On Maintaining Pressure Equilibrium Between a Soil CO_2 Flux Chamber and the Ambient Air

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Abstract

Pressure equilibrium between inside a soil CO_2 flux chamber and the surrounding air outside the chamber must be maintained during a measurement if measured soil CO_2 flux (F_{CO2}) is to accurately represent the rate occurring naturally outside the chamber. In previous studies, a simple vent tube connecting to the chamber has often been used to maintain pressure equilibrium. This approach, however, can be effective only under calm conditions. Under windy conditions, negative pressure excursions will occur inside the chamber that are artifacts resulting from wind passing over the vent tube's external open end, a phenomenon known as the Venturi effect. This causes anomalous mass flow of CO_2-rich air from the soil into the chamber, leading to a significant overestimation of F_{CO2}. In this present study, we found that negative chamber pressure excursions due to the Venturi effect cannot be observed unless the differential pressure measurement is made with the chamber resting on an impermeable base. Making pressure measurements with a chamber resting on porous soil can lead to the erroneous conclusion that an anomalous mass flow is not a problem precisely when it is causing serious artifacts. We also present a new vent design for a soil CO_2 flux chamber capable of maintaining pressure equilibrium between inside the chamber and the ambient air outside the chamber under both calm and windy conditions. Differential pressure measurements from field experiments show that the pressures inside our newly-designed vented chamber equal those outside the chamber when wind speed at a height of 0.5 m was up to 7 m s^{-1}, thus virtually eliminating artifacts due to the Venturi effect. Our field data show that the problem of overestimation in measured F_{CO2}, by a chamber with older vent designs under windy conditions, can be avoided with our newly-designed vented chamber.

Introduction

Recent concern over global warming and climate change has highlighted the need to improve the accuracy in estimating carbon flux across a wide range of scales. Chamber-based techniques are probably the most common approach used for studying the fluxes of CO_2 (F_{CO2}) and other trace gases at the soil surface. This approach is widely used in carbon cycle and other environmental-related research (*Norman et al.*, 1997; *Davidson et al.*, 2002).

There are two general system designs for making soil CO_2 flux measurement: the closed-chamber system (also called a transient or non-steady-state system) and the open-chamber system (also called a steady-state system) (*Livingston and Hutchinson*, 1995; *Davidson et al.*, 2002). For a closed system, air is circulated from a chamber to an infrared gas analyzer (IRGA) and then sent back to the chamber. F_{CO2} is estimated from the rate of CO_2 concentration increase inside the chamber, which has been deployed on the soil surface for a short period of time. Many custom-made closed systems have been reported *(e.g. Savage and Davidson*, 2003; *Irvine and Law*, 2002), and such systems are also commercially available (e.g. LI-6400-09 and LI-8100 from LI-COR Biosciences, Lincoln NE, USA; SRC-1 from PP Systems, Hertfordshire, UK; SRS-1000 from ADC, Hoddesdon, UK). For an open system, fresh, ambient air is pumped into or pulled from a chamber, and F_{CO2} 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 an equilibrium state. Many variations of open-chamber designs have appeared (*e.g. Rayment and Jarvis*, 1997; *Fang and Moncrieff*, 1998; *Edwards and Riggs*, 2003; *Subke et al.*, 2003; *Butnor et al.*, 2003), and some are commercially available (e.g. SRC-MV5 soil respiration chamber, Dynamax Inc., Houston TX, USA). Comprehensive reviews of the advantages and disadvantages of each type of system can be found in the literature (*Livingston and Hutchinson*, 1995; *Hutchinson and Livingston*, 2002; *Davidson et al.*, 2002). Here our discussion will be focused on the impact that small pressure differences between the chamber and ambient air can have on F_{CO2} measurements.

Soil is a complex porous medium containing CO_2 sources form both heterotrophic and autotrophic respiration. These sources combined with diffusion resistance due to the porosity and tortuosity of the soil often lead to high CO_2 concentration gradients within the soil profile and between the soil and the atmosphere. Soil CO_2 efflux is driven both by diffusion and mass flow, with diffusion being controlled by the CO_2 concentration gradient and mass flow by pressure fluctuations at the soil surface. There are several mechanisms that can cause these pressure fluctuations, which can enhance soil CO_2 efflux (*Kimball and Lemon*, 1972; *Massman et al.*, 1997; *Takle et al.*, 2004). Wind is one of the most important contributors to surface pressure fluctuations due to its turbulent nature and its interactions with various obstacles in the field, such as trees, rock outcroppings, complex terrain, etc. (*Takle et al.*, 2004). Generally, under windy conditions, higher soil CO_2 efflux could be expected, and a few experimental datasets in the literature seem to support this conclusion (*Baldocchi et al.*, 1991; *Takle et al.*, 2004).

Mass flow is more effective for long distance gas transport than molecular diffusion. Small chamber pressure deviations from the surrounding ambient pressure can cause an anomalous mass flow, leading to potentially large over- or underestimations of the soil CO_2 flux (*Denmead, 1979*; *Fang and Moncrieff*, 1998; L*und et al.*, 1999). Therefore, pressure equilibrium between inside the chamber and the ambient air must be maintained during a measurement so measured F_{CO2} can represent the rate occurring naturally outside the chamber. Despite more than a decade of research, questions on how to maintain pressure equilibrium have remained troublesome for both closed- and open-chamber systems (*Hutchinson and Livingston*, 2001; *Davidson et al.*, 2002). Furthermore, studies of the sensitivity of measured F_{CO2} to differential pressure developed between the chamber and ambient air show a wide range of variation.

In the discussion that follows, we will use the symbol ΔP to represent the difference in the static pressure between inside a chamber and the ambient air outside the chamber, with a negative sign meaning the chamber pressure is below the ambient air pressure. Many studies have been reported in which open chamber systems have been used to investigate the sensitivity of measured F_{CO2} to artificial pressure perturbations (*Kanemasu et al.*, 1974; *Fang and Moncrieff*, 1996; *Rayment and Jarvis,* 1997). For example, *Kanemasu et al.* (1974) showed that changing the static pressure inside the chamber from 2.5 Pa above ambient air to -1.0 Pa below ambient air caused an order of magnitude increase in F_{CO2}. Also, using an open system, *Denmead* (1979) showed that a ΔP of -100 Pa (equivalent of 0.01 m water) can produce a flux of N_2O ten times the rate at zero pressure difference. A ΔP of -10 Pa (equivalent of 0.001 m water) almost doubled the flux rate of N_2O. More recently, *Fang and Moncrieff* (1998) reported that a ΔP of -1 Pa caused an order of magnitude increase in measured F_{CO2}. In addition, they found that although measured F_{CO2} is less sensitive to a positive pressure difference than to a negative one, a positive pressure difference of a few tenths of a Pa will still cause a significant underestimate of F_{CO2}. *Widén and Lindroth* (2003) used their own custom-made calibration system to study the effect of pressure perturbation on F_{CO2} and concluded that a ΔP of -0.15 Pa could increase the CO_2 flux by 11% to 40%, depending on the porosity of the soil column. *Ryden et al.*, (1978) found that a ΔP of 0.05 Pa did not change the measured flux of N_2O. *Gao and Yates* (1998a,b) indicated that steady state flux may be overestimated when pressure in the chamber drops more than 1 Pa below ambient, but may be underestimated when chamber pressure is as little as 0.25 Pa above ambient.

Open-chamber systems require air to be pushed or pulled through the chamber, which can cause chamber pressures to be increased or decreased from ambient. If they exist, such pressure deviations are likely to cause mass flow across the soil surface, which will reduce or enhance the apparent soil respiration rate. Generally speaking, it would be very difficult to eliminate the pressure difference between air inside and outside the chamber while maintaining air flow through the system. Despite the difficulty, some studies report that ΔP can be effectively eliminated with specially designed soil gas exchange chambers (*e.g., Fang and Moncrieff*, 1998; *Rayment and Jarvis,* 1997). These authors concluded that it is unlikely their chambers create large enough pressure differences to drive mass flow across the soil surface. Results we present here, however, demonstrate that differential pressure measurements made with the chamber placed on the soil can lead to erroneous conclusions. We will show that significant mass flow out of the soil can occur even when the measured ΔP seems negligibly small.

Fewer studies have been reported using closed systems to investigate the impact of ΔP on measured F_{CO2}, but results from these studies also have shown that measured F_{CO2} can be very sensitive to chamber-induced pressure artifacts due to wind. For example, *Davidson et al.*, (2002) found that a ΔP as small as ±0.1 Pa between the inside and outside of a vented chamber caused approximately 15% errors in measured F_{CO2}. They also observed much larger pressure differences (±0.9 Pa) under windy conditions and came to the conclusion that F_{CO2} measurements obtained under those conditions were not reliable. *Lund et al.* (1999) showed how positive chamber pressure artifacts affected measured F_{CO2}. They placed a vented chamber (LI-6200, LI-COR Biosciences) inside a large open-top chamber in which positive pressures ranging from 0 to 40 Pa could be generated. In their experiments, both the respiration chamber and the surrounding soil in the open-top chamber were pressurized. They found that when pressure in the open-top chamber was increased by only 0.5 Pa, F_{CO2} was reduced by 20% to 70%, with a much larger underestimation from dry soil. Measured F_{CO2} was reduced by 70% to 90% when the pressure in the open-top chamber was raised by 6 Pa above the ambient pressure outside the open-top chamber.

Recognizing the potentially large impact of small chamber-induced ΔPs on CO_2 flux measurements, several authors (*Hutchinson and Mosier,* 1981; *Norman et al.*, 1992; *Savage and Davidson,* 2003) have used a vent tube connected to the chamber to maintain pressure equilibrium between the chamber and outside the ambient air. Some researchers have argued that CO_2 loss through the vent tube could be problematic, especially when the flux rate is low (*e.g. Conen and Smith*, 1998). But *Hutchinson and Mosier* (1981) showed that CO_2 loss through the vent tube is not likely to be significant if careful considerations are given to the internal diameter and length of the vent tube. Two mechanisms may lead to loss of CO_2 through the vent tube: diffusion and mass flow. Diffusion is driven by the CO_2 concentration gradient between the chamber and the ambient air. *Hutchinson and Livingston* (2001) found diffusion loss to be negligible if the vent tube is designed properly. They estimate that for a vent tube with an ID of 9 mm and a length of 15 cm, the loss was less than 0.04% of the total flux for a 14-l chamber over a 30-min measurement period. Mass flow in the vent tube in response to ambient pressure fluctuations might also cause CO_2 loss. This can be avoided almost completely if the internal dimensions of the vent tube are large enough to contain the air movement that will occur in response to the expected maximum amplitude of pressure waves normally occurring at the soil surface (*Kimball and Lemon*, 1970; *Hutchinson and Mosier*, 1981).

But using a simple vent tube located either at the top of the chamber (*Hutchinson and Mosier*, 1981; *Flessa et al.*, 1995; *Conen and Smith*, 1998; *Savage and Davidson*, 2003) or hung at the side of the chamber (*Norman et al.*, 1992; *Hutchinson and Livingston*, 2001) can be effective only under calm conditions. Under windy conditions, negative chamber pressure excursions (negative ΔP) will occur as wind blows over the vent tube's external open end, a phenomenon known as the Venturi effect (*Conen and Smith*, 1998). This will pull CO_2-rich air from the soil into the chamber, leading to a significant overestimation of F_{CO2}. Numerous studies have shown that spuriously high F_{CO2} values often are observed with the simple vent approach under windy conditions. For example, Conen and Smith (1998) observed unreasonably high N_2O flux values from their vented chamber when it was windy. After recognizing the high flux was due to the negative chamber pressure excursion, they recommended using non-vented chamber systems and concluded that "Venting can create larger errors than the ones it is supposed to overcome." *Longdoz et al.*, (2000) observed that pressure inside their vented chamber deviated from ambient pressure under windy conditions. They noted that the influence of ΔP on measured F_{CO2} was difficult to quantify, so only the data from calm conditions were reported. *Davidson et al.* (2002) noted that the accuracy of CO_2 flux measurements under windy conditions was questionable. *Hutchinson and Livingston* (2001) suggested that "the vent tube must be properly sized, should be mounted as near the ground as practical to minimize wind speed (probably in the chamber side wall rather than its top), and its outlet should be horizontal and should be pointed downward. In addition, it may be necessary to shield the vent tube's open end during strong wind."

In summary, there is still no method that has been proven to be effective to ensure chamber pressure equilibrium with the ambient air under windy conditions. As *Davidson et al.* (2002) wrote: "In general, the chamber pressure should be allowed to vary as gusts of wind cause the pressure within the surface soils to vary, but the effects of this variation can be very complex, and the topic merits more systematic study."

In this paper, we present a new vent design for soil CO_2 flux chambers. This vent allows static pressure inside the chamber to follow whatever static pressure changes occur in the surrounding air outside the chamber under both calm and windy conditions, while remaining insensitive to wind direction. First, we describe the new vent design and describe its theory. Then, we demonstrate its effectiveness using chamber pressure data measured in the field under variable windy conditions. Lastly, comparisons of field-measured F_{CO2} values obtained from chambers equipped with the new vent and chambers having older and less effective vent designs are presented.

Theory and New Vent Design

According to Bernoulli's equation, the sum of the static pressure (P_s), the dynamic pressure (P_d), and the gravitational potential pressure (P_g) is constant along a streamline.

$$P_{s1} + 0.5\rho U_1^2 + \rho g h_1 = P_{s2} + 0.5\rho U_2^2 + \rho g h_2 \qquad (1)$$

Where: P_{s1} and P_{s2} are static pressure at point 1 and 2, respectively; U_1 and U_2 are the fluid velocities; ρ is the density of the fluid, and h_1 and h_2 are the vertical distances of point 1 and 2 from a reference position. The term $0.5\,\rho U^2$ is the dynamic pressure term and ρgh is the gravitational potential pressure term. The four necessary assumptions for satisfying the Bernoulli equation include: (1) points 1 and 2 lie on the same streamline, (2) the fluid is incompressable, (3) the flow is steady and (4) there is no friction.

When air moves, its static pressure drops and dynamic pressure increases, both by an equal amount of $0.5\,\rho U^2$. Assuming air density $\rho \approx 1.0$ kg m^{-3}, when air velocity increases to a speed of 2 m s^{-1}, the dynamic pressure will be 2 Pa, while the static pressure will drop by 2 Pa. If the air velocity increases to 4 m s^{-1}, the dynamic pressure will be 8 Pa, while the static pressure drops by 8 Pa. So, the faster the wind moves, the lower the static pressure will be.

The new vent has a tapered cross section as shown in Figure 1. Conservation of mass requires that the average air flow rate drops in proportion as the vent cross section increases. Thus, the ratio of wind speed inside such a vent (U_V) to wind speed entering the vent, which is taken as equal to the wind speed at the top of the chamber (U_T), should approximate the ratio of h_1/h_2 as defined in Fiigure 1

$$\frac{U_V}{U_T} \approx \frac{h_1}{h_2} \qquad (2)$$

By slowing down the wind velocity within the vent, a major portion of dynamic pressure is converted to static pressure, raising the static pressure with which the chamber equilibrates.

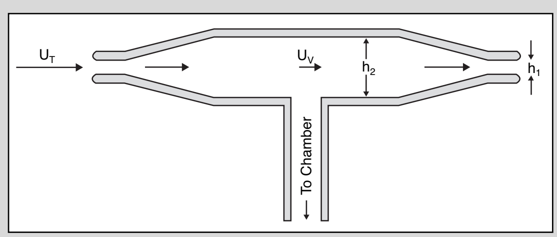


Figure 1. Cross-section view of the new vent design (patent pending). U_T is the wind speed at the height of the vent. U_V is the wind speed inside the vent near the vent tube. h1 and h2 are the edge and the central distances between the upper- and the lower-half of the vent.

Thus, it is clear we can manipulate the static pressure in the chamber by manipulating the ratio h_1/h_2. For example, reducing wind speed by a factor of 5 reduces the dynamic pressure term by a factor of 25, because the dynamic pressure varies as the square of wind speed. This design is radially symmetric so there is always a cross-section with diameter as shown in Figure 1, regardless of wind direction, thus eliminating the wind-direction sensitivity. Eq. 2 will hold at least approximately, and we can use the model to understand and predict how the vent functions.

Under windy conditions, the wind velocity at the soil surface (U_S) is much lower than that at the top of the chamber (0.23-0.25 m for chambers we used in this study). As a result, the static pressure near the soil surface will be higher than that at the top of the chamber, even after the difference in P_g is accounted for. With a simple vent, chamber pressure will drop to the static pressure at the height of the vent. The soil CO_2 efflux is influenced by the fluctuation of the static pressure at the soil surface, not the static pressure at the top of the chamber. Therefore, the vent has to be designed such that pressure inside the chamber must track the fluctuation of static pressure at the soil surface outside the chamber. Of course, under calm conditions, the static pressure at the soil surface will be the same as at any height if we account for the difference in P_g.

We designed the new vent so that the ratio of h_1/h_2 approximates the ratio of U_S/U_T, which depends on the shape of the wind profile. Due to the complexity of the wind profile inside a vegetation canopy, the ratio of U_S/U_T is difficult to determine. It is likely a function of the roughness of the surface and the vegetation height. We roughly estimated that the ratio should be around 1/5 based on the logarithmic wind profile for short canopy vegetation, assuming the wind speed near the soil surface equals that just above the zero displacement height. We verified the ratio with field experiments by looking at the response of ΔP to wind speed at different values of h_1/h_2 (data not shown).

The first field experiments to test the new vent design were conducted in a short grassland ecosystem in Lincoln, Nebraska. We found that when the ratio h_1/h_2 is 1/5, the chamber pressure always closely followed the pressure outside the chamber (see the data presented in Figures 11 and 12C). We also tested the new vent design in a grassland at the Fort Lauderdale Research and Education Center, University of Florida. Results indicated that the 1/5 ratio worked well in that environment also. Although we did not test the new vent design in other vegetations, our preliminary analysis suggests that 1/5 ratio should work well in many environments. For a tall vegetation canopy, such as a forest, if the lower canopy is quite open, then a new logarithmic wind profile will likely be developed with a new zero plane displacement very near the soil surface (*Campbell and Norman*, 1998). Under such conditions, we expect the 1/5 ratio of h_1/h_2 to also work properly. In dense canopies with large LAI, e.g. vigorously growing wheat or corn fields, any type of vent design (including our new vent, simple pigtail vent tubing, etc.) should work fine, simply because the wind speed inside those canopies at a height of 25 cm will be close to zero. Nevertheless, additional field measurements are needed to determine how well vents with the ratio of h_1/h_2=1/5 will perform in different vegetation types. Also, the ratio of 1/5 can only be applied to our commercial chambers or other custom-designed chambers with similar heights (23-25 cm). Most likely, the ratio would need to be adjusted for chambers that have different heights and performance should be verified with ΔP measurements in the fields.

Materials and Methods

Soil CO_2 flux system

An automated soil CO_2 flux system (LI-8100, LI-COR Biosciences, Lincoln, NE, USA) was used in this study. The system is designed for continuous and unattended long-term measurements to obtain high temporal resolution of soil CO_2 flux when used with a 20-cm long-term chamber. This is necessary because soil respiration changes dynamically in response to changes in soil temperature, moisture, rain pulse, and phenology (*Xu et al.*, 2004). The long-term chamber moves completely away from the soil measurement area when a measurement is not in progress to ensure that the moisture and temperature of the soil within the measurement collar are similar to the surrounding soil. The LI-8100 also supports rapid survey measurements when used either with a 10-cm survey chamber or with a 20-cm survey chamber. For the survey chambers, a pressure/vacuum air flow system expands and contracts a bellows to raise and lower the chamber over the soil collar to make the flux measurements. The heights of the three chambers range from 23-25 cm.

The LI-8100 is a non-steady state, transient system. The flux is estimated using the initial slope of a fitted exponential curve at the ambient CO_2 concentration (*McDermitt, et al.*, 2004; LI-COR, LI-8100 Manual). This is done to minimize the impact of the altered CO_2 concentration gradient across the soil surface after the chamber is closed. Chambers of the LI-8100 are vented to maintain pressure equilibrium between the chamber and the ambient air. The vent tube has an internal diameter of 6.4 mm and a length of 15 cm.

Differential Pressure Measurement and Pressure sensor calibration

Experimental setups for differential pressure measurements in the field are illustrated in Figure 2. The vent shown in the figure is the initial vent design, which consists of two round flat plates (7.6 cm in diameter) placed 0.3 cm apart. In Figure 2A, the chamber was resting on a collar that was inserted into soil. In Figure 2B, the chamber was resting on a collar that has a sealed bottom. The high side (H) of a differential pressure transducer (Model PX653, Omega Engineering Inc., Stamford, CT, USA) was connected to the chamber, and the low side (L) to the ambient air just above the soil surface.

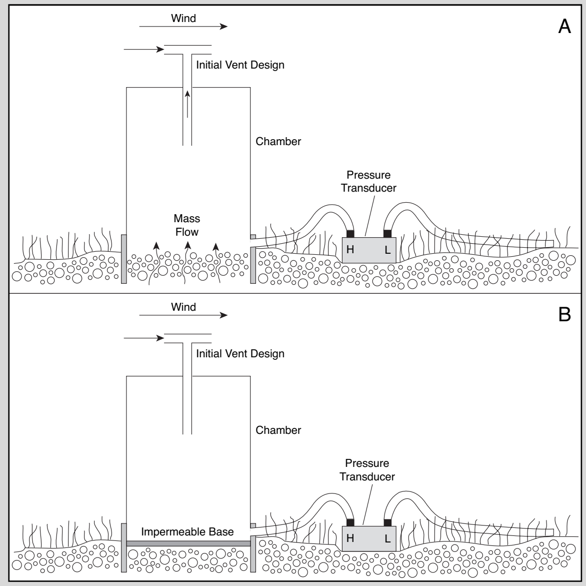
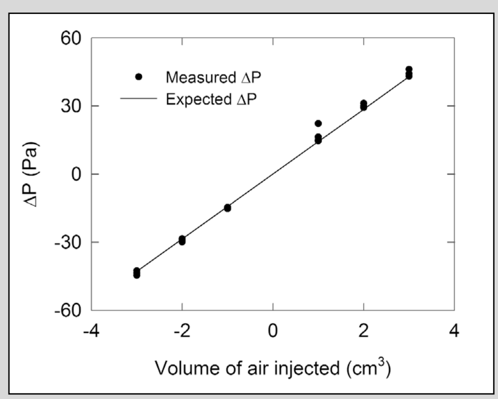


Figure 2. Schematic diagram of the experimental setups used to measure *ΔP* between inside and outside the chamber in the field. The high side (H) of the differential pressure transducer was connected to the chamber, whereas, the low side (L) was exposed to the ambient air in a grass canopy just above the soil surface. The vent shown in the figure was the initial vent design, which consisted of two round flat plates (7.6 cm in diameter) placed 0.3 cm apart. In panel A, the chamber was resting on a collar that was inserted into soil. In panel B, the chamber was resting on a collar that has an impermeable base.

Figure 3. Calibration of the differential pressure transducer. Chamber pressure change (*ΔP*) resulting from injecting a known volume of air compared to the expected *ΔP* calculated from the chamber volume and injected air volume using the ideal gas law. An automated soil CO_2 flux chamber (LI-8100, LI-COR Biosciences, Lincoln, NE, USA) with a 20-cm survey chamber was used. The chamber was resting on an impermeable aluminum base and the vent tube was sealed with electrical tape. The total volume of the system was 6993 cm^3. See the text for more description of the calibration procedure.



The differential pressure transducer has a resolution of 0.032 Pa and a response time of 4 Hz. The calibration of the pressure transducer was done inside a greenhouse. Pressure changes were imposed by injecting known volumes of air into the LI-8100 system with a syringe. The LI-8100 was connected to a 20-cm survey chamber resting on a collar that was sealed to an aluminum plate with silicon adhesive and its vent was also sealed with electrical tape.

First, the high side of the differential pressure sensor was connected to the chamber (and low side at ambient) and the positive pressure change resulting from injecting known air volumes were compared to the expected ΔP values, which were calculated from the ratio of injected air volume to total system volume (6993 cm^3) at an ambient pressure of 98 kPa (Figure 3).

The pressure sensor connections were then reversed (high side at ambient, low side to chamber), and precise volumes of air were again injected into the system, this time leading to negative pressure values. The volumes of these injections are reported as apparent negative values in Figure 3. The calibration result demonstrates that both the resolution and accuracy of the pressure transducer met the requirements for the present study. The analog signal from the pressure transducer was first digitized by a sonic anemometer used for wind speed measurement, and was then recorded with a laptop computer.

Wind speed at the height of 0.5 m was measured with a sonic anemometer (Model 81000, RM Young Company, Traverse City, MI). The digital signal from the sonic anemometer was recorded with the same laptop computer as the one used for recording the differential pressure data.

Field testing sites

We conducted the initial field testing for LI-8100 in a riparian ecosystem near Lincoln, Nebraska during the summer and the fall of 2004. The site is about 2 km west of Lincoln, Nebraska (40° 50' N, 96° 48' W, 350 m above m.s.l.). It has a humid continental climate. The soil is a Sharpsburg silty clay loam (Typic Argiudall) and the ground cover is primarily fescues (*Festuca* spp.) with a mean vegetation height of approximately 5 cm.

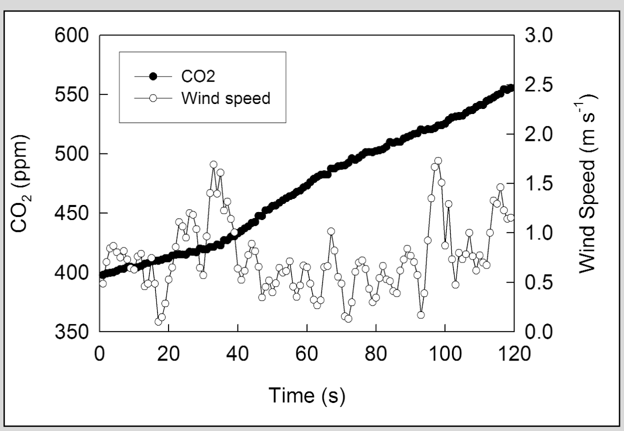


Figure 4. An example of the impact of wind on measured soil CO_2 flux with a chamber equipped with the initial vent design, consisting of two flat plates placed 0.3 cm apart. The dataset is a 2-min measurement obtained with the LI-8100 10-cm survey chamber. Wind speed at 0.5 m high was measured using a sonic anemometer (RM Young). Data were obtained at 14:25 central time on July 1, 2004, in a riparian grassland near Lincoln, Nebraska. The height of the grass was approximately 5 cm.

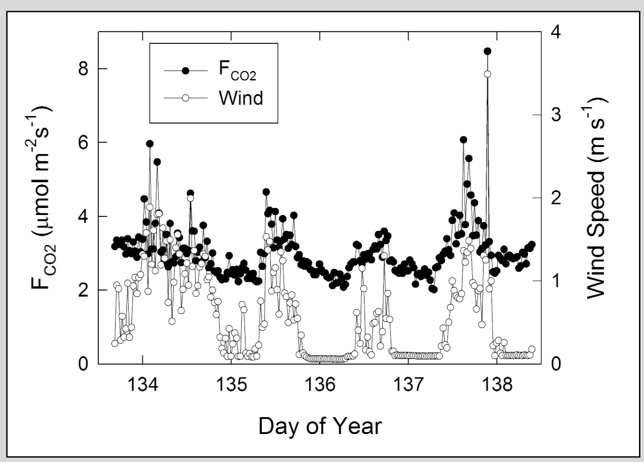


Figure 5. Soil CO2 flux (F_{CO2}) data measured over a 4-day period with a 10-cm survey chamber equipped with the initial vent design and wind speed measured at a height of 0.5 m high with a sonic anemometer (RM Young). The CO_2 flux measurements were made every half hour with each measurement lasting 2 min. Wind speed is the average for the 2-min measurement periods.

We conducted another field experiment to compare F_{CO2} measured with two chambers; one was equipped with the new vent design and the other with an earlier vent design. This was carried out in a grassland at the Fort Lauderdale Research and Education Center, University of Florida, Davie, Florida (26°03' N, 80°13' W, 3 m above m.s.l.) during the period of Feb 10-16, 2005. The site has a subtropical climate with a wet season (June-Nov) and a dry season (December-May). According to National Cooperative Soil Survey, the soil was siliceous, hyperthermic Lithic Psammaquent. The ground cover is primarily *Richardia grandiflora* (Cham. & Schlecht.) Steud, *Sida acuta* Burm. F., *Spermacoce verticillata* L. etc. The vegetation height is approximately 5 cm.

Results and Discussions

Overestimation of F_{CO2} with an early vent design chamber

Before we demonstrate the performance of the new vent design, we first present some of our early field data to illustrate the effect of wind on F_{CO2} measurements. The data (Figures 4 and 5) were obtained using a 10-cm survey chamber with our initial vent design. The vent was located at the top of the chamber to avoid sensitivity to wind direction. Figure 4 shows a 2-min time series for chamber CO_2 concentration and wind speed at a height of 0.5 m obtained during a windy period. A prominent gust of wind occurred at 32-40 s into the measurement, after which the slope of CO_2 concentration vs. time showed a significant increase. The estimated flux for this particular example was 9.4 µmol $m^{-2}s^{-1}$, while the flux under calm conditions around the same period was only 3.5 to 4.5 µmol $m^{-2}s^{-1}$. During field testing throughout the summer of 2004, we consistently found unusually high F_{CO2} values whenever there was wind during the measurement period. Figure 5 shows the correlation between the wind speed and F_{CO2} from a 4-day period in May 2004.

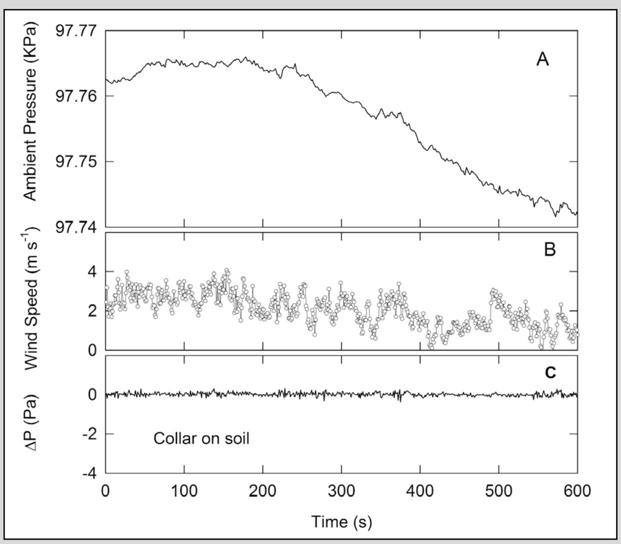


Figure 6. Time series of the absolute ambient pressure at the soil surface (A), wind speed at 0.5 m high (B), and the pressure difference (*ΔP*) between the inside and outside of a 20-cm survey chamber (C) for a 10-min period obtained in a riparian ecosystem near Lincoln, Nebraska. The 20-cm survey chamber has the initial vent design and was resting on a collar on the soil surface. The ambient pressure and the wind speed were measured with an absolute pressure transducer (Model 6220, Ruska Instrument Inc., Houston, TX), and a sonic anemometer (RM Young), respectively.

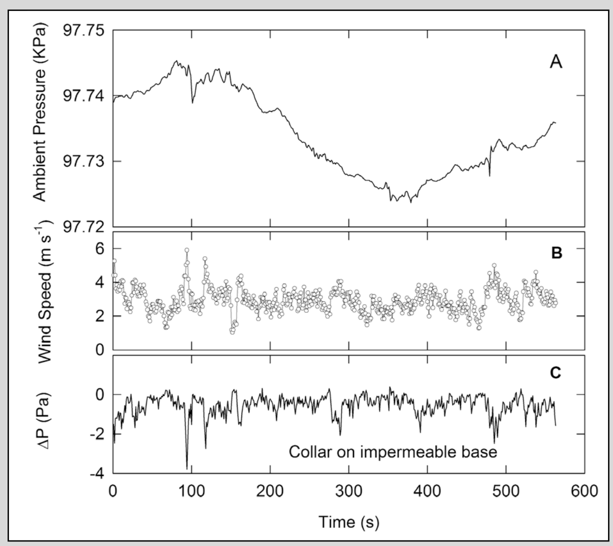


Figure 7. Time series of the absolute ambient pressure at the soil surface (A), wind speed at 0.5 m high (B), and the pressure difference (*ΔP*) between the inside and outside of a 20-cm survey chamber (C) for a 10-min period obtained in a riparian ecosystem near Lincoln, Nebraska. The chamber had the initial vent design, and was resting on a collar that had an impermeable base, NOT on the soil surface.

The question to be answered is whether the high F_{CO2} values observed under windy conditions are artifacts arising from the interaction of wind with the chamber, or if they reflect the natural effect of wind on F_{CO2} across the landscape.

Chamber pressure measurement

To determine whether the high F_{CO2} values observed under windy conditions were artifacts resulting from the interaction of wind with our initial vent design via the Venturi effect, we measured the absolute ambient pressure at the soil surface (Model 6220, Ruska Instrument Inc., Houston, TX), the pressure difference between the inside and outside of a 20-cm survey chamber (ΔP), and the wind speed at a height of 0.5 m in the field (Figure 6). This experiment was done with a chamber equipped with the initial vent. The chamber rested on a collar that was inserted into the soil, as shown in Figure 2A. The high side of the differential pressure transducer was connected to the chamber with a 25 cm tube having an I.D. of 6.4 mm, while the low side was exposed to the ambient air by a same tube placed in the grass canopy just above the soil surface. Even though chambers equipped with the initial vent design always gave unusually high F_{CO2} values under windy conditions, measured ΔP data did not indicate that negative chamber pressures were occurring. During the 10-min experimental period, the absolute pressure changed by about 23 Pa from 97.765 to 97.742 kPa (Figure 6A), and wind speed varied in the range of 0-4 m s^{-1} (Figure 6B); however, surprisingly, ΔP did not show any significant response to wind (Figure 6C). The mean and the standard deviation of ΔP for the 10-min period was 0±0.092 Pa. At first glance, these results seemed to suggest that the initial vent design was working properly and wind was not causing significant chamber pressure perturbations in the chamber. But the possibility remained that air might have been drawn from the soil, relaxing any pressure gradients that developed due to the interaction of wind with the chamber.

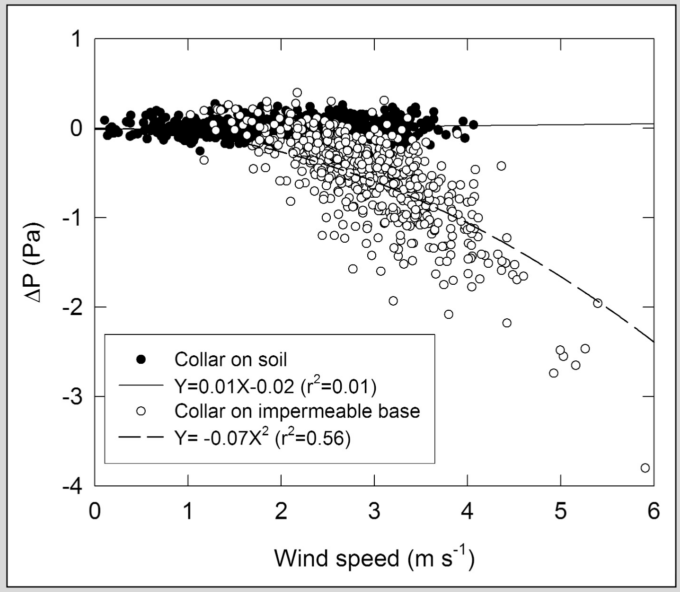


Figure 8. Contrast responses of îP to wind speed when a chamber was resting on a collar on the soil surface and a chamber on a collar that has an impermeable base (see the Figure 2 for more detail of experiment setups). The two datasets were fitted with a linear and a quadratic relationship respectively.

To answer this question, we conducted another similar experiment. This time we placed the same chamber on a collar that had an impermeable base, not directly on the soil surface, as shown in Figure 2B. The ranges of variation in the absolute ambient pressure and the wind speed were similar to the previous experiment (Figure 7A & 7B), but now the ΔP data revealed a completely different story. Large negative chamber pressure excursions always occurred whenever there was wind (Figure 7C). In Figure 8, we show the data from Figures 6 and 7 plotted as ΔP versus wind speed. When the chamber was placed on soil, the slope of ΔP versus wind speed was not significantly different from zero. But when the chamber was placed on an impermeable base, we obtained a negative quadratic relationship with wind speed as predicted by the Bernoulli's equation.

The only explanation for the results in Figures 6, 7 and 8 is that soil, being porous, allows air to exchange freely across its surface inside the chamber, which can dampen out most of the pressure change signal caused by the wind.

This is because a large fraction of the volume of soil above the saturated zone consists of gases. In addition, only a small volume of air exchange is needed to negate the ΔP caused by Venturi effect. For a 5-l chamber and at an ambient pressure of 100 kPa, only 0.5 cm^3 of air is needed to relieve a 10-Pa ΔP signal. If the chamber has a diameter of 20 cm covering a soil with an area of 314 cm^2 and with air filled porosity of 40%, then 0.5 cm^3 of air represents an average vertical air displacement of only 40 µm! It is likely that such a small displacement occurs very quickly, leaving a residual pressure signal that is almost undetectable with a pressure transducer that has a limited sensitivity and response time and using a data-logger that has a limited logging frequency. If this is true, then a significant mass flow may occur even before a measurable or significant ΔP can be observed. Thus, the pressure measurements made with a chamber resting on soil (Figure 2A), as has been the case in almost all the relevant published studies, can lead to the erroneous conclusion that mass flow is not occurring, when, in fact, just the opposite may be true. Therefore, to determine the performance of any kind of chamber system used for studying gas exchange between the soil and the atmosphere, *we strongly recommend that any differential pressure measurements should be made with the chamber resting on a collar with an impermeable base (as shown in Figure 2B), not on a collar placed on soil.*

Based on results presented in Figures 4 through 8, we conclude that the high F_{CO2} values observed under windy conditions were overestimated due to artifacts resulting from negative chamber pressure excursions because of the interaction of wind with our initial vent. Furthermore, such negative chamber pressure excursions were not observable unless the chamber was placed on an impermeable base.

In the experiment presented in Figure 6, negative pressure excursions created by the wind due to the Venturi effect were almost completely relieved by air exchange across the soil surface inside the chamber, resulting in near-zero ΔP signals. If a negative pressure excursion persisted and became stronger as the wind speed increased, the air flow out of the soil would also increase continuously to collapse the pressure gradient, until at some point, the air flow out of the soil could no longer satisfy the strong pressure differential, and a measurable ΔP would begin to be observed. Thus, depending upon the capacity of the air-filled porosity of the soil and the resistance to refilling those spaces, we might expect to find a threshold of air exchange (i.e. the mass flow) that would have to be reached before a measurable ΔP could be observed. The threshold also would depend on the resolution and response time of the pressure transducer. In general, a dry sandy soil will most likely have a larger threshold than a loamy soil, while a wet clay soil normally would have the smallest threshold. Thus, the magnitude of measured ΔP as a function of wind speed is likely to vary from no effect up to what is observed over an impermeable base, depending upon soil conditions.

It is clear from this discussion that the amount of air exchange across the soil surface does not have a simple 1-to-1 relationship with measured ΔP or wind speed. So depending upon the soil type and soil moisture level, the same wind speed is likely to cause varying mass flow rates and measurable ΔP levels, leading to different magnitudes of the error in measured F_{CO2} . In addition, the error should also depend on the CO_2 concentration gradient between the soil and the air (*Fang and Moncrieff*, 1998), with larger errors arising from soils with a high organic carbon content and high soil CO_2 concentration. This combination of factors is probably why such a wide range of sensitivity of measured F_{CO2} to ΔP has been observed in the literature, as summarized in the Introduction.

Positive pressure perturbations in a soil CO_2 flux chamber should cause mass flow of air into the soil in a manner similar to the way negative chamber pressure changes cause mass flow out of the soil; however, the impact of positive pressure on measured F_{CO2} might be less than that of the negative pressure. Consider F_{CO2} when there is either a mass flow out of the soil or into the soil. The impact of negative and positive pressure perturbations on measured F_{CO2} can be illustrated with the following two equations:

$$-\Delta P: \qquad F_{CO2} = g(C_s - C_c) + \frac{u}{s}(C_s - C_c) \qquad (3)$$

$$+\Delta P: \qquad F_{CO2} = g(C_s - C_c) - \frac{u}{s}(C_c - C_a) \qquad (4)$$

where g is conductance for CO_2 exchange at the soil surface (mol m^{-2}s^{-1}). C_s, C_c, and C_a are the CO_2 concentration for soil air, chamber air and the atmosphere (mol CO_2 mol^{-1} air), respectively. u (mol s^{-1}) is the rate of mass flow across the soil surface s (m^2) due to the pressure gradient. Under pressure equilibrium conditions, F_{CO2} depends on the CO_2 concentration gradient (i.e., C_s-C_c) only. Whereas, under pressure disequilibrium conditions, there is a mass flow term in Equations 3 and 4 that contributes to the gas exchange in addition to the diffusion term. Generally speaking, C_s-C_c should be much larger than C_c-C_a. For this reason, we should expect to see a smaller impact from the positive pressure perturbation as compared with that from the negative pressure perturbation. This analysis might explain why *Fang and Moncrieff* (1998) observed a smaller sensitivity of measured F_{CO2} to a positive pressure difference than to a negative one.

Some scientists (e.g. *Lund et al.*, 1999) recommend that ΔP should be measured along with F_{CO2}. They suggest that the relationship between ΔP and the measured F_{CO2} might be useful for correcting measured F_{CO2} under a pressure bias. Based on the data presented in Figures 6, 7 and 8, and discussion that followed, we argue that such post-experiment data correction might have a limited value, because the relationship between ΔP and F_{CO2} (e.g. Figure 6 of *Fang and Moncrieff*, 1998) is very complicated, and they are not intrinsically related. It will vary from site-to-site, or collar-to-collar at a single site because soil properties are highly non-uniform in the field. Even for the same collar, it will vary with the soil moisture content. To make accurate soil respiration measurements, one has to avoid any chamber pressure disequilibrium with the ambient air.

We just demonstrated that a small ΔP caused by a gust of wind could have a significant impact on measured F_{CO2}, because it continuously pulls soil air with a high CO_2 concentration into the chamber; however, the impact of one-time pressure change with a similar magnitude, for instance caused by a small air sample being removed from the chamber, will have a much smaller impact on measured F_{CO2}. From our previous discussion, removing a 0.5 cm^3 air

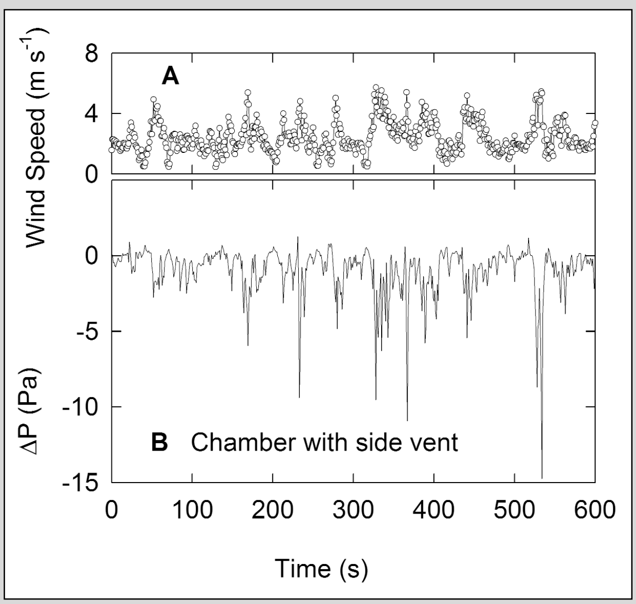


Figure 9. Time series of the wind speed at 0.5 m high (A) and the pressure difference (*ΔP*) between the inside and outside of a 20-cm survey chamber (B) for a 10-min period obtained in a riparian ecosystem near Lincoln, Nebraska. The chamber has a vent tube facing downward and located at SE side of the chamber, it was resting on a collar with an impermeable base, NOT on the soil surface.

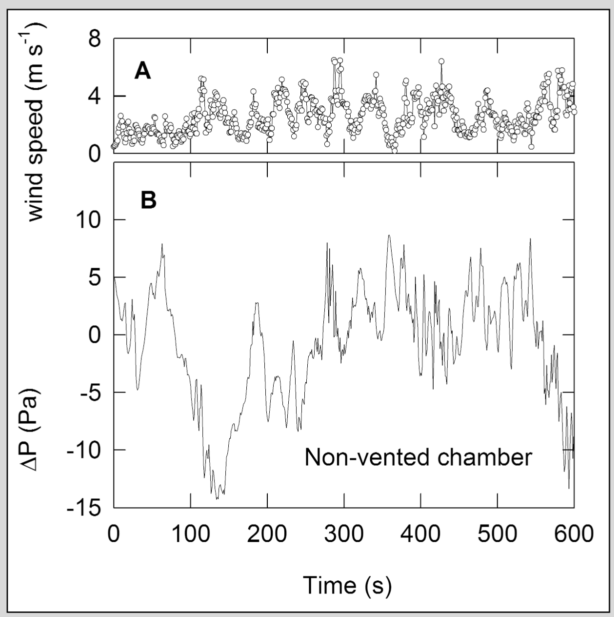


Figure 10. Time series of the wind speed at 0.5 m high (A) and the pressure difference (*ΔP*)) between the inside and outside of a 20-cm survey chamber (B) for a 10-min period obtained in a riparian ecosystem near Lincoln, Nebraska. The non-vented chamber was resting on a collar which has an impermeable base, NOT on the soil surface.

sample from a 5-l chamber will create a 10-Pa ΔP. If we assume the chamber has a CO_2 concentration of 400 µmol mol^{-1} and the removed air is refilled with soil air having a CO_2 concentration of 10,000 µmol mol^{-1}, then the chamber CO_2 concentration will increase by only 0.96 µmol mol^{-1} to 400.96 µmol mol^{-1}

$$\left(\frac{4999.5 \times 400 + 0.5 \times 10{,}000}{5000} = 400.96\right).$$

Therefore, removing a few small air samples during a measurement will have a much smaller impact on F_{CO2} measurements than would a similar but continuous ΔP change.

Problem of improperly vented chambers

Some researchers have recommended using a plain vent tube (with no vent device) at one side of their chambers (*Norman et al.*, 1992; *Hutchinson and Livingston*, 2001). Again, this approach works effectively only under calm conditions. Under windy conditions, it can cause positive or negative pressure perturbations, depending on the wind direction, as demonstrated theoretically (*Young et al.*, 2001) and experimentally (*Kutsch et al.*, 2001). The chamber pressure will increase when the wind blows directly toward the vent. Wind from all other directions will cause the chamber pressure to drop. The data in Figure 9 show that with a side-vented chamber, the chamber pressure can drop as much as 15 Pa in winds of 4 to 5 m s^{-1}. In this experiment, the chamber pressure only shows a negative response to wind speed. This was probably because the wind blew mostly from the SW direction, while our vent was located on the SE side of the chamber. Hutchinson and Livingston (2001) suggest that vent tubes should be placed near the ground level, and pointed away from the wind. This may reduce the problems with vent tubes, but it is unlikely to eliminate them.

We also measured ΔP for a non-vented 20-cm survey chamber placed on a sealed collar in the field (Figure 10). Contrary to *Conan and Smith's* (1998) recommendation, we found that eliminating the vent tube led to pressure changes that were larger in both magnitude and duration than those observed with vented chambers (Figures 6 and 7). Also, ΔP values were either positive or negative (Figure 10). A non-vented closed chamber system is tight but not sealed, so pressure perturbations relax more or less slowly. For example, a decrease in ambient static pressure outside the chamber will create a positive ΔP between inside the chamber and outside ambient air. The chamber will slowly equilibrate with this new pressure causing ΔP to relax at some rate that depends on the seal around the gaskets and porosity of the soil. If static pressure increases outside the chamber, then ΔP will become negative, and so on. Water evaporation from the soil and temperature increases during a measurement can also cause chamber pressure disequi-

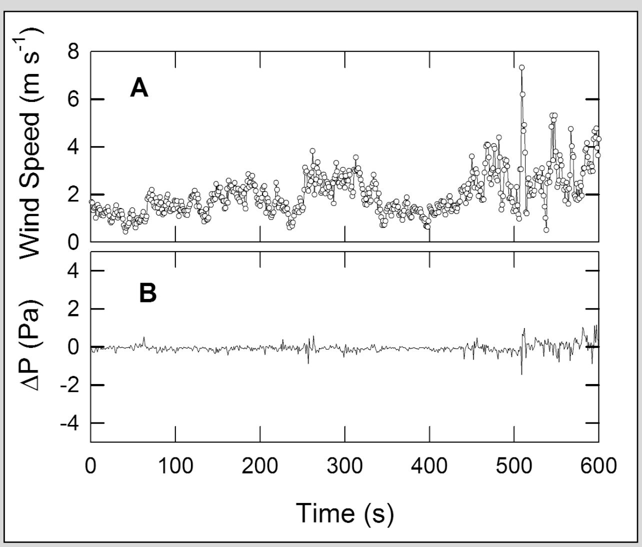


Figure 11. The performance of the new vent, showing that the pressure difference (ΔP) between inside and outside of a 10-cm survey chamber fitted with the new vent design did not respond to the wind speed. The chamber was resting on a collar with an impermeable base. Wind speed was measured with a sonic anemometer (RM Young) at the height of 0.5 m. Data were obtained around 4:00 p.m. local time on Nov 15, 2004.

librium in a non-vented chamber. According to the ideal gas law, for every one degree of deviation in chamber temperature, chamber pressure could change by as much as 333 Pa! And, water evaporation can easily cause several tenths of a *kilo* Pascal change in vapor pressure. These effects will lead to overpressures that may cause flux to be underestimated.

There is yet another possible factor that can cause F_{CO2} to be underestimated using a non-vented chamber. When a chamber closes and the gasket compresses, a significant volume of air with ambient CO_2 concentration is pushed into the soil surface layer, greatly reducing the CO_2 diffusion gradient. It might take a long time for the soil CO_2 profile to readjust after being disturbed (*Denmean,* 1979; *Hutchinson and Livingston,* 2001) because such readjustment is mainly a diffusion process. With a properly vented chamber, large pressure pulses during chamber closing can be avoided by allowing air to exit the chamber via the vent tube (*Davidson et al.*, 2002).

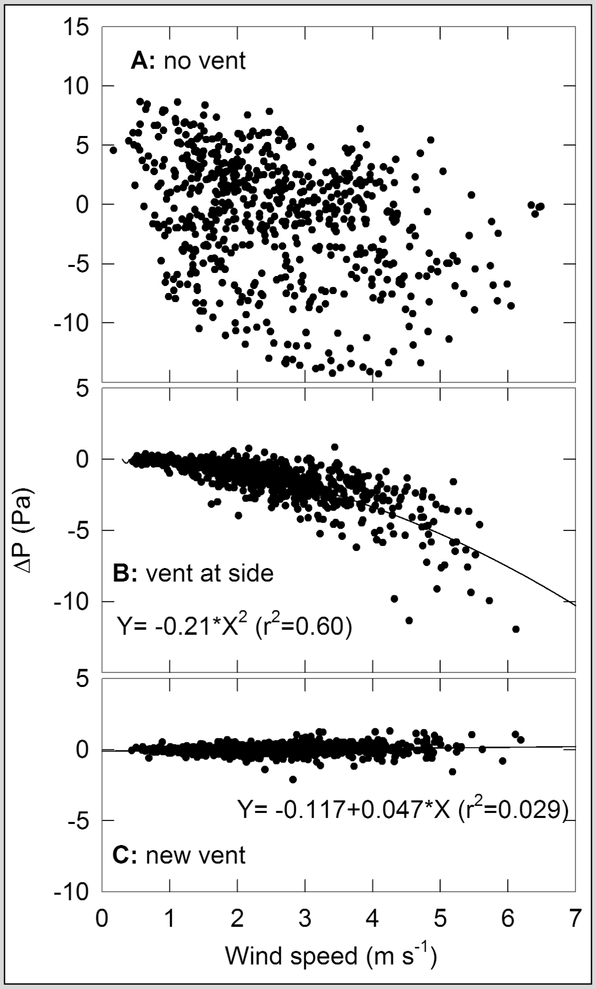


Figure 12. Comparison of the response of *ΔP* to wind speed for three configurations of vent designs: no vent (A), vent located at one side of the chamber and 4 cm above the ground (B), and new vent (C). All of the measurements were made with chambers resting on collars with impermeable bases. Notice the different scale for y-axis in panel A from other two panels. The data were obtained in a riparian grassland near Lincoln, Nebraska in fall 2004.

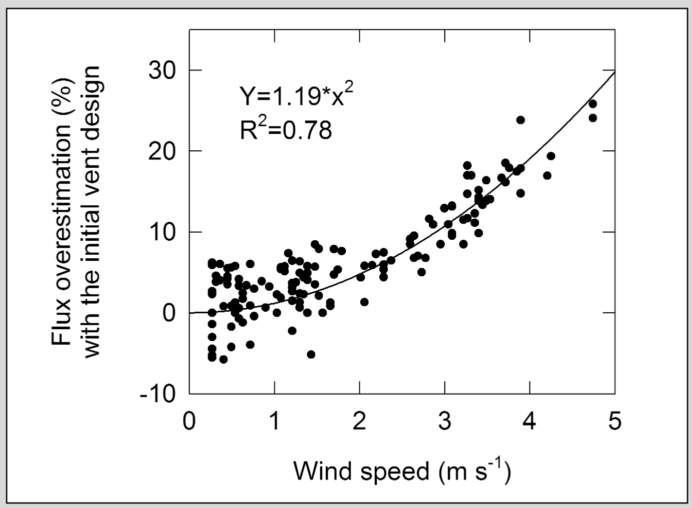


Figure 13. Comparison of the impact of wind on fluxes obtained from two 10-cm survey chambers set side by side, one equipped with the initial vent design and one with the new vent design. Flux overestimation with the initial vent chamber was calculated based on the flux rate measured with the new vent design chamber. This 3-day dataset was obtained at the Fort Lauderdale Research and Education Center, University of Florida, in February 2005. The soil respiration rate during the experimental period normally ranged from 0.5 to 2.5 µmol m^{-2}s^{-1}, depending mainly on the soil temperature. Wind speed at 0.5 m high was measured with a sonic anemometer (RM Young).

Effectiveness of new vent design

The data in Figure 11 were obtained using a 10-cm survey chamber equipped with the new vent design resting on an impermeable base. We found that ΔP was always near zero when the wind speed varied from 0 to 7.5 m s^{-1}, indicating that chamber pressure closely followed the ambient static pressure under both calm and windy conditions. Linear regression of ΔP vs. wind speed shows that the slope was not significantly different from zero (Figure 12C). Thus, the consequences of Venturi effect were virtually eliminated by slowing down the wind speed inside the vent apparatus. By placing the vent at the top of the chamber, the wind-directional sensitivity is also eliminated. We also demonstrate the effectiveness of the new vent design by comparing the response of ΔP to wind speed with other vent configurations (Figure 12). It is clear that when the vent tube (just the 6.4 mm ID tube, no vent device attached) was hung at one side of the chamber, negative chamber pressure excursions occurred under windy conditions (Figure 12B). With the non-vented chamber, the chamber pressure always deviated from the ambient pressure and no clear relationship existed between ΔP and wind speed (Figure 12A).

Experiments with other chambers, including a 20-cm survey chamber and a 20-cm long-term chamber, all show no responses of ΔP to wind when they are equipped with the new vent (data not shown), indicating the effectiveness of the new vent design.

We also demonstrate the performance of the new vent design with a comparison of measured F_{CO2} from two chambers placed side-by-side in the field – one chamber had the initial vent design and the other was equipped with the new vent design. The experiment was conducted in a grassland at Fort Lauderdale Research and Education Center, University of Florida, in February 2005. Figure 13 illustrates the percentage increase in measured F_{CO2} from the chamber equipped with the initial vent design compared with F_{CO2} measured using the chamber equipped with the new vent design, as a function of wind speed. Results show clearly that our initial vent led to significant overestimation of the flux and the overestimations increased with wind speed. Under calm conditions, the two chambers gave no consistent difference in measured F_{CO2}. The relationship between the percentage overestimation and wind speed follows a quadratic curve, which has the same relationship as that of dynamic pressure and wind speed. The details of the relationship shown in Figure 13 would likely depend on the porosity of the soil and CO_2 source strength.

We have demonstrated the performance of our new vent design in terms of maintaining pressure equilibrium between inside and outside the chamber under calm and windy conditions; however, closed chambers also reduce or inhibit the natural turbulence of air at the soil surface, possibly altering the pressure fluctuations that "pump" air into and out of the soil (*Kimball and Lemon,* 1971; *Mosier,* 1989; *Baldocchi and Meyers,* 1991). For this reason, many researchers believe that any closed-chamber technique may underestimate the flux (*e.g. Mosier,* 1989; *Fang and Moncrieff,* 1998). This might be true for a non-vented chamber, in which natural pressure fluctuations are completely removed or dampened out; however, the following discussion suggests that for a properly vented chamber, this underestimation might be not significant.

In the early 1970s, *Kimball and Lemon* (1970) conducted a series of field experiments to investigate air pressure fluctuations at the soil surface. Their results showed that the spectra of pressure variations covered a frequency range from 10^{-4} Hz to 10^{2} Hz. Synoptic events could cause even lower frequencies (<10^{-4} Hz) in barometric pressure changes. Medium frequency (10^{-4} to 10^{-1} Hz) pressure variations are probably due to wind blowing across irregular topography (*Takle et al.*, 2004); while high frequency components (>10^{-1} Hz) can be attributed to near-surface atmospheric turbulences (*Massman et al.*, 1997).

Although we know that pressure fluctuations generally will enhance gas exchange (*Kimball and Lemon,* 1971; *Mosier,* 1989; *Takle et al.*, 2004), little is known about the relative contribution to gas exchange from pressure fluctuations at different frequencies. In principle, different frequencies should contribute differently to gas exchange. The amplitudes of pressure waves drop dramatically as frequency increases (*Kimball and Lemon,* 1972), so lower frequency pressure waves should influence soil gas exchange more than higher frequency pressure pulses. Results from a few laboratory studies (*Kimball and Lemon,* 1972) and field experiments (*Kimball,* 1983; *Massman et al.*, 1997) appear to support the conclusion that high frequency components (>1 Hz) have only small effects on gas exchange at the soil surface or at the snow surface. Their data indicate that the major contribution is from low frequency pressure changes.

With a vented chamber, only high frequency pressure fluctuations are likely to be attenuated because of resistance to air movement in the vent tubing (*Massman et al.*, 1997). A vented chamber should easily follow pressure fluctuations at lower frequencies (<1 Hz), as shown in Figures 6 and 7. The lack of any correlation between ΔP and low frequency pressure change in our data (Figures 6 and 7) show that our vented chamber followed low frequency pressure quite well. Therefore, with a vented chamber, the underestimation of F_{CO2} caused by altered pressure fluctuations might be not as significant as previously thought. This topic merits a more detailed investigation, as these results (*Kimball and Lemon,* 1972; *Massman et al.*, 1997) and our discussion here are not conclusive.

Besides the impact on soil CO_2 flux via pressure fluctuations, wind can also influence soil CO_2 efflux by two other mechanisms. One is that wind affects the soil CO_2 efflux by changing the aerodynamic resistance to CO_2 transport near the soil surface. At present, unfortunately, it appears to be insurmountable to vary the aerodynamic resistance inside a chamber in such a way that it matches conditions outside the chamber. Wind can also affect soil CO_2 efflux by enhancing the mixing of the atmosphere, removing respired CO_2 accumulated at the soil surface. In a chamber-based soil CO_2 flux system, although it is well mixed, the chamber CO_2 concentration cannot be maintained at ambient levels. This is because the chamber CO_2 concentration must be allowed to rise in order to compute the slope of dCO_2/dt, which is needed to calculate F_{CO2}. Thus, the soil CO2 diffusion gradient is altered. This altered CO_2 concentration will likely cause underestimation in F_{CO2} (*Healy, et al.*, 1996). To minimize this underestimation, non-linear curve fitting has been proposed to account for the change in the gradient (*Hutchinson and Mosier,* 1981; *Welles et al.*, 2001; *McDermitt et al.*, 2004; LI-COR, 2004). Shortening the measurement period also is used sometimes to reduce the impact of increasing chamber CO_2 concentration, especially when data are analyzed by linear regression. With a high resolution and fast response CO_2 gas analyzer, it is practical to shorten the measurement period to less than 2 min; however, the time required to achieve good mixing places limits on how short the measurement period can be, and even such short measurement periods are not sufficient to correct the bias toward underestimates that are almost inevitable from linear fits (data not shown).

Although, to some degree, a chamber does interfere with the natural processes transporting trace gases out of the soil by creating an artificial environment, the chamber-based technique is still a valuable and cost-effective approach for studying CO_2 and other trace gas fluxes between the soil and the atmosphere (*Denmead,* 1979; *Hutchinson and Livingston,* 2001). This is especially true if the chamber is designed in such a way that pressure disequilibrium between the chamber and the surrounding ambient air is avoided. The new vent design presented here represents a significant advance in our understanding of how to avoid artifactual chamber pressure perturbations due to the interaction of wind with a soil CO_2 flux chamber. These results should be applicable to measurements of other trace gases across the soil-air boundary. Also, the new vent design can be applied to other chamber-based trace gas flux systems to effectively maintain pressure equilibrium between the chamber and the ambient air, although the ratio of h_1/h_2 may need to vary with different chamber heights.

Conclusions

In this paper, we describe a new vent design based on Bernoulli's equation for a soil CO_2 flux chamber. It allows pressure inside the chamber to track pressure at the soil surface outside the chamber under calm and windy conditions. Differential pressure data measured in the field show that the new vent design virtually eliminates the occurrence of artifactual negative chamber pressure excursions under windy conditions, a problem other vented chambers have had due to the Venturi effect. Our data showed that chambers with old vent designs or no vent at all will cause chamber pressure to deviate from ambient pressure under windy conditions, causing measured F_{CO2} to be biased. We found these pressure deviations could be as large as -15 Pa to 8 Pa at wind speeds up to 6.5 m s^{-1}.

It is necessary to prevent the occurrence of any ΔP if chamber-based CO_2 flux measurements are to accurately represent rates occurring naturally outside the chamber. The ΔP measurement must be made with a chamber resting on a collar with an impermeable base, not on a collar resting directly on the soil, to determine the performance of the chamber. Soil allows air exchange between the chamber and soil that can dampen pressure signals, resulting in an almost zero ΔP. This can lead to the erroneous conclusion that mass flow is not occurring when, in fact, the opposite is true. We show that mass flow occurred even before a measurable ΔP was observed.

Results from field experiments show that improperly vented chambers significantly overestimate F_{CO2} as compared with a chamber with our new vent design under windy conditions, while, under calm conditions, no consistent difference between measured F_{CO2} data from the two chambers was observed.

After we submitted this manuscript, we learned that an independent study from Professor Wofsy's group at Harvard University also found results nearly identical to some of ours. Their soil CO_2 flux chamber was vented with a simple opening at the top of the chamber. They observed the wind-induced overestimation in measured F_{CO2} because of negative chamber pressure excursions due to the Venturi effect. They also found that these negative pressure excursions could not be observed unless the chamber was placed on a collar with an impermeable bottom (*Bain et al.*, 2005).

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