Technical Memo 1504.2: Wind Effects on Soil Gas Flux Measurements at Ground Level

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Easy set-up. Expert results.

Summary

Recent laboratory data generated by Colorado State University (CSU) comparing three soil gas flux measurements (gradient method, passive CO_2 traps and the dynamic flux chamber) suggested that these measurements might be affected by wind velocity (Tracy, 2015). This document provides a background on wind velocity profiles with respect to ground level, discusses a new (third generation) passive CO_2 trap design, and presents new laboratory data on the magnitude of wind-induced bias on E-Flux's new CO_2 trap design.

Recommendations and best practices for deploying CO_2 traps when high wind bias is a concern at a particular site are presented at the end of this document. Previous versions of this document (versions 1504.0 and 1504.1 dated 4/21/2015 and 4/29/2015, respectively) addressed some of these points, but lacked the laboratory performance data on the new trap design presented here. Additionally, both previous versions stated that the standard practice for reporting wind velocity was at an elevation of 2 m (v_{2m}). After a more detailed literature review, it was found that the standard elevation for reporting wind velocity is 10 m (v_{10m}), with departures from such convention being rare. This report uses the standard practice (v_{10m}) as reference for field-representative velocities.

The CSU experiment properly identified wind velocity as an interfering variable for soil gas flux measurements. However, the reported magnitude of the bias from such experiments should be carefully considered. The CSU methodology had two limitations: a) the CO_2 trap design included a first-generation 0.56 m high rain cover (only used on the first prototypes tested from 2009-2010) combined with a second generation trap, and b) the wind profile achieved by the experimental setup in those experiments is not representative of field conditions.

These two limitations were addressed experimentally, by deploying the third generation CO_2 traps on a soil column where known CO_2 fluxes were imposed (i.e., a soil flux calibration column). Wind was simulated with a box fan and field representative conditions were achieved by adjusting the distance between the box fan and the flux calibration column. A simulated length of ground was also emplaced between the fan and the flux calibration column. Field representative conditions were based on two criteria: a) comparison of the laboratory measured wind velocity profiles with model-predicted values, and b) a target high wind velocity of v_{10m} = 5.2 m/s (11.7 mi/hr). This high wind velocity value was the annual average v_{10m} for the top 100 windiest cities in the U.S. (out of a total of 3,573 urban sites).

The new trap design, implemented by E-Flux in 05/2015, is 0.17 m (7 in) tall, and 0.10 m (4 in) in diameter. These dimensions result in a 68% shorter and 78% smaller cross sectional area than the early prototype used by CSU. To our knowledge, wind-related performance data on the intermediate second generation trap and rain cover in use from 2010-2015 (0.30 m tall, 0.15 m diameter) does not exist.

Achieving wind profiles representative of field conditions was successful. A good fit was obtained using the Prandtl logarithmic wind profile model, suitable for near ground wind velocities. However, the wind velocities achieved were significantly higher than the target. The wind velocities measured correspond to v_{10m} values between 6.7 and8 m/s, approximately 30-55% larger than the target v_{10m} = 5.2 m/s (11.7 mi/hr).

In addition to measurements using the CO_2 traps, this study included paired measurements using the dynamic flux chamber (DFC) method, for further validation of the tests. The gradient method was not implemented.

Despite differences in methodologies, the present study generated many similar findings to the CSU study:

i) In the absence of wind, measurements from the CO_2 traps and the DFC are in close agreement with each other.
ii) Both CO_2 traps and DFC showed a low bias in the order of 15%, with respect to the imposed fluxes in the absence of wind. This value is also consistent with earlier trap calibration values (McCoy et al, 2014).
iii) The wind-induced bias on the DFC is negative.
iv) The wind-induced bias on the CO_2 traps is positive.

The data presented in this document differs from the CSU study in the following ways:

i) This study found the negative wind-induced bias on the DFC to be in the order of -5% to -30% at near ground velocities of $v_{0.17m}$ 1.6 and 2 m/s, which correspond to v_{10m} values between 6.7 and 8 m/s (15-20 mi/h). The CSU study reported a bias in the order of -50% to -70% with wind velocities measured near ground of 2.9 and 4.9 m/s. Assuming a Prandtl logarithmic wind profile, the reported velocities in the CSU study correspond to v_{10m} values in the range of 9 and 15 m/s (22-38 mi/h). This finding highlights the need to achieve field-representative conditions during laboratory experiments.
ii) The positive wind-induced bias of the third generation CO_2 traps measurement is in the order of 20-30% at near ground velocities of $v_{0.17m}$ 1.6 and 2 m/s, which correspond to v_{10m} velocities of 6.9 and 8 m/s (15-20 mi/h). The CSU study found larger positive bias, in the order of 60-120% at conditions corresponding to v_{10m} values in the range of 9 and 15 m/s (22-38 mi/h). This large difference is likely due to a combination of different flow profiles and a different trap design (the smaller third generation CO_2 trap design vs. the device tested by CSU).

Whereas the present study provides improved understanding of the wind effects on soil gas flux measurement methodologies, it only addressed one variable (wind velocity) over a relatively narrow interval of v_{10m} of 6.7 and 8 m/s (15-20 mi/h). Limitations of this study include: only the third generation CO_2 trap design was tested, target flow profile was terrain with moderate cover (agricultural), the CO_2 flux was fixed (2.5 µMoles/m^2.s), and a DFC custom design was used (similar to the LiCor 8100A chamber). Although we believe the results presented here are realistic order of magnitude estimates of the wind induced bias, different conditions might result in deviations.

Introduction

This section offers an overview of the dependence of wind velocity on elevation above ground level. Site-specific wind velocity information can be inferred from weather reported data, which by convention refers to wind velocity values measured at 10 m (32.8 ft) above ground level (indicated as v_{10m} in this document) (WMO, 2008; NOAA, 2015). Specific protocols might differ from this convention. For example, USDA Forest Service stations often collect wind velocity values at 6.1 m (20 ft) (USDA, 2003; NWFCG, 2014), although they are still reported on a v_{10m} basis, after a correction for height. At ground level, boundary layer theory indicates that the wind velocity approaches a null value (Crowe and Roberson, 1996). Thus, interpolation of wind velocities in-between these end points is necessary. Available wind velocity models are reviewed, with emphasis on their suitability to the domain of interest near ground (where the devices used to measure soil gas fluxes are located).

The average of the mean wind velocity for the top 100 windiest locations out of 3,573 urban areas in the United States (population of 50,000 or higher) was selected as a benchmark high wind velocity value (CityData, 2015; USDoC, 2013).

In addition to careful consideration to wind velocities near ground, wind-induced biasing effects on soil gas fluxes depend on the aerodynamics of the flux measuring devices. The larger the dimensions of such devices (i.e., height and cross sectional area), the larger the wind drag. Large drag can result in differential pressures between the soil and the device, which can generate advection-driven fluxes and bias. Steps taken to mitigate this effect will be addressed in the methodology section.

International unit system will be used, although equivalent values in Imperial units will be provided for a few key parameters.

Wind Velocity Dependence on Elevation

Two empirical models are available to estimate wind velocity values at non-zero elevations:

a) The power law
b) The Prandtl logarithmic wind profile

The power law is typically used for wind turbine design (Hau et al, 2006) and also to adjust the reported wind velocities from weather stations if their elevation differs from the standard 10 m. The Prandtl logarithmic wind profile model is considered more accurate at locations near ground level. For this reason it has been used in previous studies to estimate the effects of wind and ground cover on the transport of CO_2 in the vadose zone (Oldenburg and Unger, 2004).

The Power Law Model

The power law model indicates that the ratio of wind velocity at two different elevations is proportional to the ratio of elevations above ground level to a power:

$$v_2 = v_1 \left(\frac{z_2}{z_1}\right)^{\alpha} \qquad \text{(Equation 1)}$$

in which α is the shear exponent, and v_1 and v_2 are velocities at two different heights (z_1 and z_2, respectively) (Hau, et al, 2006). The shear exponent (α) depends on the roughness of the ground cover (i.e., flat water surface, vegetated cover, etc) and the turbulence of wind flow. For example, assuming α = 0.30 (a value for human inhabited areas) (Hau, et al, 2006), a velocity of 5.2 m/s (11.7 mi/hr) at an elevation of 10 m (v_{10m} = 5.2 m/s = 11.7 mi/hr) corresponds to a velocity of 4.9 m/s (10.9 mi/hr) at an arbitrary height of 2 m (v_{2m} = 4.9 m/s = 10.9 mi/hr).

The Prandtl Logarithmic Wind Profile Model

The Prandtl logarithmic wind profile model is similar to the power law model, but accounts for a finite thickness above ground z_o (called the roughness height) in which the wind velocity is essentially null (Oldenburg and Unger, 2006; McLelland, 2010) (see Figure 1).

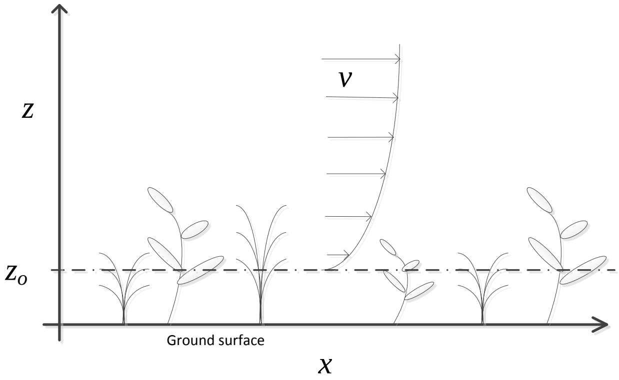

Figure 1. Diagram of the Prandtl logarithmic wind profile (adapted from Oldenburg and Unger, 2006). The elevation z_o depends on the type of ground cover. Wind velocities within z_o are null.

The Prandtl logarithmic wind profile formula is

$$v_z = \frac{v_*}{k}\, ln\left(\frac{z}{z_o}\right) \qquad \text{(Equation 2)}$$

In which v_z is the wind velocity at an elevation z, v_* is the friction velocity (an empirical parameter that governs the shape of the wind profile near ground depending on the surface cover type), k is the von Karman's constant (k = 0.4), and z_o is the roughness height (which depends on the surface cover type). The roughness height z_o varies between 0.008 m for barren soil to 0.7 m for urban locations. As CO_2 traps are rarely deployed at completely barren sites, a low (conservative) value for agricultural land of z_o = 0.04 m (1.6 in) (Schram, 1998) was chosen as a reference target value for this study. As an example, for z_o = 0.04 m (1.6 in) a velocity of 5.2 m/s (11.7 mi/hr) at an elevation of 10 m (v_{10m} = 5.2 m/s = 11.7 mi/hr) corresponds to a velocity of 3.6 m/s (8 mi/hr) at an arbitrary height of 2 m (v_{2m} = 3.6 m/s = 8 mi/hr).

Model Selection at Near Ground Level Elevations

Figure 2 compares wind profiles described by the power law model (Equation 1) and Prandtl logarithmic profile (Equation 2) to achieve a target high wind velocity of v_{10m} = 5.2 m/s (11.7 mi/hr). For the power law model, two values of the exponent α were considered, α = 0.14 (for surfaces with minimal cover) and α = 0.30 (for surfaces with moderate cover), while an agricultural cover of z_o = 0.04 m (1.6 in) was chosen for the Prandtl logarithmic profile.

Figure 2 shows that the power law model for minimal cover terrain (α = 0.14) estimates higher wind velocity values than those predicted by the Prandtl logarithmic profile, with the largest differences being at low elevations (i.e., less than 0.28 m). The power law for terrain with moderate cover (α = 0.30) and Prandtl logarithmic wind profile models are in relative agreement (differences of velocity in the order of 10-15%) at elevations higher than 0.30 m (1 ft). However, at elevations in the order of ~0.1 m (near the dimension of the new, third generation CO_2 trap) the difference can be up to one order of magnitude (90%). Consistent with the literature, this work will use the Prandtl logarithmic profile model as a basis to reconcile wind velocity values at elevations near ground (< 0.30m) with wind velocity values at the standard reference elevation of 10 m (v_{10m}).

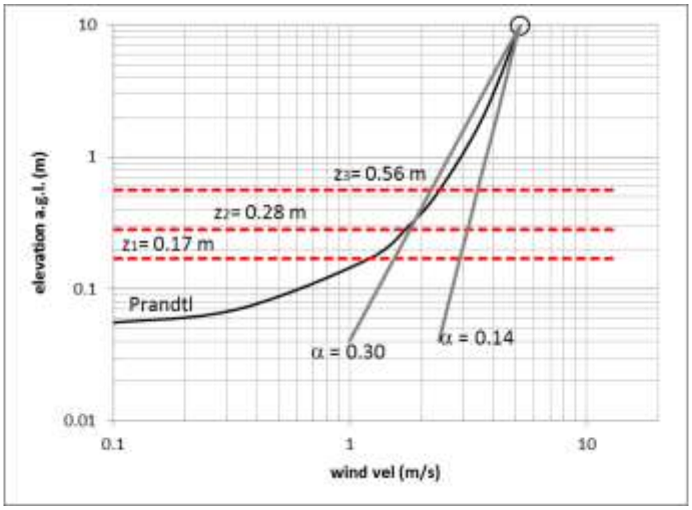

Figure 2. Comparison of power law and Prandtl logarithmic wind profile (black solid line) with a target wind velocity of v_{10m} = 5.2 m/s (11.7 mi/hr). Prandtl logarithmic wind profile is shown as a black solid line and target v_{10m} is shown as a black circle. Solid gray lines are power law predictions for α = 0.14 , and α = 0.3, respectively (with the same target wind velocity v_{10m}). The heights of the three CO_2 trap designs (1st, 2nd, and 3rd generations) are shown as dotted red lines.

Figure 3 displays the Prandtl logarithmic profile for z_o = 0.04 m (1.6 in) and a target velocity v_{10m} = 5.2 m/s (11.7 mi/hr), together with the Prandtl logarithmic profile for the two conditions tested by CSU (wind velocities of 2.9 and 4.9 m/s near ground (Tracy, 2015). The CSU study mentioned the wind velocity “was measured at the surficial methods [*sic*] with a handheld wind meter…” (Tracy, 2015), but did not provide the specific elevation value for the measurement. Based on our wind velocity measurements from elevations in the range of 0 to 0.56 m (see Appendix 1), it was determined that the velocity values reported by the CSU study were consistent with an elevation of 0.28 m, half of the height of the first generation CO_2 trap tested in those studies. Assuming that the location of the measurement was closer to ground would result in larger v_{10m} values, so this assumption was considered conservative. It can be seen in Figure 3 that the conditions used by the CSU study correspond to v_{10m} values between 9 and 15 m/s (22-38 mi/h) (2 to 4 times larger than the v_{10m} value determined as characteristic of high wind velocity sites).

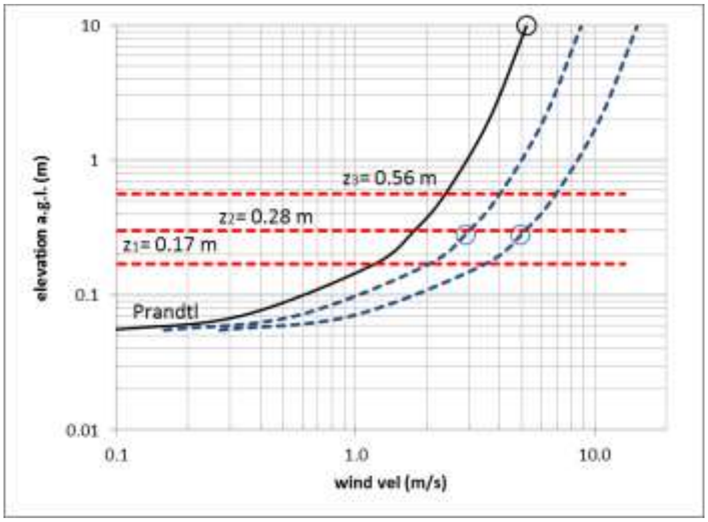

Figure 3. Comparison of the Prandtl logarithmic wind profile for z_o = 0.04 m (black solid line) with a target wind velocity of v_{10m} = 5.2 m/s (11.7 mi/hr) (black circle) with the conditions tested in the CSU study (shown in blue circles). Dotted blue lines correspond to the Prandtl logarithmic profile meeting the CSU-reported conditions. The height of the three CO_2 trap designs (1st, 2nd, and 3rd generations) are shown as dotted red lines.

The analysis presented in this section illustrated the importance of selecting models that are suitable for near ground elevations. Model selection is crucial as wind velocity predictions at elevations of 0.5m or lower can vary by over an order of magnitude. The following section addresses trap design changes to mitigate wind bias, along with describing the experimental conditions to match field conditions.

Methodology

CO_2 Trap Design

E-Flux's latest CO_2 trap was specifically designed minimize wind bias. This was achieved by replacing the former 6 in diameter, 12 in tall rain-cover of the second generation design with a thin, 6 in diameter cap attached to the top element of the trap. The cartridge itself was redesigned to be shorter (resulting in the sorbent layer being only 7.5 cm (3 in) over the ground surface, and elevation found to be optimal (Tracy, 2015)). The sorption cartridge retained the same cross sectional area for soil gas flux measurement and the same sorbent capacity as the second generation CO_2 trap. Figure 4 compares the design of the three CO_2 trap generations. Design specifics for each of the three generations can be seen in Table 1. The new design achieved significant height and cross sectional area reductions, offering less resistance to wind and lower drag. The Results section presents flux measurements associated with the new trap design upon different imposed wind profiles.

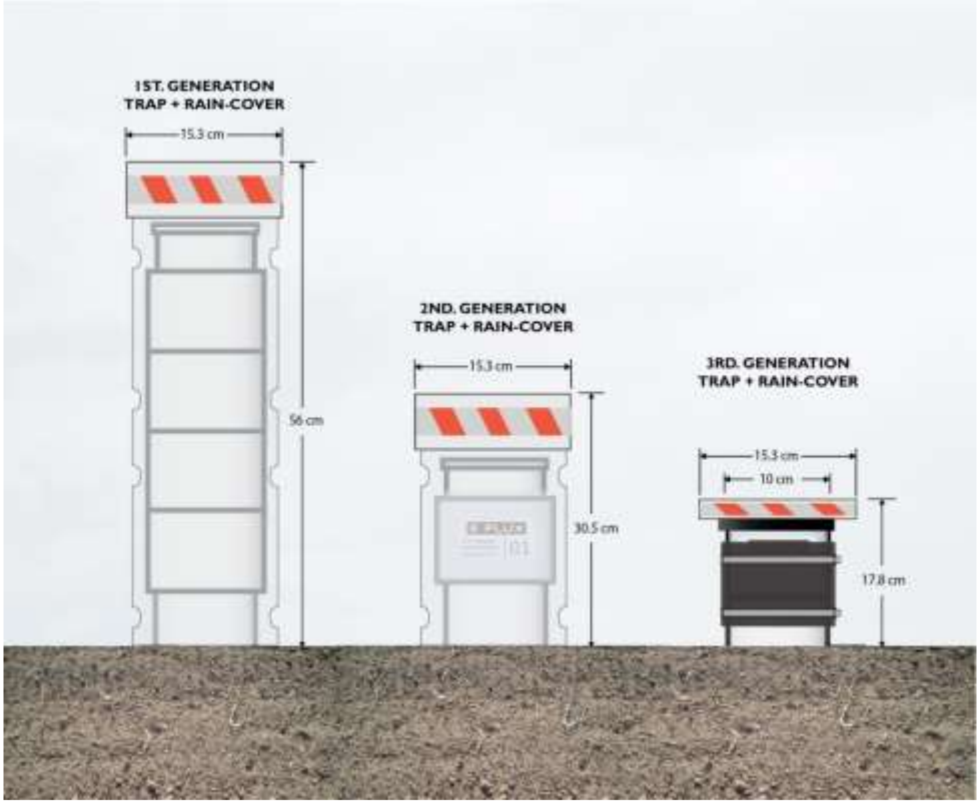

Figure 4. From left to right, first, second and third generation CO_2 trap and rain cover design.

Table 1. Comparison of features for the three CO_2 trap designs and approximate periods of use.

Feature	**First Generation Design**	**Second Generation Design**	**Third Generation Trap Design (Current)**
Height (at top of rain cover)	0.56 m	0.30 m (12 in)	0.17 m (7 in)
Diameter of the bulk trap	0.15m (6 in)	0.15m (6 in)	0.10 m (4 in)
Cross Sectional Area	857 cm^2	467 cm^2	184 cm^2 (including rain cover)
Period of implementation	2009-2010*	2010-2015	05/2015 to date

*Small deviations from the stated dimensions may have occurred in some traps as design changes from 1st generation to 2nd were iterative.

Column Experiments

A 0.58 m (23 in) diameter column filled up with sand was subject to measured CO_2 flows, resulting in known imposed fluxes. Figure 5 illustrates this flux calibration column, which is similar to the one used by Colorado State University in previous experiments (Tracy, 2015). Although similar to the CSU setup, modifications to the relative fan position and the flux column were introduced to achieve a field representative flow profile. Measurement of such flow profile and adjustments to the fan position relative to the flux column are described in Appendix 1. An additional difference was that this study used the third generation rain cover and CO_2 trap design while the CSU study used a first generation rain cover design (0.56 m high) coupled to a second generation CO_2 trap. The reasoning for such inconsistency between trap and rain cover designs was not reported.

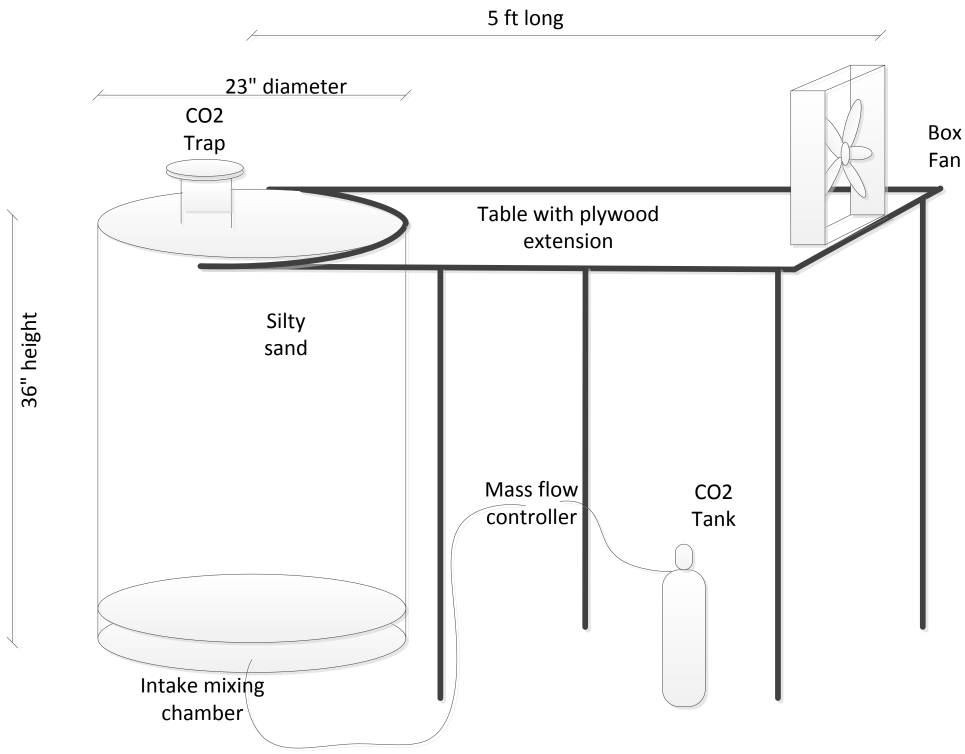

Figure 5. Experimental setup of the CO_2 flux soil column used to calibrate the flux measurements.

The CO_2 flow rate to the column was controlled with a mass flow controller (MFC Aalborg GFC17), and measured typically twice a day with an Agilent soap film gas meter. The column was filled with 100-mesh silica sand. The CO_2 stream (pure, bone-dry CO_2 from a compressed gas tank) was introduced to the bottom of the column into a 5 cm tall mixing chamber to achieve uniform soil gas flow. The mixing chamber was filled with medium sand (20-mesh). A 2 cm thick gradation of coarse to fine sand (60-mesh, 80-mesh) was used at the top of the 20-mesh sand to keep the 100-mesh sand from entering the mixing chamber. Different locations at the top of the calibration column were sampled with the dynamic flux chamber (DFC) and found to be within 3% of each other, indicating that the CO_2 flow was radially uniform.

The CO_2 fluxes on top of the column were measured with:

a) Dynamic CO_2 flux chambers (DFCs)
b) CO_2 traps

The DFC used consisted of a custom made chamber with a photoacoustic gas sensor (Innova 1312, Lumasense Technologies, Denmark) configured to measure greenhouse gases. The chamber was 0.20 m (8 in) in diameter, 0.15 m (6 in) tall, and designed to fit over a 0.20 m (8 in) receiver pipe. Twenty-two laboratory and 5 field soil gas flux measurements were conducted over a flux interal between 2.1 and11 µMole/m^2.s and compared to those from a LiCor 8100A unit. The two instruments were found to make nearly identical measurements. Appendix 2 describes a comparison of both of these DFCs in further detail.

The flux calibration column was operated under simulated windy conditions at a fixed CO_2 flow rate resulting in an average imposed flux of 2.5 µMole/m^2.s. A box fan (50.8 cm, Lasco Galaxy 20200, the replacement of the discontinued model used in the CSU study) was located 1.83 m (6 ft) away from the soil column, on a table horizontally aligned with the top of the column. The table was prolonged with a plywood sheet cut flush with the column perimeter. The top 0.05 m (2 in) of sand in the flux calibration column was removed to achieve a field representative roughness height in the order of 0.04 m (per Equation 2).

Wind velocity profiles at variable elevations were measured with a hot wire anemometer (Extech, Nashua, NH) on the upwind side of the CO_2 trap. This instrument was selected because it can make point measurements at different elevations above ground with minimal disturbance of the flow field. One CO_2 trap was deployed for a period of 3-4 days under each fan setting. Upon a change in conditions, the soil column was allowed to operate for a minimum of 12 hr before deploying the traps. Such period was estimated as sufficient to allow the column to reach steady state conditions, based on measurements in the absence of wind using the DFC.

Results and Discussion

Flux Measurements Using DFC and CO_2 traps in the absence of wind

Without wind, measurements from the CO_2 traps and the DFC were in close agreement (see Figure 6), in agreement with previous data (Tracy, 2015). Vertical error bars reflect the error of the measurement (either multiple measurements of the DFC once or twice a day or the carbonate analysis variability on the traps), while horizontal error bars represent the standard deviation of the multiple CO_2 flow meter measurements or duplicate CO_2 analysis for traps. Best fit values for the data shown in Figure 6 (slopes of 0. 86 and 0.84 for the DFC and chambers, respectively) reflect a negative bias of both techniques (i.e., both measured slightly lower values than the imposed flux). The bias under no wind conditions was -14% for the DFC and -16% the CO_2 traps, similar to the Tracy, 2015 experiment.

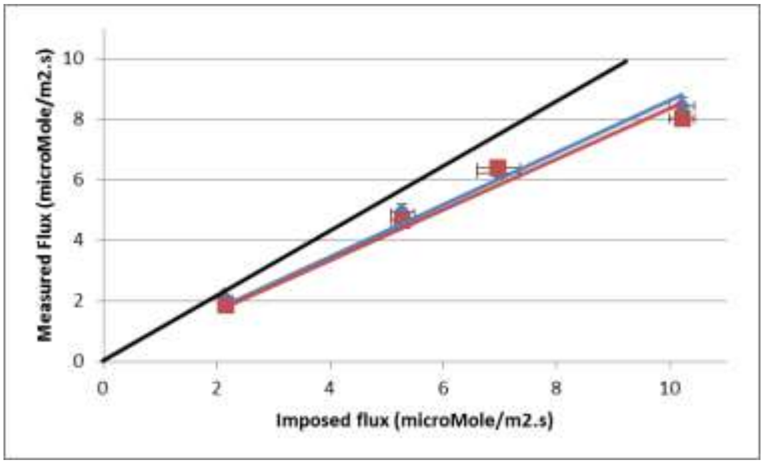

Figure 6. Measured flux with the dynamic flow chambers and the CO_2 traps as a function of the imposed flux. Blue diamonds are for DFC, and red squares for CO_2 traps. Black line represents ideal correlation. Horizontal error bars represent standard deviation of multiple flow rate measurements. Vertical error bars represent the standard deviation of multiple DFC measurements, and those for CO_2 traps are the standard deviation of duplicate carbonate analysis on a single trap.

Measured Wind Profiles

The wind velocity profiles achieved using the experimental setup described in Figure 5 are shown in Figure 7. Table 2 shows that the Prandtl logarithmic wind profile parameters which fit the data adequately (R^2 values of 0.86 and 0.94 at the low and high fan setting, respectively). The best fit roughness height associated with these conditions is in the interval of 0.038 and 0.053 m, which includes the target 0.04 m reported as characteristic of agricultural areas (Schram, 1998). Figure 8 compares the flow profile achieved in this study and the one achieved by setting the fan next to the flux calibration column (similarly to the conditions of the CSU study). The profile achieved under the conditions tested by CSU shows decreasing wind velocities for an elevation range between 0.30 m and 0.50 m (within the height of the first generation trap design used in those tests) and a local minimal velocity at an elevation of 0.25 m, likely due to the position of the fan shaft. Both of these are inconsistent with field-like profiles (i.e., as described by Equations 1 or 2). Additionally, no appreciable roughness height was measurable at these conditions. A flux measurement at ground level is likely to be very sensitive to these conditions, as a significant pressure difference between the flux measurement device and the soil might be generated.

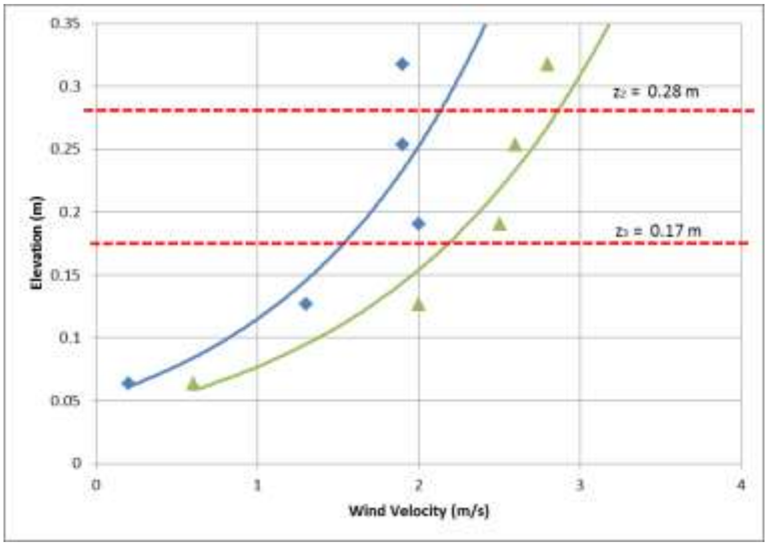

Figure 7. Velocity profiles upon fan operation and best fit curves for the Prandtl logarithmic profile under the low and high fan settings (blue and green symbols and lines, respectively). The heights of the second and third generation CO_2 trap designs are shown as dotted red lines labeled with z_2, and z_3 (respectively).

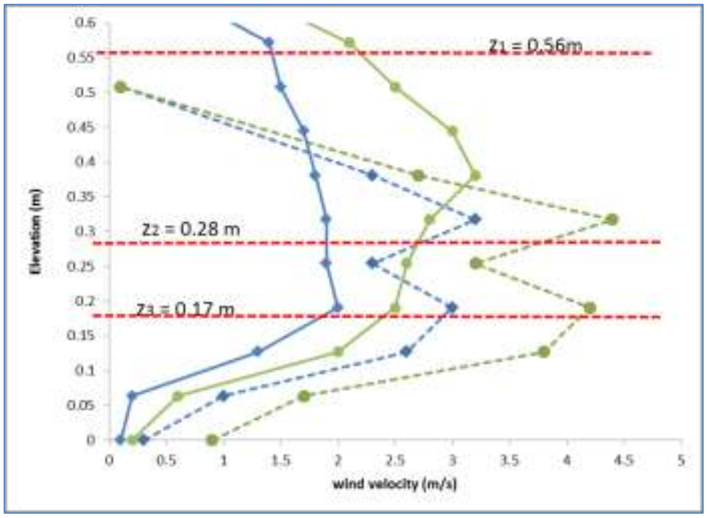

Figure 8. Wind velocity profiles achieved under the low and high fan settings (blue and green, respectively). Solid lines correspond to conditions in this study (distancing the fan 1.8 m away from the CO_2 trap and a 0.05 cm (2-in) step roughness on the ground between the fan and the trap). Dotted lines represent wind velocities 0.60 m away from the fan and without the step roughness (similar to those of the CSU experiment). For reference, the heights of the three generation CO_2 trap designs are shown as dotted red lines labeled with z_1, z_2, and z_3 (for first, second and third generation traps, respectively).

Table 2. Prandtl logarithmic wind profile equation parameters to fit the experimental data. Five wind velocity measurements for each fan setting were used to fit the Prandtl logarithmic wind profiles, from an elevation of 0.06 to 0.31m.

	Low fan setting	**High fan setting**
Best fit roughness height (zo, m)	0.053	0.038
v_* (friction velocity, m/s)	0.51	0.58
Regression coefficient (R^2)	0.86	0.94

A comparison of the Prandtl logarithmic flow profile achieved under the experimental conditions used in this study and the target Prandlt logarithmic flow profile described in the Introduction section is presented in Figure 9. It is noted that although the fit of the logarithmic wind profile to the data is reasonable, the v_{10m} values correspond to more stringent conditions (i.e., higher wind velocities) than those of the target profile. The low fan setting achieved a v_{10m} = 6.7 m/s (15 mi/h) and the high a v_{10m} = 8.0 m/s (20 mi/h). Although these values are significantly higher than the target v_{10m}= 5.2 m/s (11.7 mi/h), it seems reasonable to assume that the magnitude of the wind-induced bias is proportional to the magnitude of the wind velocity (i.e. $v_{0.17m}$) in the range between null and those measured in this study (as it was found in the CSU study) (Tracy, 2015).

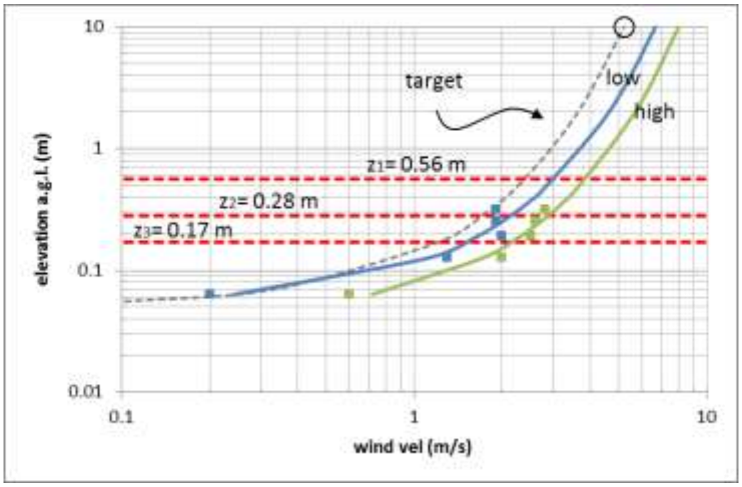

Figure 9. Prandtl logarithmic profile models. The target was based on the Prandtl logarithmic profile, assuming a roughness height of 0.04m and a v_{10m}= 5.2 m/s (11.7 mi/h) (shown as a black circle). Blue and green lines are best fits to the Prandtl logarithmic profile using the experimental conditions in this study at the low and high fan settings, respectively.

Fluxes Under Simulated Wind

The measured CO_2 flux at each of the imposed wind conditions are shown in Figure 10. The target imposed flux was 2.5 µMole/m^2.s. As the flow rates varied (likely due to variability in the mass flow controller), imposed fluxes varied for each trap deployment period. For this reason the data was normalized to the imposed flux calculated from daily measurements of the CO_2 flow rate for each period when the CO_2 trap was deployed (which varied between 3.4-4.8 days). The coefficient of variation of the measured flow rates was 15% (i.e., the imposed flux interval was 2.0-2.7µMole/m^2.s).

Error bars for the imposed fluxes shown in Figure 10 correspond to the flow rate variability for the period of deployment of the CO_2 traps. Deployment of the CO_2 traps varied between 3.4 and 4.8 days. Error bars on the DFC measurements reflect the standard deviation from multiple measurements during trap deployment. Error bars on the CO_2 traps are standard deviation on duplicate analysis of a single trap (error bars collapse within the symbol size).

At the average imposed flux of 2.5 µMole/m^2.s the wind-induced bias on the CO_2 traps was 7% and 27%, for $v_{0.17m}$ values of 1.5 and 2.2 m/s (3.5 and 4.5 mi/h). $v_{0.17m}$ was used in this study since it was available from actual measurements. Using the Prandtl logarithmic profile parameters (as shown in Table 2), these correspond to v_{10m} wind velocity values of 6.7 and 8 m/s (15 and 20 mi/hr), respectively. Based on best fit lines (Figure 6), the bias without wind was nearly -15% for both the CO_2 traps and the DFC measurements (over a range of imposed fluxes between 2 and 9 µMoles/m^2.s). The wind-induced bias was near linear with the magnitude of the wind velocity (similarly to the Tracy, 2015 experiments). However, the magnitude of the wind-induced bias was larger in the CSU experiment, probably due to a combination of a different trap design and a different imposed wind profile. Although the magnitude of the bias on the DFC chamber was not monotonic (i.e., the magnitude of the bias was lower at the higher wind speed), this may had been caused by the larger variability of the DFC chamber measurements under imposed wind conditions.

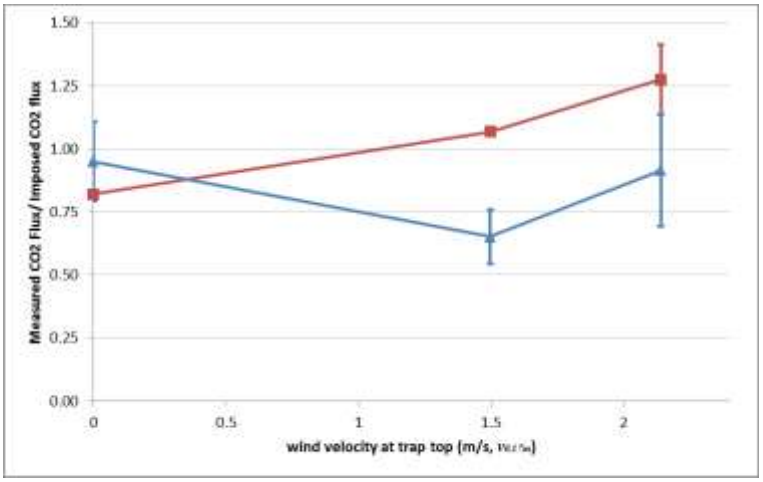

Figure 10. Normalized measured flux (relative to the imposed flux) at an average imposed flux of 2.5 µMole/m^2.s and variable wind velocities measured at the top of the trap ($v_{0.17m}$). Normalized fluxes are shown in red and blue for CO_2 trap measurements and DFC measurements, respectively. Error bars for the DFC measurements are standard deviations for the duration of the trap deployment. Duplicate CO_2 traps were deployed at the high fan setting only (standard deviation shown as error bar).

Study Limitations and Conclusions

The study presented made significant efforts to achieve field representative conditions, as determined by wind-profiles that follow reported relationships between wind velocity and elevation above ground. By controlling the distance from the fan to the flux calibration column and introducing a surface roughness between the fan and the flux measuring device, the experimental wind velocity profile matched the Prandtl logarithmic wind profile equation reasonably well (i.e. R^2 value between 0.86 and 0.94, and a fitted roughness height close to the target value of 0.04 m). Despite these efforts, the following limitations to this study are acknowledged:

- Tested wind velocities were relatively high (v_{10m} = 6.7 and 8.0 m/s (17 and 20 mi/h)) in comparison with wind velocity data at the windiest cities. A new experimental setup is being developed that will achieve a wider wind velocity range that includes lower wind velocities.
- Wind velocity profiles are strongly dependent on location (i.e., surrounding ground cover). The target conditions used in this study only addressed one type of field cover (agricultural). Actual field conditions should be carefully considered to assess differences with those tested in this document. Reported fitting values for wind velocity profiles depending on ground cover should be helpful in making such assessment.
- This study only included the standard third generation CO_2 trap. In some cases the traps are modified to suit specific objectives, for example increasing the sampling area (to avoid local heterogeneities) by coupling the traps to 8 in receivers. Extrapolations of the findings of this study to any other trap design (i.e., previous generation ones or to modifications to the current one) should be made carefully.

- The DFC design used was a custom made chamber. Off-the-shelf DFC equipment (i.e., the LiCor 8100A unit) might have a different bias than reported in this document.

This study was able to confirm that the CO_2 traps are subject to a positive wind induced bias, while also confirming that the DFC is subject to a negative wind induced bias. For the CO_2 traps, the bias was in the range of 7 to 30%, while the DFC showed a wind-induced bias of -9 to -35%. In the absence of wind, both methods were in close agreement with each other, although both methods gave measurements approximately 15% lower than the imposed flux value. At this point it is not known if the bias in the absence of wind is due to uncertainty in the imposed/measured CO_2 flow rate, or a systematic error on both measurement techniques.

For the CO_2 traps, it seems that the relationship between the magnitude of bias and the wind velocity is approximately linear (consistently with previous studies (Tracy, 2015)). This linear behavior is useful, as it suggests that under constant soil gas fluxes, long term wind-induced bias might be estimated based on average wind velocity for the period of deployment.. While future experiments will address the limitation of having a narrow wind range imposed on the flux measurement devices, it seems reasonable to approximate the bias under field conditions as proportional to the average v_{10m} value.

Recommendations and Best Practices

This section provides a general framework with the purposes of assessing the magnitude of the wind velocity near ground, estimate the magnitude of the potential wind biasing effects, and if necessary, mitigating them to obtain adequate data quality. These broad recommendations are not intended as a rigid guideline. In any particular application, the user should make a judgement about when the data quality has been compromised. Field conditions, monitoring program objectives, and the required precision of the estimate might be considered in this decision.

Comparison of wind velocities from different sources needs to be done at the same elevation above ground, as different data sources measure and/or report wind velocity at different elevations. Wind velocity from weather stations (the most widely available source) is typically reported at a reference height of 10 m (v_{10m}). Although velocities in this document, measured at laboratory conditions near ground level, have been referenced to an elevation of 10 m, wind biasing effects on any soil gas flux device depend on velocities near ground. Thus, model-predicted or weather-reported data needs to be extrapolated to the near ground flow field.

While considering biasing effects, one might define a tolerable level of error. For example, a 10% bias might be tolerable if soil gas fluxes are to be used as order of magnitude estimates for rates of contaminant natural source zone depletion. Figure 9 suggests that average wind velocities in excess of $v_{0.17m}$ = 1.7 m/s (3.8mi/h) might exceed such 10% bias level. In that case, the following steps can be taken to make a more detailed assessment of the bias and mitigate it if necessary (these are summarized in a flow chart shown in Figure 11):

1. Assess wind velocity at a field site for the time period the measurement of soil gas fluxes will take place. Two options are available:

   a. Weather station reported wind velocities. If these values happen to be reported at a different elevation than 10m, they can be corrected to that basis using one of the wind profile equations discussed in this document, using the relevant parameters consistent with terrain cover from literature.
   b. Actual measurements near ground (i.e., at an elevation of 0.17m, the elevation of the CO_2 trap rain cover). A hot wire anemomenter is particularly suitable, as its dimensions enable point measurements with minimal interference of the flow field. If one needs to reconcile these measurements with wind velocities from weather stations, the use of the Prandtl logarithmic profile equation with a proper choice for the roughness height z_0 is recommended. Use of the exponential equation is not recommended for this purpose. As input to the Prandtl logarithmic profile, field measured estimates of z_0 should be more reliable than those from literature (depending on terrain cover). As weather station data is often high frequency (i.e., multiple measurements per hour), reconciliation of weather reported wind velocities and measured values near ground level (both during the period of measurement of soil gas fluxes) might provide the benefit of improving estimates of the variability of wind velocity near ground.
2. Estimate the wind induced bias from laboratory data (i.e., Figure 10 or equivalent). As the velocity near ground is very different to that at an elevation of 10 m, selection of the relevant elevation basis for wind velocity is very important. Thus, make sure that the elevation above ground used as basis for wind velocity at field conditions is the same as that to the bias estimate.
3. If the data quality is acceptable for the monitoring objectives (i.e., the wind-induced bias is sufficiently low), no further action is needed.
4. If the bias results in unacceptable data quality, some mitigating alternatives exist. In all cases, verification of wind velocity values near ground might be required to confirm the effectiveness of the mitigating action(s).
   a. Consider modifying the design to achieve a lower profile (i.e., installation closer to ground surface or finish at grade).
   b. Deploy shallow ground cover (i.e., hay bales or similar) around the traps, which will result in a lower velocity profile near ground.
   c. Reconsider the period of deployment to avoid high wind conditions.

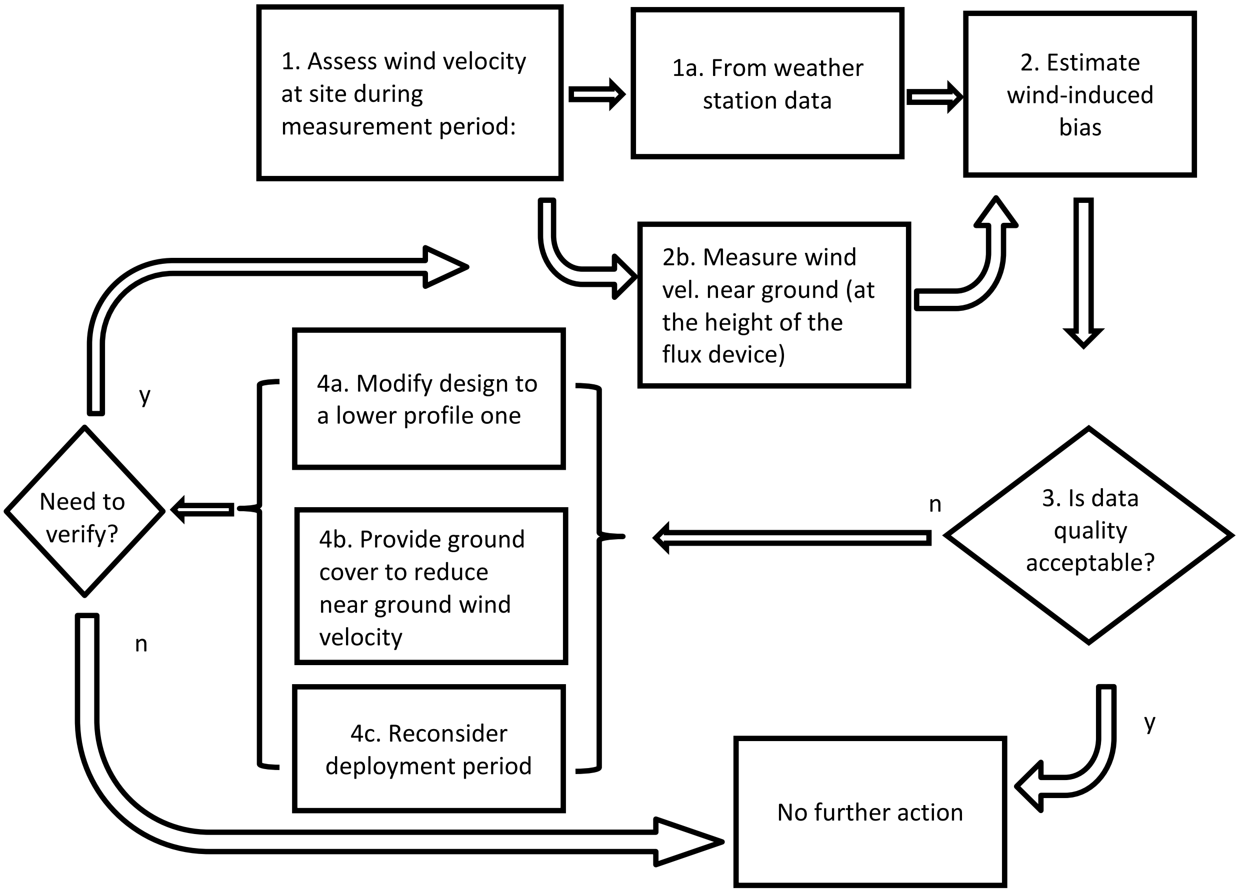

Figure 11. Recommendations flow chart to assess and mitigate wind-induced bias to soil gas flux measurements.

References

CityData, 2015. Top 101 cities with the highest average wind speeds (population 50,000+) http://www.city-data.com/top2/c467.html

Crowe, C. and J. A. Roberson. Engineering Fluid Mechanics. John Wiley & Sons, 1995.

Hau, Erich, and Horst von Renouard. The wind resource. Springer Berlin Heidelberg, 2006.

McCoy, K. J. Zimbron, T. Sale and M. Lyverse. 2014. Measurement of Natural Losses of LNAPL Using CO2 Traps. Groundwater.

McLennan, W. 2010. Wind Energy. The University of Edinburgh. https://willmclennan.files.wordpress.com/2010/04/wind-energy.pdf

MRC, 2015. Metereological Resource Center, Wind Speed Profiles, available at http://www.webmet.com/met_monitoring/625.HTML

Nelson, v. 2013. Wind Energy: Renewable Energy and the Environment, Second Edition. CRC Press. 311 pp.

NWFCG (National Wildfire Coordinating Group), 2014. Interagency Wildland Fire Weather Station Standards & Guidelines. Publication number: PMS 426-3. 50 pp. Available Online at: http://raws.fam.nwcg.gov/nfdrs/pms426-3.pdf

Oldenburg, C. M., and A. J.A. Unger. 2004. Coupled vadose zone and atmospheric surface-layer transport of carbon dioxide from geologic carbon sequestration sites. Vadose Zone Journal 3.3 (2004): 848-857.

Schram, T. 1998. Energy Production Potential of Wind Resources in Texas. http://www.crwr.utexas.edu/gis/gishydro99/class/schram/project.html

Tracy, M. 2015. Comparison of Methods for Analysis of LNAPL Natural Source Depletion Using Gas Fluxes. Colorado State University M.Sc. Thesis. 143 pp.

U.S. Census. 2010. Census Urban and Rural Classification and Urban Area Criteria https://www.census.gov/geo/reference/ua/urban-rural-2010.html

Zachariassen, Z., K.F., N. Nikolov, and T. McClelland. 2003. A review of the Forest Service Remote Automated Weather Station (RAWS) network. Gen. Tech. Rep. RMRS-GTR-119. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 153 p + CD.

Appendix 1. Simulated Wind Conditions on the Flux Calibration Column.

A set of experiments was designed to determine the wind velocity profile (wind as a function of elevation) at variable distance from the 50.8 cm, located on the floor (covered with carpet tile material) to identify field representative conditions. The fan was the same brand and model as in the CSU experiments (Tracy, 2015). Wind velocity profiles were measured with an ExTech hot wire anemometer. Figures A1.1 and A1.2 show these wind velocity profiles for the low and high box fan settings at various distances.

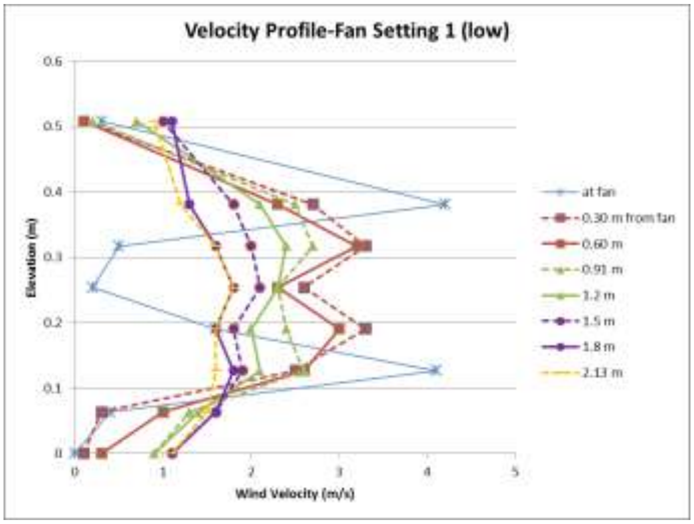

Figure A1.1. Wind velocity profile at different distances from the box fan at the lowest fan setting.

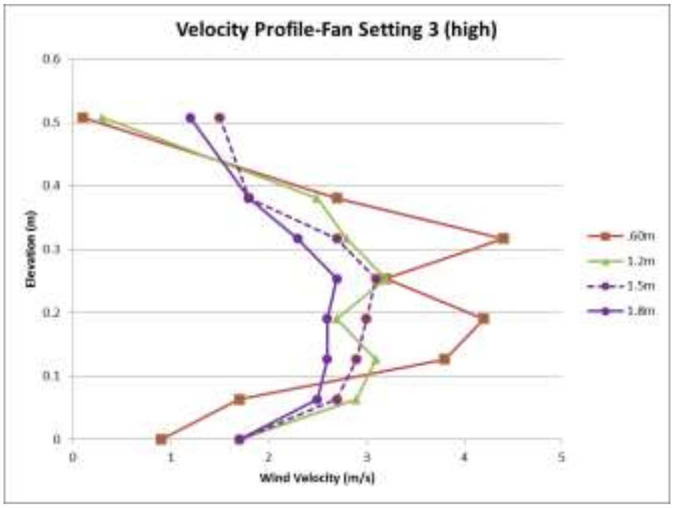

Figure A1.2. Wind velocity profile at different distances from the box fan at the highest fan setting.

Figures A1.1 and A1.2. show that a minimum distance of 1.5 m (5ft) to the box fan is required to avoid a local minimum (near the center of the interval) caused by the fan shaft. It is noted that for both fan settings the wind velocity near the ground is non-zero. In fact, the wind velocity near ground still increases as the distance away from the fan increases, indicating that the flow profile is not fully developed.

Although Figures A1.1 and A1.2 indicate that the wind velocity profile is improved at distances greater than 1.5m (5 ft) from the box fan, none of these settings achieved the target roughness height of 0.04 m. For this reason, 0.05 m (2 in) of sand were removed from the top of the flux calibration column. This 0.05 m (2 in) drop in the ground surface resulted in the desired effect, as shown in Figure 8 (main document body). Figure 9 shows the best fit data for a subset of the data (at elevations between 0.06 and 0.31 m, including the third generation trap design). Prandtl parameters forthe best fit shown in Table 2 of the main document.

Appendix 2. Comparison of CO_2 Flux Measurements from two Dynamic Flow Chambers (Li-Cor 8100A and Innova1312).

Appendix 2 describes the design of a custom-made dynamic chamber and a comparison with the LiCor 8100A chamber. The purpose of the custom made dynamic chamber is to measure additional gases not available from the LiCor 8100A (which measures only CO_2 based on an infrared gas analyzer, IRGA), enabling broader applications. The gases of interest are mainly N_2O and methane (CH_4), which in addition to CO_2, can be measured with a Photoacoustic Analyzer (Innova 1312). E-Flux has developed this capability as part of a tool box to estimate the soil gas flux of green-house gases (GHG) and also as a screening tool to survey CO_2 and CH_4 fluxes at contaminated field sites. Additionally, the gas meter is also setup to measure SF_6 as a tracer gas for research purposes. Although the LiCor 8100A unit includes proprietary features (i.e. the LiCor software and a patented vent design), the chamber method is non-proprietary (Hutchinson and Livingston, 2004).

A picture and diagram of the custom chamber are shown in Figure A2.1. Table A2.1 includes a comparison of features between the LiCOr 8100A unit and the custom designed chamber fitted with the photoacoustic sensor.

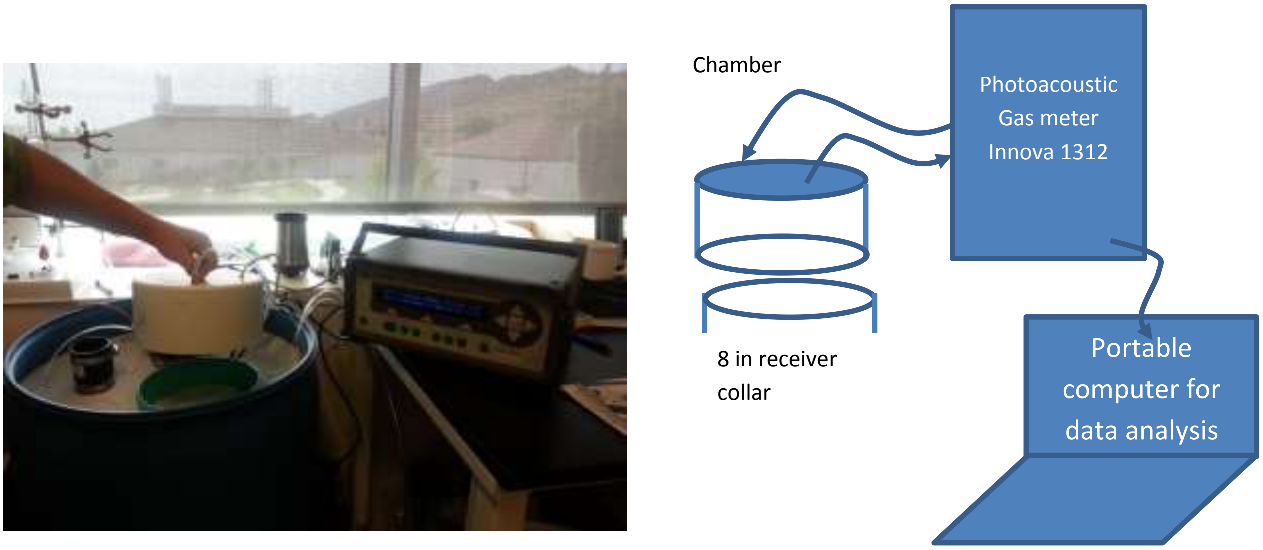

Figure 2.1. Picture and diagram of dynamic flux chamber (DFC) fitted with photoacoustic gas meter.

Table A2.1. Comparison of dynamic chamber designs (LiCor 8100 vs. custom chamber fitted with Photoacoustic Detector).

	LiCor 8100A	**Chamber with Photoacoustic Detector**
Receiver Collar diameter	8 in	8 in
Chamber Volume	Chamber volume: ~8.5L (for a receiver 5 cm (2 in) out of the ground)	Chamber volume: ~4.9 L (for a receiver 5 cm (2 in) out of the ground)
Chamber Design, Operation	Vented chamber, LiCor proprietary design (pneumatically operated)	Vented/unvented chamber, manually operated
Sensor	Infrared gas analyzer (IRGA) for CO_2	Photoacoustic Analyzer (can measure up to 5 gases simultaneously)
Monitoring time interval	Programmable time interval	Programmable time interval
Software	Li-Cor proprietary software uses the linear or exponential fit	Custom software based on the linear fit o non-linear fit (Livingston, et al, 2006)

Results

Figure A2.2 shows a comparison of paired measurements using both chambers. These include 22 laboratory measurements and also six field measurements. The range of measurements was between 2-11 µMoles/m^2.s. The algorithm used for both chambers was the linear fit in all cases (which proved adequate).

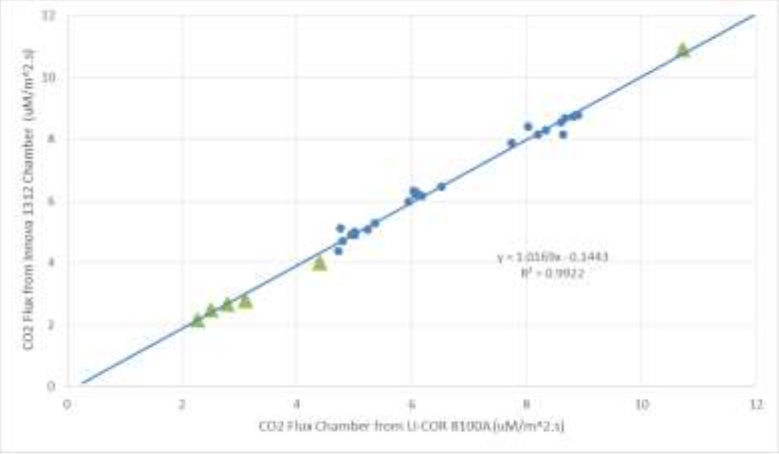

Figure A2.2 Comparison of paired measurements using LiCor 8100 DFC and custom made DFC fitted with Photoacoustic gas meter for greenhouse gas emissions (GHGE). Green triangles represent field measurements, blue circles measurements on a laboratory calibration column. Best fit line is for both types of measurement.

References

Hutchinson and Livingston, 2004. J. Dane and C. Topp (eds.) Soil Atmosphere Gas Exchange. Methods of Soil Analysis, Part 4. National Soil Science of America Book Series. pp. 1159-1182.

Livingston, G. P., G. L. Hutchinson, and K. Spartalian. 2006. Trace gas emission in chambers. Soil Science Society of America Journal 70.5: 1459-1469.