Accurate Soil CO$_2$ Flux Measurement at High Spatial and Temporal Resolution

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INTRODUCTION

Information about seasonal and spatial variations in soil CO$_2$ flux is essential to understanding how environmental and biological factors regulate soil CO$_2$ flux of an ecosystem. We have developed a 16-port automated multiplexing system for measuring soil CO$_2$ flux at high temporal and spatial scales. It is a closed dynamic system, and has the capability to sequentially measure the soil CO$_2$ flux at up to 16 locations. Each cycle of measurements can be done in one hour. Soil CO$_2$ flux is mostly driven by diffusion and mass flow, with the diffusion being controlled by the CO$_2$ concentration gradient and mass flow pressure fluctuations at the soil surface. In a closed chamber system, the slope of dCO$_2$/dt is required to compute the flux. To minimize the impact of decreased CO$_2$ diffusion gradient on the CO$_2$ flux measurement, the chamber CO$_2$ concentration versus time is fitted with an exponential function. We have also developed a vent design that helps avoid pressure perturbations inside the chamber. Based on Bernoulli's equation, we allow pressure in the chamber to fluctuate along with pressure at the soil surface outside the chamber under both calm and windy conditions. Pressure data measured in the field shows that the new vent design virtually eliminates the Venturi effect.

In this paper we:

❖ Present a system overview of the LI-8150 Multiplexer and data showing a leak test using the bellows pump on the LI-8100.
❖ Present a new way to compute F$_{CO2}$ to minimize the impact of decreased CO$_2$ diffusion gradient inside the chamber, and demonstrate that there is a consistent underestimation of the F$_{CO2}$ using a linear fit as compared with that of an exponential fit.
❖ Discuss the theory and data behind the new vent design.
❖ Present test data from our new multiplexer that demonstrates the temporal and spatial variability of F$_{CO2}$ in a corn field and a grass field, and examine the temperature response of soil CO$_2$ flux.

Multiplexing System Description
The LI-8150 Multiplexer

The automated multiplexer can sequentially measure soil CO$_2$ flux at up to 16 different locations and cover an area with a radius of 17 m (Figure 1). The LI-8150 can operate in temperature ranges between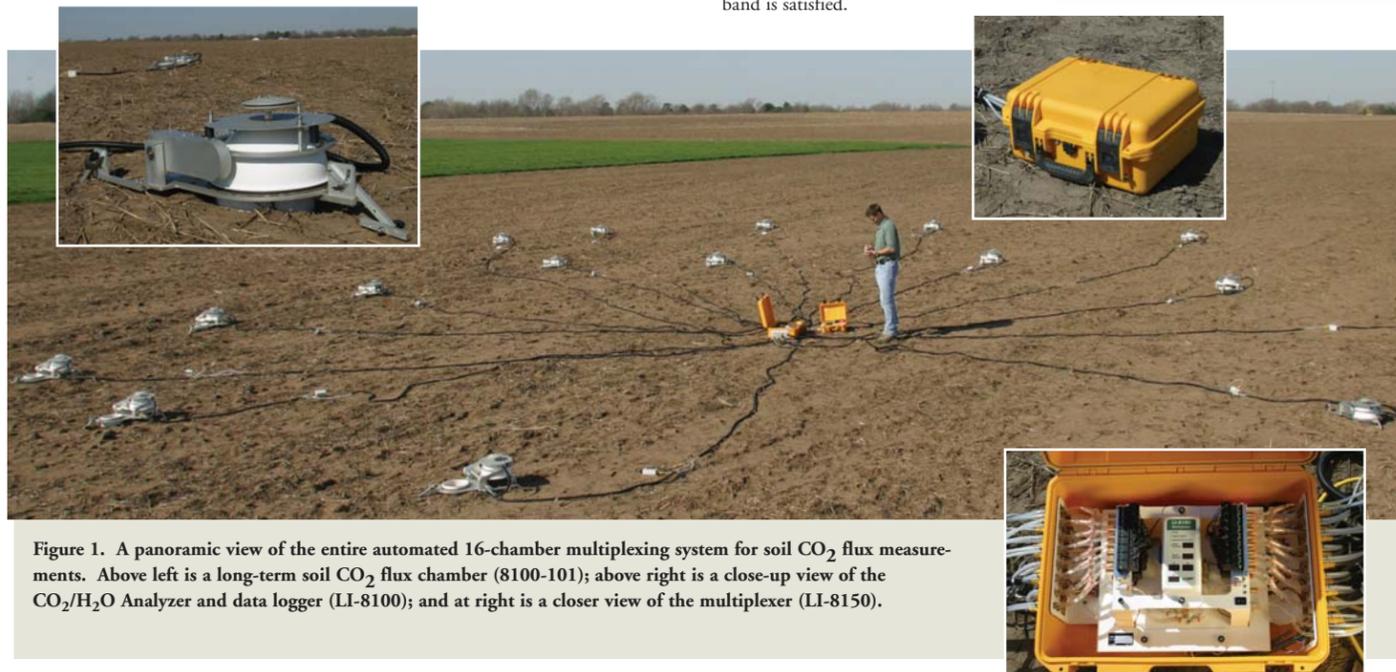 -20°C and 45°C. The combined LI-8100 and LI-8150 system allows for wireless communication with a Personal Digital Assistant (PDA). The chambers have a diameter of 20 cm and a volume of 4.03 liters. The chambers move away from the soil when not in measurement mode. This is to minimize the disturbance from the chamber deployment to the soil inside the collar. To ensure quality data, a leak test can be performed with the software. This leak test uses the bellows pump from the LI-8100 analyzer control unit to pressurize each port in sequence. If a particular port does not remain pressurized for a pre-set time interval, a leak is assumed and further investigation is needed (Figure 2).
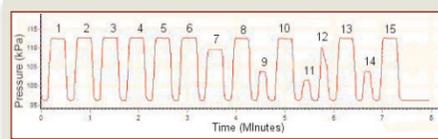
Figure 2. Results from a leak test that show no leaks on chambers 1-6, 8, 10, 13, and 15. Port 7 had twice the cable length attached, explaining the drop in pressure but still showed no leak. Ports 9, 11, 12, and 14 did have a leak. Port 16 was used as the purge port and was tested after all the others. The total time it takes to run a 16-chamber leak test is less than 15 minutes.

Soil CO$_2$ Flux Estimation

The LI-8100 and LI-8150 Multiplexer is a non-steady state, closed chamber system. When the chamber is in measurement mode, sample air is drawn from the chamber to the CO$_2$ gas analyzer, then sent back to the chamber. F$_{CO2}$ is estimated based on the increase rate of CO$_2$ concentration (dCO$_2$/dt). Obtaining the slope of dCO$_2$/dt allows the chamber CO$_2$ concentration to rise; thus the soil CO$_2$ flux inside the chamber is suppressed due to the decreased CO$_2$ diffusion gradient. To overcome this, we first fit the time series of chamber CO$_2$ concentration (C$_t$) with the following exponential function after a dead band is satisfied.
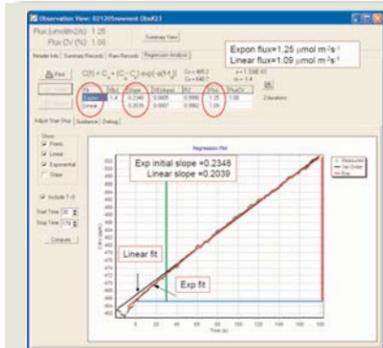
Figure 3. LI-8100 approach to measure the soil CO$_2$ flux (F$_{CO2}$) at ambient CO$_2$ concentration. In this example, the measurement lasts for 2 min with a dead band of 30 s.

$$C_t = C_x + (C_o - C_x)\, e^{-a(t-t_o)}$$

Where C$_x$ is CO$_2$ concentration in the soil surface layer, C$_o$ is initial chamber CO$_2$ concentration when the chamber closes. F$_{CO2}$ is then estimated by calculating the initial slope from this exponential function at t$_o$, which is when the chamber CO$_2$ concentration equals the ambient (Figure 3). The underestimation of F$_{CO2}$ when using linear fit gets more severe when you have lighter soil or forest soil with a lot of organic matter because of high conductance at the soil surface.

Chamber Pressure Equilibrium

Many studies have demonstrated that a small pressure change inside the chamber can cause a large bias for the measured F$_{CO2}$ (Denmead et al., 1979; Davidson et al., 2002), so it is necessary to prevent any pressure difference between the chamber and ambient air if measured values of F$_{CO2}$ are to accurately represent rates outside the chamber.
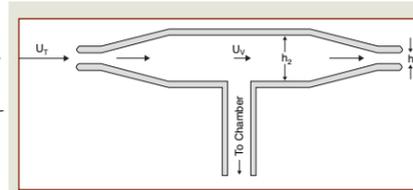
Figure 4. Cross-section view of the new vent design (patent pending). T is the wind speed at the height of the vent, Uv is the wind speed inside the vent near the vent tube, and h1 and h2 are the edge and the central distances between the upper and lower halves of the vent.

Each chamber is equipped with our newly designed vent that maintains pressure equilibrium inside the chamber and the ambient air under calm and windy conditions (Xu et al., 2005) (Figure 4). The new vent was based on Bernoulli's equation. This novel vent design reduces the speed of wind as it passes over the vent opening, increases the static pressure of the air at the vent opening and eliminates the pressure differences between the chamber and the surrounding air. This solves the problem of unequal pressure equilibrium under windy conditions (Bain et al., 2005).

Field Testing

The LI-8100 and LI-8150 Multiplexer, fully deployed, can allow the user to obtain high temporal and spatial resolution soil CO$_2$ flux data in an ecosystem. Figure 5 shows a 2-week testing dataset obtained with the automated 16-chamber multiplexing system. The system was deployed in a dryland cornfield in September 2005 at the Agricultural Experiment Station, University of Nebraska-Lincoln, near Mead, NE. The corn plant was at the end of senescence stage. To study the spatial variability of F$_{CO2}$ in the field, 8 chambers were installed between rows and 8 chambers within rows. From this 2-week experiment, we show:

1. F$_{CO2}$ was significantly higher within row than between rows;
2. A strong diurnal variation in F$_{CO2}$ for both between rows and within row;
3. A rain event occurred on DOY 271, causing a sudden increase in F$_{CO2}$;
4. The diurnal variation in F$_{CO2}$ after the first frost (on DOY 272) became smaller, probably due to a significant decrease in the autotrophic respiration.

Figure 5. Diurnal variation of soil CO$_2$ flux for between rows and within rows from a dryland cornfield near Mead, NE. Each data point represents the mean and one standard error with the sample number ranging from 4 to 8.
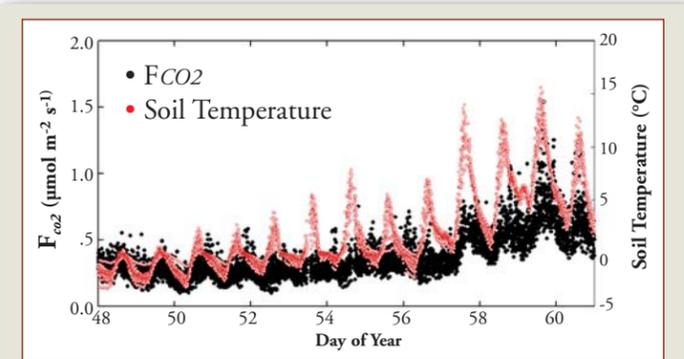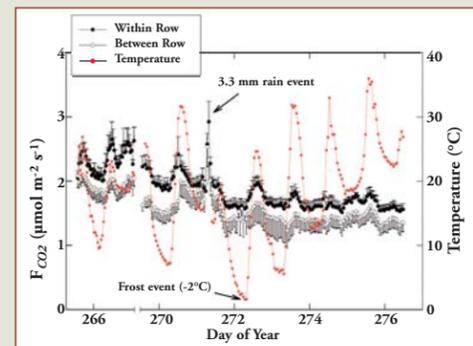
Figure 6. Time series of soil CO$_2$ flux data obtained with an automated 16-chamber soil CO$_2$ flux multiplexing system at LI-COR Biosciences research facility in February 2006. Also shown in the figure are the soil temperature data at a depth of 5 cm at each chamber.

Relationship between F$_{CO2}$ and soil temperature (Q$_{10}$)

Figure 6 shows a dataset from testing with the LI-8100/8150 multiplexer at the LI-COR research facility in February of 2006. Because of a warmer than usual Nebraska winter, data were obtained with the 16-chamber multiplexer system at a range of temperatures. Soil temperature at 5 cm depth near each soil collar was also measured via auxiliary input channels at each chamber. Results indicate that the soil CO$_2$ flux followed soil temperature nicely in a well-known Q$_{10}$ relation. The Q$_{10}$ was 2.1 (Figure 7).

Figure 7. Response of soil CO$_2$ flux (F$_{CO2}$) to change in soil temperature at the depth of 5 cm. Same dataset as presented in Figure 6.
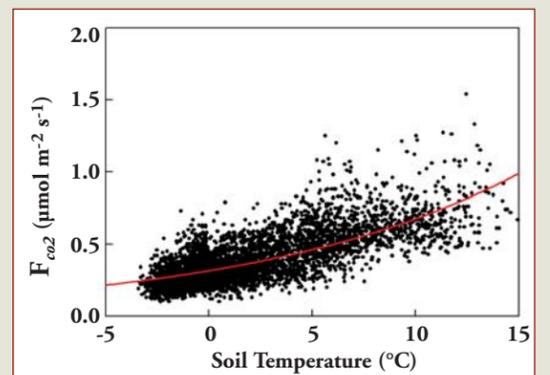
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Figure 1. A panoramic view of the entire automated 16-chamber multiplexing system for soil CO$_2$ flux measurements. Above left is a long-term soil CO$_2$ flux chamber (8100-101); above right is a close-up view of the CO$_2$/H$_2$O Analyzer and data logger (LI-8100); and at right is a closer view of the multiplexer (LI-8150).

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