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Wind-induced error in the measurement of soil respiration using closed dynamic chambers

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Abstract

We assess errors in soil respiration fluxes of CO_2 obtained using the closed dynamic chamber method. Particular attention is given to small pressure gradients between the chamber headspace and the external environment that may induce mass flow of soil air, leading to overestimation of soil respiration. These pressure gradients develop as air movement creates a Venturi effect at the vent that is designed to insure pressure equilibration, leading to aspiration of air from within the chamber. During field experiments at the Harvard Forest, the Venturi effect produced pressure gradients of approximately 1 Pa per 1 m s^{-1} for a chamber sealed to an impermeable plate, but no pressure gradient was observed in an identical system deployed on the forest soil. Mass flow of soil air compensated for the wind-driven pressure gradients, and increases in CO_2 fluxes exceeding a factor of 2 were observed in response to wind events even under a dense forest canopy. The high porosity of forest soils allows pressure artifacts induced by winds or by sampling flows to perturb the diffusive flux from soils, potentially affecting virtually all chamber methods. Associated errors in soil respiration measurements must be addressed through chamber design and evaluation.

Keywords: Respiration; Carbon dioxide; Forest ecosystem; Pressure gradient; Gas exchange

1. Introduction

Terrestrial uptake of carbon accounts for a significant fraction of the global emission of fossil fuel CO_2. Understanding the processes controlling the terrestrial uptake of carbon is needed to predict the future course of atmospheric CO_2. Photosynthesis is reasonably well understood from the leaf to whole canopy scale (Farquhar and Sharkey, 1982), but basic understanding of respiration lags behind. In particular, we do not adequately understand the partitioning between heterotrophic and autotrophic respiration in forest soils, the individual processes that contribute to total soil respiration, or the factors that control them across the landscape (Schimel et al., 2001).

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Forest soil respiration, or the sum of live root and soil-microbial respiration and decomposition of forest litter and soil organic matter, can account for 80% or more of total forest respiration (Davidson et al., 1998; Wofsy et al., 1993). Because CO_2 production rates in soil are large, and diffusion across the soil–air interface is slow, large concentrations of CO_2 build up in the soil (Bajracharya et al., 2000) making it difficult to observe the efflux of CO_2 without disturbing the flux. Hence, uncertainties in the measurement of rates for forest soil respiration continue to plague accounting of the forest carbon budget (Andrews et al., 1999).

The key to an unbiased soil respiration measurement is to accurately measure the CO_2 evolved from the soil surface without perturbing the diffusion gradients or inducing mass exchange. Eddy covariance measurements near the forest floor (Baldocchi et al., 1988) or flux gradient approaches (Liu and Foken, 2001) have the advantage of minimally disturbing the soil, but it can be very difficult to identify the specific area that contributes to observed fluxes. Furthermore, there are systematic errors in eddy flux measurements, they are expensive to implement, and both sub-canopy eddy flux and gradient measurements include contributions from above ground respiration and photosynthesis by vegetation below the sensor.

This paper examines artifacts associated with measurements of soil CO_2 fluxes using "closed dynamic enclosures" placed over the soil. Chamber-based measurements are direct observations and are relatively easy to implement, and therefore are widely used for calculating forest soil respiration. There are three principal types of enclosures used: static, open dynamic and closed dynamic. Static chambers seal a plot of soil and observe the rise of CO_2 concentration by chemical absorption and analysis (known as non-flow-through steady-state or NFT-SS) or periodic collection of an air sample by syringe (known as non-flow-through non-steady-state or NFT-NSS) (Hutchinson and Rochette, 2003). This method has been common historically, but the build up of CO_2 and H_2O in the chamber (or the depletion chemical absorption) and the pressure pulses associated with sampling provide obvious perturbations to the observed rates of CO_2 increase in the chamber.

The availability of continuous gas analyzers has made dynamic ("flow-through") chambers the more common approach recently. An open dynamic chamber (also known as flow-through steady-state or FT-SS; Livingston and Hutchinson, 1995) continuously flushes ambient air through the chamber, allowing calculation of the soil flux from the difference in CO_2 concentration between air entering and leaving the chamber (Lund et al., 1999). The build up of CO_2 in the chamber is reduced, but air flow through the chamber could introduce pressure differentials that induce mass flow through the soil, and the circulation may perturb diffusion through porous upper soil layers.

An alternative approach is a closed dynamic chamber, which has also been labeled as flow-through non-steady-state or FT-NSS (Livingston and Hutchinson, 1995). Generally, an external CO_2 analyzer (such as infrared gas analyzer) is attached to the chamber and air is re-circulated through the chamber and analyzer. In principle, an in situ open-path analyzer could be used inside the chamber, thus eliminating the need for pumping. These systems do not achieve a steady-state; after sealing the chamber, CO_2 concentrations increase in the headspace and the time history is used to calculate flux, typically by extrapolating the observed rate of CO_2 increase back to the time the chamber was placed on the soil. A small opening to the atmosphere, usually a short section of tubing, is included in order to eliminate pressure gradients between the inside and outside of the chamber and to reduce the effects of placing the chamber on the soil (Hutchinson and Livingston, 2001). By making the sampling duration short (Healy et al., 1996) and extrapolating the rise in CO_2 concentration to the starting point, biases due to altering the concentration gradient are minimized.

Closed dynamic chamber systems are widely used (Norman et al., 1992; Davidson et al., 1998), although there remains the potential for pressure gradients to develop between the internal chamber and external environment. Kanemasu et al. (1974) demonstrated that chamber pressure gradients of a few Pascal have the potential to create errors in gas flux measurement as large as an order of magnitude. This error is primarily attributed to the pressure-induced mass flow of soil gases, which are predominantly diffusion-driven under natural conditions (Kimball and Lemon, 1971).

Pressure gradients in normally operating closed dynamic chambers have not been reported, leading many to conclude that these systems are relatively free of systematic measurement error. However, Goulden et al. (1996) and Davidson et al. (1998) both found that chamber-based measurements of soil respiration fluxes were greater by 50% or more than those measured by the eddy correlation method over the same area. This disparity in measured respiration was particularly noteworthy during windy periods according to Goulden et al. (1996). Davidson et al. (1998) concluded that ‘‘no plausible explanation’’ exists for the systematic overestimation of soil respiration by closed dynamic chambers, although several other researchers noted concerns about the effects of wind on chamber-based flux measurements (e.g. Norman et al., 1992; Matthias et al., 1980).

Of particular interest, Conen and Smith (1998) concluded that wind movement around the vent of a closed chamber created a ‘‘Venturi effect’’ leading to overestimated soil gas efflux. Conen and Smith (1998) proposed that wind de-pressurized the chamber by pulling air out of the chamber headspace, leading to the mass flow of soil gases from the permeable soil column into the chamber interior. The chamber de-pressurization was approximated to $0.6V^2$, where V is equal to wind speed in m s^{-1}, or a 2.4 Pa pressure deficit for a steady 2 m s^{-1} wind, which resulted in a 233% increase in measured soil emissions. Even under very calm conditions ($V < 1$ m s^{-1}), systematic errors of 10–50% might be expected. Recently, Davidson et al. (2002) noted chamber pressurizations of 0.9 Pa under windy conditions, raising the question of the accuracy of chamber-based measurements under such conditions and suggesting further research on the phenomenon.

We performed a series of experiments under both controlled and natural conditions to document the pressure gradients induced by wind across a respiration chamber of conventional design, and to examine their affect on observed respiration rates. Pressure gradients by themselves would not create a bias in respiration measurements—it is the mass flow of soil air in or out of the soil column that adds an advective flux of CO_2 in addition to the unperturbed diffusive flux. To quantify the true driving force for mass flow in soil chambers, we compared the pressure gradients in a chamber placed over an impermeable surface to the gradients in a chamber over natural soil.

2. Materials and methods

Two parallel, closed dynamic chamber systems were constructed for comparison during field experiments, arranged as shown in Fig. 1. Each closed chamber system utilized a 5 L PVC chamber with a vertically oriented vent tube (0.19 cm vent tube inner diameter, 3.56 cm vent tube length). A pump circulated air though the chamber at approximately 0.5 L/min in a closed loop through a LI-COR (Lincoln, NE) infrared gas flux analyzer (IRGA)—one system used a LI-6252 CO_2 Analyzer and the other used a LI-6262 CO_2/H_2O Analyzer. A 30 s lag was evident between changes in chamber conditions and a response in the CO_2 signal, consistent with the flushing rate of chamber headspace and transit time in the sample lines. The IRGA reference air was scrubbed with soda lime and the measurement systems were regularly pressure tested by separately capping inlet or outlet ports and applying compressed air to identify and repair any leaks in the plumbing that would contribute to instrumentation-imposed chamber pressurizations. For example, a leak on the high-pressure side of the pump would have to be compensated by an influx of air elsewhere that induced mass flow into the chamber, or altered the pressure gradients. Periodic leak checking is essential

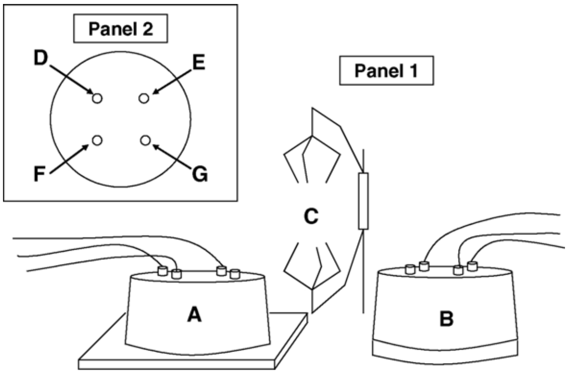

Fig. 1. Experimental schematic. Panel 1 displays the basic orientation of the parallel chamber systems (A and B) and sonic anemometer (C) while simultaneously deployed during field experiments. Chamber A was sealed to a plexiglass plate and placed adjacent to Chamber B, which was deployed on a PVC collar inserted 2–4 cm into the forest soil. Panel 2 displays the basic orientation of vents in both chamber systems, as viewed from above. Vents (D and E) were connected through 3 m lengths of PVC tubing to an IRGA intake (D) and exhaust (E). Vent (F) was connected through a 3 m length of PVC tubing to the micromanometer. Vent (G) was the pressure equilibration vent (0.19 cm inner diameter) and was left open to ambient air. The Venturi effect results from the interaction of wind on the pressure equilibration vent (G).

as normal field operation may cause fittings to loosen over time.

Internal chamber pressures were measured with an Infiltec (Waynesboro, VA) DM4 micromanometer. The DM4 micromanometer measures differential pressure between −750 and +750 Pa at a resolution on the order of 0.1 Pa on two parallel channels. The micromanometer was placed in a thermally insulated box—each of the two signal ports of the micromanometer was connected to a chamber with approximately 1.5 m of PVC tubing and each reference port was left open to air inside the insulated box, which served as a steady ‘‘reference’’ atmospheric pressure by damping ambient pressure and temperature fluctuations (D. Saum, Infiltec, personal communication, 2001). The micromanometer channels self-zeroed every 11.5 s, closing a pneumatic switch to ‘‘zero’’ differential pressure for 1 s at an offset of 5.75 s between the parallel channels. A data analysis algorithm was used to remove these zeroing events from the pressure data. The micromanometer was modified to provide an analog signal output for use with a datalogger (D. Saum, Infiltec, personal communication, 2001).

Ambient wind was measured with a three-dimensional Campbell (Logan, UT) CSAT3 sonic anemometer, mounted level with the soil chamber vent tube openings (approximately 0.25 m above ground), usually centered between the parallel chambers (see Fig. 1). Data outputs from the measurement instruments were recorded with a Campbell CR10X datalogger.

Trials were conducted periodically during consecutive 36 h periods on August 21–22 and 30–31, 2001. The field site was located on well-drained soil in the measurement footprint of the Harvard Forest eddy flux tower, at 42.537755°N, 72.171478°W, in an aggrading upland forest ecosystem in the Harvard Forest near Petersham, MA (Goulden et al., 1996; Barford et al., 2001).

Three trial methods were employed during field experiments: comparative trials under both—(1) fan-induced and (2) natural wind conditions, as well as (3) single chamber trials under natural wind conditions for extended time periods.

During comparative field trials, the parallel chamber systems were simultaneously and adjacently deployed for 2–5 min periods. One chamber system was placed over the soil onto a PVC collar inserted to a depth of 2–4 cm in the forest soil; the second was sealed with vacuum grease to an impermeable plexiglass plate and placed next to and level with the first system. A 24 in. (60 cm) household electric fan, baffled with a cardboard mesh to reduce turbulence and straighten the flow, was used to control wind conditions during fan-induced wind trials. CO_2 flux was measured by the chamber system deployed on the soil. Blank runs for the sealed system showed no leaks of CO_2 into, or out of, the closed loop circulation. In addition to comparison trials, extended measurements of chamber pressure gradients under natural wind conditions were conducted with a single chamber system deployed on the impermeable plate for 5–10 min periods.

3. Results

Under fan-controlled wind conditions in the field, the chamber system deployed on an impermeable plate consistently developed a slight vacuum relative to the outside in response to horizontal wind—the ‘‘Venturi effect’’ proposed by Conen and Smith (1998) (Fig. 2) that de-pressurizes the chamber relative to the soil underneath. The Venturi effect was demonstrated across 13 field trials (Fig. 3), yielding an approximately 1 Pa drop in pressure per 1 m s^{-1} increase in horizontal wind at low wind speeds. This wind–pressure relationship roughly approximates the values

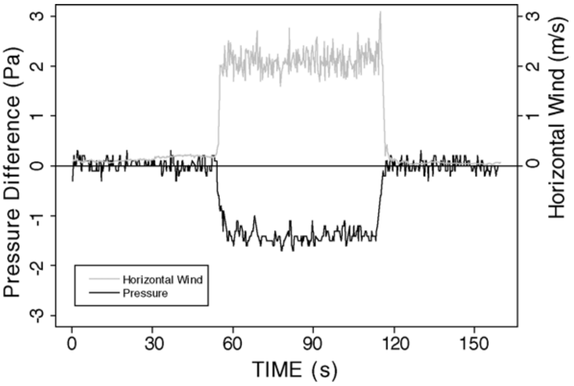

Fig. 2. The Venturi effect is demonstrated by a time series of the pressure gradient (chamber interior–exterior) in a closed chamber system sealed to a plexiglass plate and fan-induced horizontal wind during a field trial. The pressure data were smoothed with a three-point (0.75 s) running median and processed to remove instrument zeros.

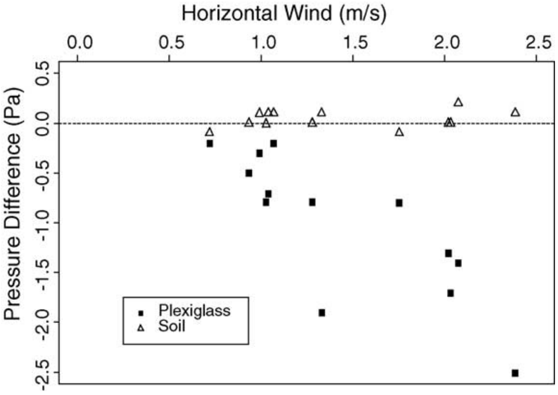

Fig. 3. Comparison of horizontal wind and chamber pressure gradients. Two parallel, adjacent, closed chamber systems were operated simultaneously and subjected to the same fan-induced wind during 13 field trials: one system was sealed to a plexiglass plate and the other was deployed over natural soil. Data are median values during fan operation. The sealed system shows a reproducible pressure gradient, approximately 1 Pa per 1 m s^{-1} of horizontal wind speed at wind speeds less than 2.5 m s^{-1}, due to the Venturi effect. The system over soil shows no pressure change.

predicted by Conen and Smith (1998) at wind speeds less than 2 m s^{-1}.

In contrast, fan-generated winds impinging on the chamber system deployed on natural soil induced approximately zero pressure gradients during 13 field experiments (Fig. 3). Although this result might be construed to mean that the Venturi effect was negligible, the opposite is true. The chamber systems were identical, adjacent, and simultaneously deployed; therefore, the same fan-induced wind should have created pressure gradients in the chamber placed on soil. Their absence implies that mass flow through soil was occurring and compensated for the chamber pressure gradient.

Indeed, the absence of a negative pressure gradient in a soil-deployed chamber system was observed to correspond to a CO_2 flux increase in response to a fan-induced wind (Fig. 4). The Venturi effect induces a mass flow of soil air through the chamber headspace. Advection of CO_2 with this flow increases the estimated CO_2 flux.

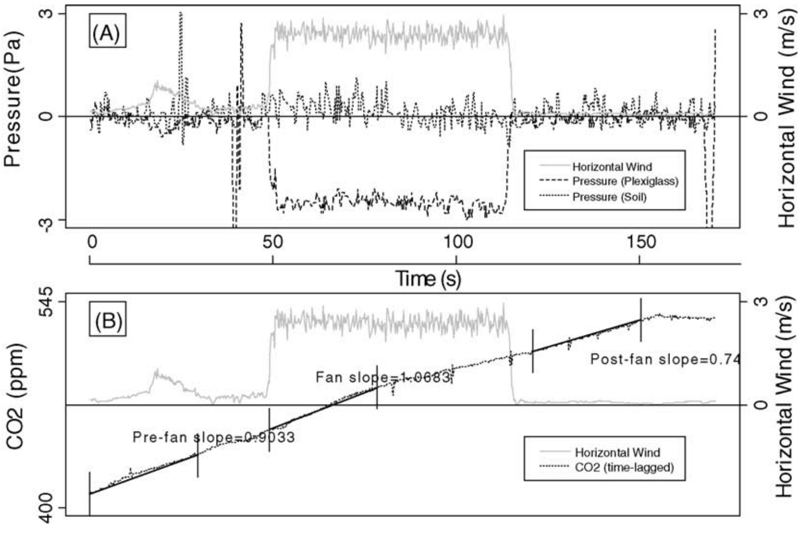

Fig. 4. The Venturi effect and the mass flow of soil air. Panel A demonstrates the absence of a negative pressure gradient in the chamber on natural soil during a field trial under fan-induced wind. The absence of an apparent Venturi effect is accounted for by the mass flow of soil air exhibited by the CO_2 concentration in Panel B. Mass flow during operation of the fan increases the CO_2 slope 30% above the average observed during the pre-fan and post-fan intervals. The CO_2 signal has been offset 30 s to account for the air transit lag time through the system and smoothed using a four-point (1 s) running median. The pressure data was smoothed using a three-point (0.75 s) running median and processed to remove instrument zeros. Slopes are shown for initial periods before, during and after the fan was turned on to illustrate the changes in CO_2 emission caused by the step change in wind speed.

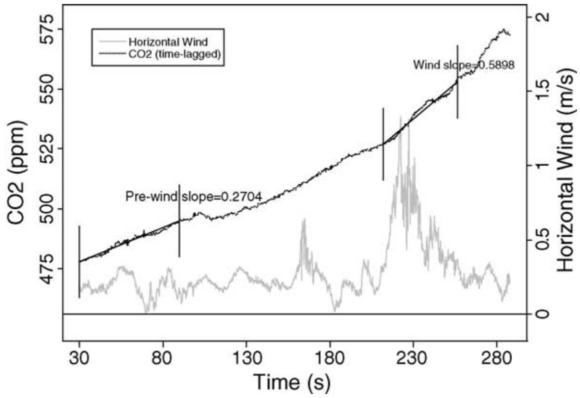

Fig. 5. Natural wind-induced mass flow of soil air. During a field trial conducted under natural wind conditions, an approximately 45 s natural wind gust (median velocity = 0.517 m s^{-1}, maximum = 1.33 m s^{-1}) forced a 116% increase in CO_2 slope in a chamber system deployed on natural soil. The CO_2 signal has been offset 30 s for the air transit lag time through the system and twice smoothed using a three-point (0.75 s) running median.

Similar, though more variable, pressure results were recorded under natural wind conditions (Fig. 5). A field trial conducted under natural wind conditions shows that natural wind at the surface, in a forest on a summer day, can induce the mass flow of soil air in chamber systems. Wind-induced advection of CO_2-rich soil air into the chamber created a positive bias in the soil fluxes derived from these observations.

To better determine the Venturi effect under natural wind conditions, eleven field trials were conducted with a single chamber system deployed on an impermeable plate in natural wind conditions for 5–10 min periods. The pressure and wind data for these trials were twice-smoothed using 10-point (2.5 s) running medians. Five of these trials, including the three trials conducted at nighttime, demonstrated the expected Venturi effect, where horizontal wind induced negative pressure gradients into the chamber as in Figs. 2 and 3. The R^2 value for change in pressure versus horizontal wind velocity across these five trials was 0.3226 ($p < 0.0001$, $n = 7612$ points or 1903 s) when data greater than three standard deviations of the mean was removed, supporting the Venturi effect (Fig. 6). However, the other six trials provided unexpected results—the R^2 values for these six trials was 0.0033 ($p < 0.0001$, $n = 8315$), suggesting other factors may dominate chamber pressurization in a natural wind regime.

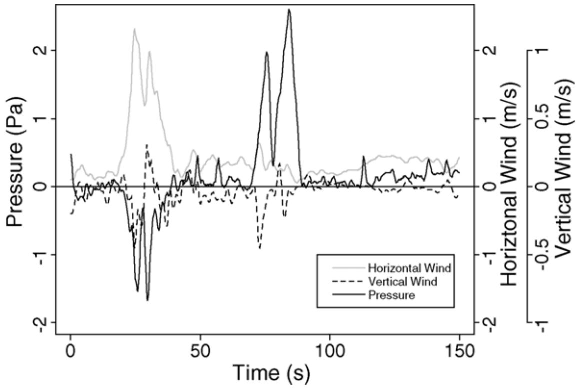

Fig. 6. Effects of horizontal and vertical components of natural wind on chamber pressure gradients. A single chamber system sealed to a plexiglass plate deployed for extended measurements under natural wind conditions demonstrated that horizontal wind is not always the dominant influence on chamber pressure gradients. The positive pressure spike (greater than 2 Pa) corresponds to an approximately 0.5 m s^{-1} gust in the vertical component of natural wind, suggesting a downdraft induced a positive chamber pressure gradient. The pressure and wind data were twice smoothed using a 10-point (2.5 s) running median.

Examination of the data showed that wind direction, and steadiness of the wind, both influenced chamber pressure gradient. The dependence on wind direction reflects the influence of roughness elements on the forest floor (rocks, vegetation), which provide turbulence and vertical components of the wind. Short bursts of wind led to unpredictable pressure variations inside the chamber. This is an unexpected result in the vegetative cover of the forest understory, previously considered a ‘‘safe’’ venue for chamber measurements of soil flux, where anomalous pressure effects would be negligible.

4. Discussion

It is evident that natural wind conditions can induce selective systematic error in vented, closed dynamic chamber systems through the Venturi effect, providing a plausible explanation for the overestimation of forest soil respiration by chambers as discussed by Goulden et al. (1996). Our results highlight two notable difficulties in quantifying error caused by the Venturi effect: quantification of the ‘‘true’’ internal pressure of soil-deployed chambers and turbulent pressure anomalies.

Several studies (e.g. Kanemasu et al., 1974; Lund et al., 1999) have attempted to quantify error in chamber-based soil gas flux measurements by analyzing the internal pressure of chamber systems. In the absence of a measured internal pressure, chambers were assumed to be operating free of pressure-induced error. However, substantial flux changes were noted in our results (Fig. 4) because of the absence of significant pressure gradients. The parallel chamber system displayed significant negative pressure gradients under essentially identical conditions when deployed on an impermeable plate.

Evidently the absence of pressure changes under windy conditions does not imply the absence of Venturi effects, but may reflect mass flow through the soil. Demonstration that a particular chamber design does or does not induce pressure gradients must be made while sealed to an impermeable surface.

Both Matthias et al. (1980) and Norman et al. (1992) warned of anomalous pressure effects at measurement sites with little vegetative cover. Our results suggest that wind turbulence may significantly affect chamber measurements even in the relatively dense summer vegetation of mid-latitude forest understory. We also noted significant pressure excursions during the placement of the chambers on the plates or soil, even though great care was used to avoid them. Anomalous pressure effects appear to pose major challenges for accurate chamber-based measurements given their difficulty to measure or control.

5. Conclusion

These results provide evidence for systematic overestimation of soil respiration by the dynamic chamber method when exposed to even weak surface winds, as suggested by Goulden et al. (1996), and attributed to the ‘‘Venturi effect’’ by Conen and Smith (1998). But these results also highlight greater potential biases in the chamber methodology, noting potential error in measuring the ‘‘true’’ chamber pressure gradient over a soil column and demonstrating anomalous pressure effects unexpected in the vegetative cover of the forest understory; errors unapparent under ‘‘normal’’ operating conditions.

The extent to which these results would be replicated in chamber systems with different designs, notably the orientation and dimensions of the chamber vent, is unclear. Rather than reject the dynamic chamber methodology in favor of static or sealed, closed chamber systems, as proposed by Conen and Smith (1998), it appears much more appropriate to improve the design of dynamic chamber systems. Closed, non-vented chambers may be less sensitive to wind forcing, but they are more sensitive to pressure changes associated with sampling and with any leaks in the associated flow systems. One possible solution deserving investigation is the addition of a ‘‘pigtail’’ extension to the chamber vent, oriented to dampen the Venturi effect. High-resolution differential pressure measurements in chambers that are sealed at the bottom provide a systematic way to evaluate the design of chambers and vents and to eliminate the induction of pressure gradients as much as possible. In order to conclusively account for soil respiration using the closed dynamic chamber methodology, the Venturi effect and any anomalous pressure effects resulting from wind turbulence must be eliminated through proper chamber design. Xu et al. (submitted for publication) has proposed such a chamber vent design with promising initial field results deserving further investigation.

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References

Andrews, J.A., Harrison, K.G., Matamala, R., Schlesinger, W.H., 1999. Separation of root respiration from total soil respiration using C-13 labeling during free-air carbon dioxide enrichment (FACE). Soil Sci. Soc. Am. J. 63, 1429–1435.

Bajracharya, R.M., Lal, R., Kimble, J.M., 2000. Erosion effects on carbon dioxide concentration and carbon flux from an Ohio Alfisol. Soil Sci. Soc. Am. J. 64, 694–700.

Baldocchi, D.D., Hicks, B.B., Meyers, T.P., 1988. Measuring biosphere–atmosphere exchanges of biologically related gases with micrometeorological methods. Ecology 69, 1331–1340.

Barford, C.C., Wofsy, S.C., Goulden, M.L., Munger, J.W., Pyle, E.H., Urbanski, S.P., Hutyra, L., Saleska, S.R., Fitzjarrald, D., Moore, K., 2001. Factors controlling long- and short-term sequestration of atmospheric CO_2 in a mid-latitude forest. Science 294, 1688–1691.

Conen, F., Smith, K.A., 1998. A re-examination of closed flux chamber methods for the measurement of trace gas emissions from soils to the atmosphere. Eur. J. Soil Sci. 49, 701–707.

Davidson, E.A., Belk, E., Boone, R.D., 1998. Soil water content and temperature as independent or confounded factors controlling soil respiration in a temperate mixed hardwood forest. Global Change Biol. 4, 217–227.

Davidson, E.A., Savage, K., Verchot, L.V., Navarro, R., 2002. Minimizing artifacts and biases in chamber-based measurements of soil respiration. Agric. For. Meteorol. 113, 21–37.

Farquhar, G.D., Sharkey, T.D., 1982. Stomatal conductance and photosynthesis. Annu. Rev. Plant Physiol. 33, 317–345.

Goulden, M.L., Munger, J.W., Fan, S.M., Daube, B.C., Wofsy, S.C., 1996. Measurements of carbon sequestration by long-term eddy covariance: methods and a critical evaluation of accuracy. Global Change Biol. 2, 169–182.

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.

Hutchinson, G.L., Livingston, G.P., 2001. Vents and seals in non-steady-state chambers used for measuring gas exchange between soil and the atmosphere. Eur. J. Soil Sci. 52, 675–682.

Hutchinson, G.L., Rochette, P., 2003. Non-flow-through steady-state chambers for measuring soil respiration. Soil Sci. Soc. Am. J. 67, 166–180.

Kanemasu, E.T., Powers, W.L., Sij, J.W., 1974. Field chamber measurements of CO_2 flux from soil surface. Soil Sci. 118, 233–237.

Kimball, B.A., Lemon, E.R., 1971. Air turbulence effects upon soil gas exchange. Soil Sci. Soc. Am. Proc. 35, 16–21.

Livingston, G.P., Hutchinson, G.L., 1995. Enclosure-based measurement of trace gas exchange: applications and sources of error. In: Matson, P.A., Harriss, R.C. (Eds.), Biogenic Trace Gases: Measuring Emissions From Soil and Water. Blackwell Scientific Publications, Oxford, pp. 14–51.

Liu, H., Foken, T., 2001. A modified Bowen ratio method to determine sensible and latent heat fluxes. Meteorologische Zeitschrift 10, 71–80.

Lund, C.P., Riley, W.J., Pierce, L.L., Field, C.B., 1999. The effects of chamber pressurization on soil-surface CO_2 flux and the implications for NEE measurements under elevated CO_2. Global Change Biol. 5, 269–281.

Matthias, A.D., Blackmer, A.M., Bremner, J.M., 1980. A simple chamber technique for field measurement of emission of nitrous oxide from soil. J. Environ. Qual. 9, 251–256.

Norman, J.M., Garcia, R., Verma, S.B., 1992. Soil surface CO_2 fluxes and the carbon budget of a grassland. J. Geophys. Res. 97, 18,845–18,853.

Schimel, D.S., House, J.I., Hibbard, K.A., Bousquet, P., Ciais, P., Peylin, P., Braswell, B.H., Apps, M.J., Baker, D., Bondeau, A., Canadell, J., Churkina, G., Cramer, W., Denning, A.S., Field, C.B., Friedlingstein, P., Goodale, C., Heimann, M., Houghton, R.A., Melillo, J.M., Moore, B., Murdiyarso, D., Noble, I., Pacala, S.W., Prentice, I.C., Raupach, M.R., Rayner, P.J., Scholes, R.J., Steffen, W.L., Wirth, C., 2001. Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. Nature 414, 169–172.

Wofsy, S.C., Goulden, M.L., Munger, J.W., Fan, S.M., Bakwin, P.S., Daube, B.C., Bassow, S.L., Bazzaz, F.A., 1993. Net exchange of CO_2 in a mid-latitude forest. Science 260, 1314–1317.

Xu, L., Furtaw, M.D., Garcia, R.L., Madsen, R.A., Anderson, D.J., McDermitt, D.K. On maintaining pressure equilibrium between a soil respiration chamber and ambient air. J. Geophys. Res., submitted for publication.