have been described in the literature (e.g. *Savage and Davidson*, 2003; *Irvine and Law, 2002*) and commercial systems are also available. Figure 1 presents a schematic diagram for an automated closed-chamber system (LI-8100, LI-COR Biosciences, Lincoln, NE USA).

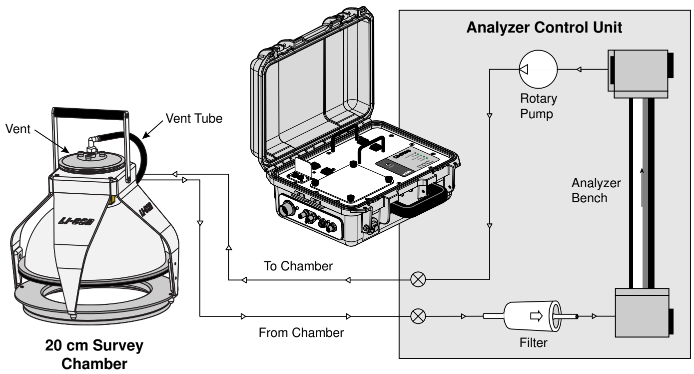

Figure 1. Schematic diagram of the measurement flow path for the Automated Soil CO_2 Flux System (LI-8100, LI-COR Biosciences, Lincoln, NE USA). A 20-cm survey chamber is shown with the control unit. The system can also support measurements with a 10-cm survey chamber and a 20-cm Long-term Chamber.

The concept of chamber-based soil CO_2 flux measurements can at first seem quite simple, because the only items needed for making a measurement are a chamber, a pump, a CO_2 gas analyzer, and a data-logging device. However, we must take many considerations into account in the process of instrument design and making the measurements in order to have accurate flux data. As stated above, soil CO_2 production strongly depends on many environmental conditions. Also, soil CO_2 flux is a physical process driven primarily by the CO_2 concentration diffusion gradient between the upper soil layers and the atmosphere near the soil surface. The fundamental challenge for making accurate soil CO_2 flux measurements is that the deployment of chambers must have minimal or no disturbance to environmental conditions that impact CO_2 production and transport inside the soil profile. The four most important considerations for an accurate measurement are (1) maintaining the chamber-pressure equilibrium with ambient air pressure, (2) ensuring good mixing of the air inside the chamber, (3) dealing with an altered diffusion gradient inside the chamber, and (4) minimizing the disturbance to the environment. Below we will discuss each of these considerations and how we carefully address them.

Maintaining pressure equilibrium between inside a chamber and the ambient air.

Pressure equilibrium between inside a flux chamber and the surrounding air outside the chamber must be maintained during the measurement. A simple open vent tube connecting to the chamber has often been used for the chamber pressure equilibrium (e.g. Hutchinson and Mosier, 1981; Davidson *et al*. 2002). This approach, however, is effective only under calm conditions. Under windy conditions, negative chamber pressure excursion will occur as wind blows over the vent tube's external open end because of the Venturi effect. This will cause a mass flow of CO_2-rich air from the soil into the chamber, leading to a significant overestimation of soil CO_2 flux. In fact, some researchers (e.g. Conen and Smith 1998) recommended eliminating the vent tube after recognizing the potential problem from the Venturi effect.

Scientists and engineers at LI-COR Biosciences have developed a novel vent design for our chambers. The new vent has a tapered cross section as shown in Figure 2. Conservation of mass requires that the average air flow rate drops as the air enters the vent. According to Bernoulli's equation, as the air flow rate decreases, a major portion of dynamic pressure is converted to static pressure, raising the static pressure with which the chamber equilibrates. This design is radially symmetric to eliminate wind-direction sensitivity. Data from field experiments on differential pressure measurements between inside the chamber and the outside ambient air show that chambers equipped with our newly designed vent always have internal chamber pressure equal to outside the chamber under both calm and windy conditions. Our new vent thus virtually eliminates the Venturi effect. For more details, see our published journal paper (Xu *et al*. 2006).

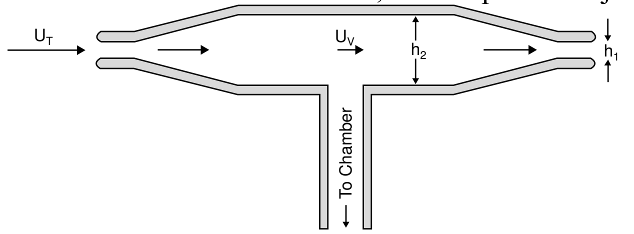

Figure 2. Cross-section view of the new vent design (patent pending). U_T is the wind speed at the height of the vent. U_V is the wind speed inside the vent near the vent tubing. h_1 and h_2 is the edge and the central distance between the upper- and the lower-half of the vent. U_v depends on the ratio of h_1 to h_2.

Ensuring good mixing.
Because only a small portion of the chamber air is sent to the infrared gas analyzer to determine dC_c/dt, good mixing inside the chamber is essential. A mixing fan often has been used in many custom-made soil CO_2 flux systems to achieve good mixing, but using a mixing fan inside a chamber can also cause disturbances in the pressure equilibrium. To eliminate any potential chamber pressure perturbation, a mixing fan is not used on LI-8100 chambers. Good mixing is achieved through both optimal bowl-shaped chamber geometry or a mixing manifold.

Dealing with altered CO_2 diffusion gradients.
Soil CO_2 flux is driven primarily by the CO_2 diffusion gradient across the soil surface. With the closed-chamber technique for estimating the flux, the chamber headspace CO_2 concentration (C_c) must be allowed to rise in order to obtain dC_c/dt. However, raising C_c will reduce the CO_2 diffusion gradient across the soil surface inside the chamber, leading to an underestimation of the flux. To overcome this, a new exponential function is derived to fit the time series of C_c (Eq. 2). With the initial slope (dC_c/dt at t=0) of the fitted function (Eq. 3), the flux is then estimated at the time of chamber closing, when C_c is close to the ambient level.

$$C_c = C_s + [C_c(0) - C_s]e^{-at} \tag{2}$$

$$\frac{dC_c}{dt} = a[C_s - C_c(0)]e^{-at} \tag{3}$$

where C_s is the CO_2 concentration in the soil surface layer communicating with the chamber (µmol/mol), and a is a rate constant (1/s).

From the literature, a linear regression often has been used on the time series of C_c to determine dC_c/dt. Our experimental data show that the underestimation of F_c from the linear approach was systematic and significant, even though the linear regression sometimes gave a very high value for the regression coefficient. Furthermore, the underestimation will be greater for porous soil that has a high conductance to gas transport. Therefore we do not recommend using the linear regression on the time series of chamber CO_2 data to determine the dC_c/dt.

Minimizing the disturbance to the environmental conditions.
For a long-term soil CO_2 flux measurement, it is critical to keep the environmental conditions inside the collar as close to the natural conditions as possible. The impact of installation of the long-term chamber on radiation balance, wind field, and precipitation interception should be minimized. This issue was been addressed carefully when we designed the two long-term chambers (8100-101 and 104). Both chambers are parked away from the collar when they are not in the measurement mode. The baseplate of the two long-term chambers is also perforated to minimize the perturbation to the soil environment around the collar.

Also chambers must close and open automatically and slowly. This eliminates the possibility of pushing fresh ambient air into the soil or removing soil air during the chamber closing/opening. Temperature artifacts are minimized by careful consideration of chamber materials and coatings.

Example of soil CO_2 flux measurement over a soybean field in Nebraska
Figure 3 shows an example of diurnal soil CO_2 flux from a soybean field at the University of Nebraska Lincoln Agricultural Experimental Station near Mead, Nebraska USA. The dataset was obtained in the middle of the growing season (July 9 to 19, 2006). The flux value and soil temperature at 5 cm depth were averaged from 16 measurements at different locations with an LI-8100 sixteen chamber multiplexed soil CO_2 flux system. The soil CO_2 flux ranged from 2 to 7 µmol/m^2/s. The soil CO_2 flux shows a strong diurnal pattern and closely follows the soil temperature variations; this is because microbial respiration increases exponentially with temperature. This flux range of 2 to 7 µmol/m^2/s was comparable with other soil CO_2 flux data published in the literature obtained from similar agricultural fields in the middle of the growing season. Normally, the soil CO_2 flux from natural ecosystems can vary from less than 1 µmol/m^2/s to around 10 µmol/m^2/s, depending on the soil temperature, moisture, soil organic matter, plant canopy size, growing season, etc.

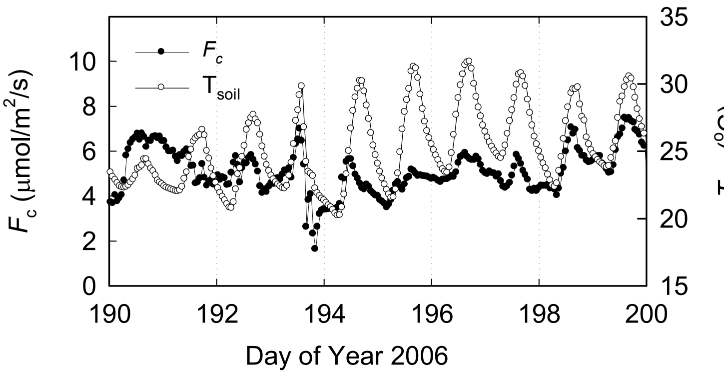

Figure 3. Example of diurnal soil CO_2 flux (F_c) measured with a LI-8100 sixteen chamber multiplexed soil CO_2 flux system from a soybean field at University of Nebraska Lincoln Agricultural Experimental Station at Mead. Soil temperature at the depth of 5 cm (T_{soil}) is also shown.

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1 – 6 August 2010, Brisbane, Australia. Published on DVD.