



Influence of high-frequency ambient pressure pumping on carbon dioxide efflux from soil

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Received 21 September 2003; received in revised form 29 January 2004; accepted 29 January 2004

Abstract

We report measurements at 2 Hz of pressure fluctuations at and beneath the soil in an agricultural field with dry soil and no vegetation. The objective of our study was to examine the possible role of pressure fluctuations produced by fluctuations in ambient wind on the efflux of CO₂ at the soil surface. We observed that pressure fluctuations penetrate to 50 cm in the soil with little attenuation, thereby providing a mechanism for bulk transport of trace gases throughout the porous medium. Concurrent measurements of CO₂ fluxes from the soil surface produced systematically larger values for larger values of root-mean-square pressure, pumping rate, and mean wind speed. Soil CO₂ fluxes measured under conditions conducive to pressure pumping exceeded the diffusional fluxes, estimated from use of Fick's Law and concurrent vertical profiles of soil CO₂, by a factor of 5–10. Extrapolation of measured fluxes to conditions uninfluenced by pressure pumping revealed that other mechanisms, such as thermal expansion of soil air caused by soil heating or flushing by evaporating water deep in the soil, may be contributing up to 60% to measured fluxes. Ambient meteorological conditions leading to flux enhancement may change on scales of hours to months, so these results underscore the need to report concurrent meteorological conditions when surface CO₂ efflux measurements are made. They further suggest that fluctuations in the static pressure fields introduced by wind interactions with terrain and vegetation may lead to pressure pumping at the surface and hence large spatial inhomogeneities in soil fluxes of trace gases. Although our measurements were made at an agricultural field site and focused on CO₂ efflux, the pressure pumping mechanism will be active on other sites, including forest environments, snow-covered surfaces, and fractured rocky surfaces. Furthermore, the physical processes examined apply to movement of other trace gases such as oxygen, water vapor, and methane.

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Keywords: Soil ventilation; Soil gas transport; Soil CO₂ flux

1. Introduction

Anthropogenic increases in atmospheric carbon dioxide over the past 30 years have brought new urgency to the need for better understanding of

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components of the natural carbon cycle. Soil respiration is second only to photosynthesis as the largest flux in agricultural and forest ecosystems (Goulden et al., 1996; Davidson et al., 2002). Accurate characterization of soil respiration, even for horizontally homogeneous soil, can be a challenge because of meteorological processes that vary on time scales from inter-annual to less than one hour. Here, we examine one of the many processes (Takle, 2003) influencing efflux of soil carbon dioxide on time scales less than 1 h, namely pressure pumping arising from variations in static pressure. In their recent review of biases and uncertainties in measurements of soil CO₂ flux, Davidson et al. (2002) quantify residual uncertainties after implementing best practices, but conclude that chamber measurements made under gusty wind conditions “merit more systematic study”. We herein show that variations in wind conditions at frequencies of 2 Hz can lead to pressure fluctuations that penetrate deep into the soil. Concurrent measurements of soil CO₂ flux suggest that these fluxes increase with increasing magnitudes of pressure fluctuations and therefore could potentially create uncertainties larger than those arising from factors quantified by Davidson et al. (2002).

Most naturally vegetated landscapes are covered by plants having a variety of heights. Agricultural landscapes, except those in regions of large-scale mechanized farming, also have fields bordered by trees or shrubs that create disturbances in the wind field. Such porous barriers create elevated sources of drag on the flow which, in turn, create pressure-field disturbances around obstacles resulting in perturbations to the flow field. These pressure disturbances are represented by a magnitude that is proportional to the square of the wind speed and a spatial distribution that has localized maxima on the upwind side of the obstacles and minima in the lee (Schmidt et al., 1995; Wilson, 1997). A summary of past reports of measurements of mean pressure around artificial windbreaks and a new set of detailed measurements are given by Wilson (1997). Schmidt et al. (1995) and Nieveen et al. (2001) present measurements of static pressure in the vicinity of vegetative barriers. Model studies of thin barriers (Wilson, 1985; Wilson and Mooney, 1997; Takle and Wang, 1997) and vegetative barriers (Wang and Takle 1995a,b, 1996, 1997) and Wang et al. (2001) give simulated horizontal and vertical profiles of static

pressure fields for a variety of barrier shapes, porosities, and horizontal structures. These reports describe the importance of static pressure gradients to the wind speed fields in and around a barrier. An area needing more research, according to Davidson et al. (2002), is the influence of pressure differentials set up under windy conditions.

Both measurements and modeling studies clearly show that static pressure fields at the earth's surface can have high spatial variability. It follows that because these perturbation-pressure fields are established by near-surface wind flow, fluctuations in atmospheric boundary-layer wind speed and direction will lead to ambient fluctuations in the perturbation pressure fields at the soil surface. And locations and magnitudes of pressure maxima and minima created by obstacles will change as either wind speed or wind direction fluctuates. In 1999, the Great Plains Regional Office of the National Institute for Global Environmental Change (NIGEC) funded a pilot project to seek answers to the following question: Do high-frequency (up to 2 Hz) fluctuations of ambient pressure have a significant impact on movement of gases in the soil, in general, and of the surface efflux of CO₂ in particular?

In this paper, we discuss the role of these wind-induced perturbations to the static pressure field on air movement in soil. We report results of a pilot experiment we conducted to explore the effect of pressure perturbations introduced by a simple landscape feature—a porous fence. A brief description of the various mechanisms for gas movement in soils and an expanded theoretical development of three-dimensional flow in soil are given in Section 2. We describe our field sites and measurement procedures in Section 3 and experimental results in Section 4. Conclusions and recommendations for further research are given in Section 5.

2. Influence of pressure fluctuations

Buckingham (1904) suggested ambient pressure pumping as a possible means of gas transport in soils, but little attention has been given to this topic until studies of influences of low-frequency (diurnal and semi-diurnal barometric waves) were reported by Clements and Wilkening (1974) and Duwe (1976) and effects of synoptic weather systems were re-

ported by Massmann and Farrier (1992), Shurpali et al. (1993), Auer et al. (1996), and Elberling et al. (1998). The possibility of pumping caused by higher-frequency processes, such as wind-speed variation and turbulence, was addressed by Farrell et al. (1966), Kimball and Lemon (1972), Kimball (1973), and Baldocchi and Meyers (1991). Topographically induced quasi-static pressure fields were identified by Massman et al. (1997) as a means of gas movement in soils. In a review of greenhouse gas exchange between soil and atmosphere, Smith et al. (2003) discuss past and recent literature on the effects of temperature, soil water content and aeration on biological processes but do not address the physical processes governing air movement in soils. Subke et al. (2003) used an open dynamic chamber to measure soil CO₂ efflux and discuss the role of pressure pumping caused by fluctuations in wind speed. Their focus is on modeling the long-term soil CO₂ efflux, however, so they assert it is not necessary to include the effects of pressure fluctuations, which affect transport but not production of CO₂.

In their studies of N₂O fluxes, Maljanen et al. (2003) concluded that, over a period of a year, fluxes calculated from the concentration gradient in the soil by use of Fick's law agreed with chamber measurements of surface fluxes. However, measurements on individual days used to create the annual mean showed differences of a factor of 10 or more between the two methods, with diffusive fluxes as likely to be larger as smaller than the chamber flux. The authors noted that day-to-day variations in weather and their mid-day sampling protocol could have contributed to uncertainty between the methods. Subke et al. (2003) used an open dynamic chamber to measure soil CO₂ efflux and discuss the role of pressure pumping caused by fluctuations in wind speed. Their focus is on modeling the long-term soil CO₂ efflux, however, so they assert it is not necessary to include the effects of pressure fluctuations, which affect transport but not production of CO₂.

Recent interest in measuring CO₂ efflux from soils has brought attention to the influence of pressure anomalies—both ambient and introduced—in the vicinity of surface-based measurement devices such as chambers. A primary concern centers on the possibility that pressure gradients introduced in the measurement process might be contaminating estimates

of the natural CO₂ flux from the surface. Kanemasu et al. (1974) addressed this issue over 25 years ago. Lund et al. (1999) describe different types of dynamic chamber measurements of CO₂ soil efflux and the attempts to minimize the impact of introduced differential pressures. Even closed chambers with firm soil contact may introduce pressure differences between inside and outside the chamber, which will influence gas movement in the soil near and under the chamber. Baldocchi and Meyers (1991) emphasize the need for minimizing pressure effects around chambers and addressing large spatial variabilities in surface fluxes. Fang and Moncrieff (1996) report that eliminating pressure differences around dynamic chambers is extremely difficult. They offer a design for a chamber that minimizes the inside/outside pressure difference.

A second issue relating to environmental conditions in the vicinity of surface-based measurement devices is the role of ambient pressure perturbations—both inhomogeneities in natural pressure fields and modifications of ambient fields resulting from the presence of the measurement system. Owensby et al. (1997) acknowledge influences of the physical structure of an open-top chamber used for CO₂ flux measurements and suggest that a use of a barrier in the soil and matching chamber pressure with atmospheric pressure are important measurement practices. Lund et al. (1999) assume that their soil respiration cylinder at the surface did not introduce additional pressure artifacts; i.e., they assumed ambient pressure fluctuations introduced by the presence of the cylinder were negligible. Most studies have focused on stationary pressure differences or pressure differences with time variations on the order of minutes or more and do not address high-frequency fluctuations that can produce a net flux of trace gas across the soil surface under vertically oscillating flow having zero mean velocity. In their evaluation of effects of pressure differential (pressure measured with a micromanometer), Fang and Moncrieff (1996) do not address the role of high-frequency pressure fluctuations, either ambient or introduced, caused by the presence of the chamber as an obstacle to the ambient flow.

Takle et al. (2003) distinguish between barrier-induced pressure fluctuations and pressure fluctuations arising in isotropic turbulent flow and assert that the former are a larger contributor to high-frequency soil-surface pressure fluctuations driving gas movement

in soils. They report high-frequency pressure gradient measurements inside, outside at the surface, and in the soil below a CO₂ measurement chamber and that the chamber, with physical dimensions of several centimeter, had no effect on the pressure field in its near vicinity that could be detected above the level of natural pressure fluctuation in the vicinity.

Static air pressure at a point (in either the atmosphere or soil above the saturated zone) is the horizontally averaged accumulated weight per unit area of atmospheric (gaseous) mass and the mass of any solid or liquid suspended by the atmosphere (birds, airplanes, liquid or solid H₂O, particulate matter, etc.) above that point. And changes in static pressure are caused by changes in the accumulated mass above the point. A point in the soil (we exclude soil locations not having a gaseous connection to the free atmosphere) therefore may experience pressure changes caused by variations in mass accumulation in the atmosphere above the point or resulting from phase changes of liquids or solids to vapors in the soil or on its surface.

For this discussion of flow mechanisms, we consider the “surface” to be the level of the atmosphere/soil interface where the mean wind speed is reduced to some arbitrary level (say 0.01 m s^{-1}) well below typical cup anemometer measurements (see Fig. 1). At and below this level, drag forces imposed on lateral flow resulting from horizontal pressure gradients would constrain the magnitude of any persistent flow. Below this level there likely will be a thin region where turbulent motions are more important mixing processes

than diffusion. And at some lower level and below (in the absence of pressure fluctuations) diffusion dominates.

To visualize the pressure changes for our measurement site we consider a 1 m high fence located in a homogeneous flat field $200 \text{ m} \times 200 \text{ m}$ with no vegetation. For this scenario, we divide the pressure changes into those generated locally and those of non-local origin. Non-local pressure influences include synoptic and mesoscale pressure patterns, pressure changes induced by diurnal heating, those established by horizontal thermal gradients (e.g., sea breezes), and orographically induced pressure variations of horizontal scale $\sim 500 \text{ m}$ (time scales $\sim 500 \text{ m}/5 \text{ m s}^{-1} \simeq 100 \text{ s}$) and vertical scale $\sim 50 \text{ m}$ or larger. We consider these to be low-frequency pressure changes.

The only non-local high-frequency pressure changes are those caused by shear or buoyant generation of turbulence kinetic energy above the surface layer and (if this is not included in the previous category) advection of hydrostatic inhomogeneities (Bedard et al., 1992).

Locally generated pressure influences include a standing wave of wavelength comparable to about 10 times the height of the barrier (Takle and Wang, 1997) created by steady (speed and direction) mean wind interacting with the fence. Evaporation of soil water leads to volume expansion, which, if the barrier shades nearby soil and suppresses localized evaporation, could create modifications to the pressure standing wave. We consider these to be low-frequency, locally generated pressure influences.

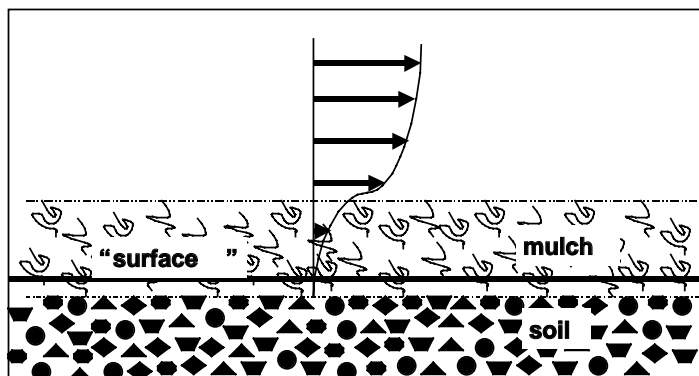


Fig. 1. Stylized depiction of how mean horizontal wind speed above the surface is diminished within a mulch or vegetation layer near the soil surface.

Fluctuations in speed or angle of attack of the mean wind will introduce fluctuations on the pressure standing wave. In addition, the obstacle generates a “plume” of turbulence whose lower frequency components persist ~ 10 barrier heights downwind in what we (ideally) consider to be a stationary turbulence pattern. Finally, the barrier may generate transient structures (vortex shedding) that induce pressure fluctuations at the surface.

All of these local influences except the modified standing wave contribute to high-frequency turbulent fluctuations at the soil surface. Therefore, high-frequency pressure fluctuations behind the fence are created primarily locally by mean flow interacting with the obstacle, with some high-frequency contributions possibly being advected over the site from non-local sources.

The movement of air in soil as a result of static horizontal pressure gradients can be visualized with the help of Fig. 2 (adapted and enhanced from Neeper, 1991). This type of flow is generated if points A and B, for illustrative purposes, are on opposite sides of an obstacle (e.g., tree, fence, rock outcropping, topo-

graphic feature) that creates a static pressure difference resulting from a uniform (non-turbulent) wind blowing from left to right (see Wang and Takle, 1995a, Fig. 5). Point A will experience high pressure and B low pressure that will move gas unidirectionally from A to B through channel C because of the pressure difference between y and y' . Passage E will experience only weak or zero flow. This process leads to horizontal as well as vertical motion in soils. Waddington et al. (1996) refer to this flow applied to gas movement in snow as topographic pumping under steady flow and point out that three-dimensional modeling is essential to capture the transport characteristics. Robinson et al. (1997) assert this mechanism is responsible for radon entry into homes. Points A and B actually need not be on opposite sides of the obstacle but simply different distances from it in order to experience a persistent horizontal pressure gradient through channel C.

Fluctuations in static atmospheric pressure could cause flow through E to be oscillatory with zero mean. The venting of trace gases from cavity D contribute to surface fluxes under this regime because of the unidirectional flow between A and C. If the obstacle is

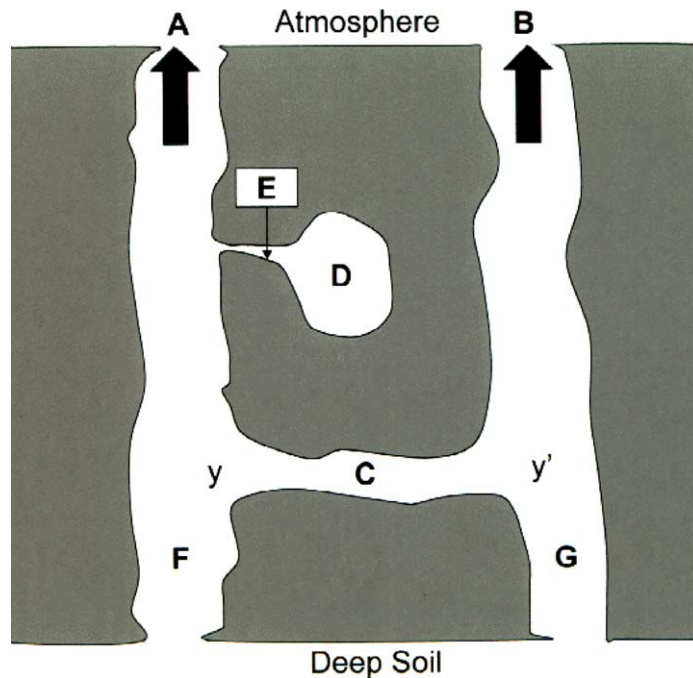


Fig. 2. Stylized view of how surface effluxes (A and B) of trace gases are influenced by gas movement through soil reservoirs (D) and pathways (A, B, C, E, F, and G) and by pressure gradients (between y and y').

not between A and B, the pressure gradient across C would still lead to unidirectional flow. Neeper (1991) discusses historical studies of periodic flows of this type in soil and the practical use of oscillatory pumping on remediation of contaminated soils. More discussion of other mechanisms causing air movement in soils is given in Takle (2003).

3. Measurement site, instruments, and procedure

3.1. Site

The field measurement program was conducted at the University of Nebraska Agricultural Research and Development Center near Mead, NE during 13–17 September 1999. Instruments were sited in a field 185 m N–S by 147 m E–W that is relatively flat but with a slight slope down to the east (see Fig. 3). South of the field is a shallow ditch, and a slightly elevated roadway is located beyond the ditch. Mature but photosynthetically active soybeans were located in an adjacent field to the north of the study site.

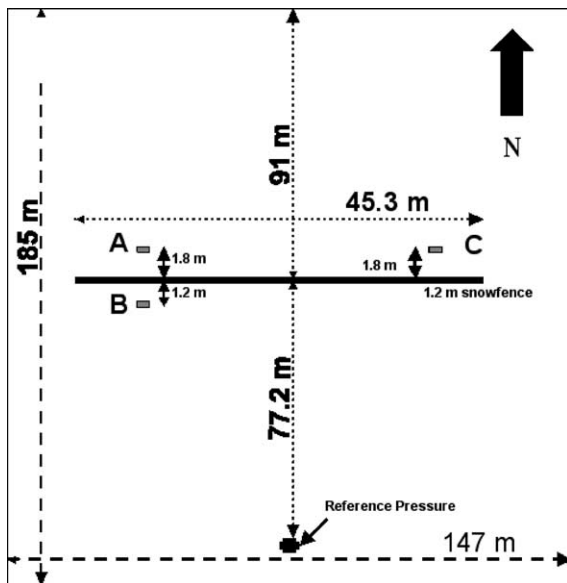


Fig. 3. Sketch of field and measurement sites with respect to the flow barrier (fence). Points A, B, and C indicate locations of measurements in relation to the fence and upwind reference pressure port.

Measurements were made in the vicinity of a 1.2 m vertical-slat snow fence having porosity of 62%. The height of the barrier, $h = 1.2$ m, is a useful length scale for expressing horizontal distances. The fence was 45.3 m long and was oriented E–W in a field in which wheat was grown in the 1999 crop season. The west end of the fence was located 70 m from the west end of the field. The soil was tilled about 1 month before the field program, so that only small amounts of live or dead plant material remained on the surface at the time of measurements. The soil is a Tomek Silty Clay Loam (Fine, smectitic, mesic Pachic Argiudoll). At the surface, the soil was dry and had been compacted with a water-filled roller prior to installation of the fence.

3.2. Pressure sensors and ports

Differential pressure was measured by use of differential pressure sensors (model 264, Setra Systems, Inc., Boxborough, MA) as described by Schmidt et al. (1995). A network consisting of 24 pressure ports distributed at various distances from the fence for various experiments was linked to the reference pressure port by a garden hose with open end at the soil surface 77.2 m south of the fence. The hose terminated in a manifold at the fence that offered reference pressure for the “reference” side of each differential pressure sensor. The “measurement” side of each transducer was connected to 6.35 mm (1/4 in.) diameter tubing of approximately 1 m length to the open port at the test location. We removed the filters from the differential pressure sensors to increase their high-frequency response. Laboratory calibration revealed that the sensors recovered to 90% value of a step function in about 0.5 s, giving a response frequency of 5 Hz.

Colbeck (1989) addressed the issue of soil pressure variations caused by turbulence. He analyzed data from Elliott (1972) to obtain a relationship between pressure fluctuations and turbulence (as approximated by use of mean wind speed) by the following:

$$p' = 0.0327 e^{0.383 U} \quad (1)$$

where p' is the magnitude of the pressure fluctuations (Pa) and U is the mean wind speed (in m s^{-1}) at 5 m above the ground. He estimated that a 10 m s^{-1} wind will displace an individual air parcel by this pumping action by only about $14 \mu\text{m}$ at the surface of a 1 m deep

accumulation of snow. [Bedard et al. \(1992\)](#) reported observations of both mean wind and turbulent pressure and offered empirical relationships,

$$p' = A U^B \quad (2)$$

for linking them, with A and B being constants depending on whether hydrostatic or dynamic effects are dominant or if an intermediate situation exists. The [Colbeck and Bedard et al.](#) formulas presumably describe turbulent pressure fluctuations in the homogeneous boundary layer, so according to the discussion of [Section 2](#), these formulas describe the pressure contribution from high-frequency, non-local turbulence. Since 2-m wind speeds during our experiment were less than 5 m s^{-1} , contributions to fluctuations in differential pressure caused by turbulence given by (1) are less than 0.24 Pa. This is in contrast to peak-to-valley variations on the order of 5 Pa that we observed ([Takle et al., 2003](#)).

The reference port for our pressure measurements, although located 77.2 m upwind of the fence and not influenced by dynamical pressure created by the fence, is influenced by boundary-layer turbulent fluctuations of the type described by [Bedard et al. \(1992\)](#). Our pressure measurements from this and previous experiments ([Schmidt et al., 1995](#)) showed that standard deviations of pressure scale roughly with mean standing wave pressure at locations near the fence, with larger pressure fluctuations near the fence. For the 10 experiments we report herein, we observed a mean wind speed (corrected to a height of 1 m) of 2.9 m s^{-1} with corresponding mean values of [Bedard et al.'s \(1992\)](#) dynamic, hydrostatic, and intermediate pressure fluctuations of 0.048, 0.120, and 0.339 Pa, respectively. The root-mean-square (rms) pressure measured in the vicinity of the fence (excluding the artificial pumping experiments) during this time was 1.27 Pa, or 3.76 times larger than the largest of the [Bedard et al. \(1992\)](#) formula estimates. We therefore expect that pressure fluctuations at the reference port contribute to pressure differences at the measurement port, but with magnitude lower by about a factor of 3–4 from those induced by the fence.

The 24 differential pressure sensors were deployed in two separate networks by two different research groups within our measurement team using separate dataloggers, and hence separate timing systems, but sharing the same reference pressure. Comparison of

the data from the two networks with the measurement ports co-located at upwind (for prevailing south winds) locations of 16, 8, 4, 2, 1, 0 h, and corresponding locations downwind of the fence showed that the two independent networks gave identical results to within a fraction of a second error in synchronization.

3.3. CO_2 measurements

Measurements of CO_2 were made with a CO_2 flux chamber (LI-6400, LI-COR, Inc., Lincoln, NE) mounted on 5-cm high cylinder that was pressed 2.5 cm into the soil. [Norman et al. \(1997\)](#) provide detailed information on procedures needed to minimize errors with such measurements.

Soil CO_2 was measured by use of tubes (wells) installed at three locations (locations B, C, and at the reference pressure site) with ports in the soil at depths of 10, 25, and 50 cm. Tubes from these ports to the surface enabled air to be withdrawn from these levels and stored for later analysis in the laboratory. A 10-ml syringe with a 20-gauge needle was used to withdraw a 5-ml sample from each depth. This sample was transferred into a 5-ml glass bottle capped with a Teflon septa, which had been purged with He and evacuated. Ambient air samples were taken at the same time to compare to flux chamber measurements and to test for possible leaks. No significant leakage was detected in any of the test bottles. The bottles were stored in a cooler ($\sim 5^\circ\text{C}$) and brought to the lab for analysis. Analysis was conducted within 96 h of obtaining the samples. CO_2 concentration was determined on a gas chromatograph (Model 8a, Shimadzu, Milton Keynes, UK) equipped with a TCD detector. Samples were extracted at different times of day on 3 days before and during the experiment.

3.4. Procedure

We located the ports of the four differential pressure sensors in a vertical profile at location A in [Fig. 3](#), which was downwind of the fence for the data reported herein. Two separate configurations of pressure ports were used. In the first, two ports were placed on the surface, one inside the CO_2 flux chamber and the other about 30 cm from the chamber. Beneath this exposed port two additional ports were installed at 10 and 15 cm depths. In a second configuration, sensors

were located at depths of 0 (surface), 15, 45, and 60 cm from the soil surface under the CO₂ flux chamber. The tube leading to the surface pressure port was buried under the cylinder so that its open end exited the soil inside the CO₂ flux chamber. Each experiment in the series consisted of samples taken at 0.5 s intervals for approximately 120 s, giving approximately 240 total samples for each of the four sensors.

Characteristics of natural pressure variations were further clarified by comparison with artificially inducing surface pressure fluctuations over a vertical array of sensors. These artificial fluctuations were created by use of an inverted cylindrical galvanized stock water tank of diameter 91.5 cm and height 60 cm placed over the chamber and array of vertical sensors. The tank was seated firmly in the dry soil to prevent large volumes of air from escaping around the perimeter. Despite some care in positioning the tank, manual pumping on the tank bottom produced a small amount of dust movement at the interface resulting from dry soil conditions at the time of the measurements. Artificial pressure fluctuations were induced into the soil by firm periodic pressure/release of the bottom of the tank, which caused abrupt downward/upward displacement of about 3 cm of the drum-like surface.

4. Results

4.1. Pressure fluctuations

Measurements were taken on 16 and 17 September 1999 under clear skies and temperatures ranging from 20 to 25 °C during the measurement period. Measurements of vertical profiles of air pressure in the soil (17 September) were made under ambient winds of 4.1 m s⁻¹ or less (at a height of 3 m), generally from the south.

The fence we deployed created a standing pressure wave as described in Section 2 as shown in Fig. 5 of Wang and Takle (1995a). Our experiments in this report were located in the low pressure region of the lee at a distance of 1–2 h. Fluctuations in wind speed will lead to fluctuations in pressure at this location of magnitude proportional to the square of the wind speed. By locating the experiment at this distance in the lee, we reduce variations caused by fluctuations in wind direction (Wang and Takle, 1996).

In a previous report (Takle et al., 2003) we showed very high correlation of pressure fluctuations among the four sensors placed at various depths below the surface. We also showed that pressure fluctuations arising from dynamic pressure variations induced by the fence were not attenuated nearly as much as those arising from the artificial pumping procedure described in Section 3. An example of the pressure fluctuations at various depths is given in Fig. 4, where P_2 is the pressure difference between the surface pressure above the vertical soil profile (at location A in Fig. 3) and the reference pressure (location also identified in Fig. 3), and P_1 , P_3 , and P_4 are pressure differences (at location A) from the reference pressure at depths of 15, 45, and 60 cm, respectively. Visual inspection of Fig. 4 reveals that the pressure fluctuations in the absence of artificial pumping (first 20 s) are essentially unattenuated with depth for the first 60 cm, but that for the artificially pumped part of the time series attenuation increases with depth.

A comparison of standard deviation of pressure fluctuations as a function of depth for the naturally pumped and artificial pumped portions of the record of Fig. 4 is given in Table 1. This shows the strong attenuation with depth for the artificially induced fluctuations.

4.2. Spectral analyses

Spectral analyses were carried out for several 2-min observing periods on 17 September. In the first set of experiments four pressure ports were distributed with two at adjacent positions on the surface (one inside the CO₂ flux chamber and one uncovered nearby) and two beneath the surface at depths of 10 and 15 cm. Two replications of this experiment revealed that the

Table 1
Standard deviation of pressure fluctuations for natural and artificial pumping at various depths

Depth (cm)	Standard deviation of pressure fluctuations (Pa)	
	Natural	Artificial
0 (sfc)	0.76	6.27
15	0.76	5.41
45	0.89	2.91
60	0.90	3.05

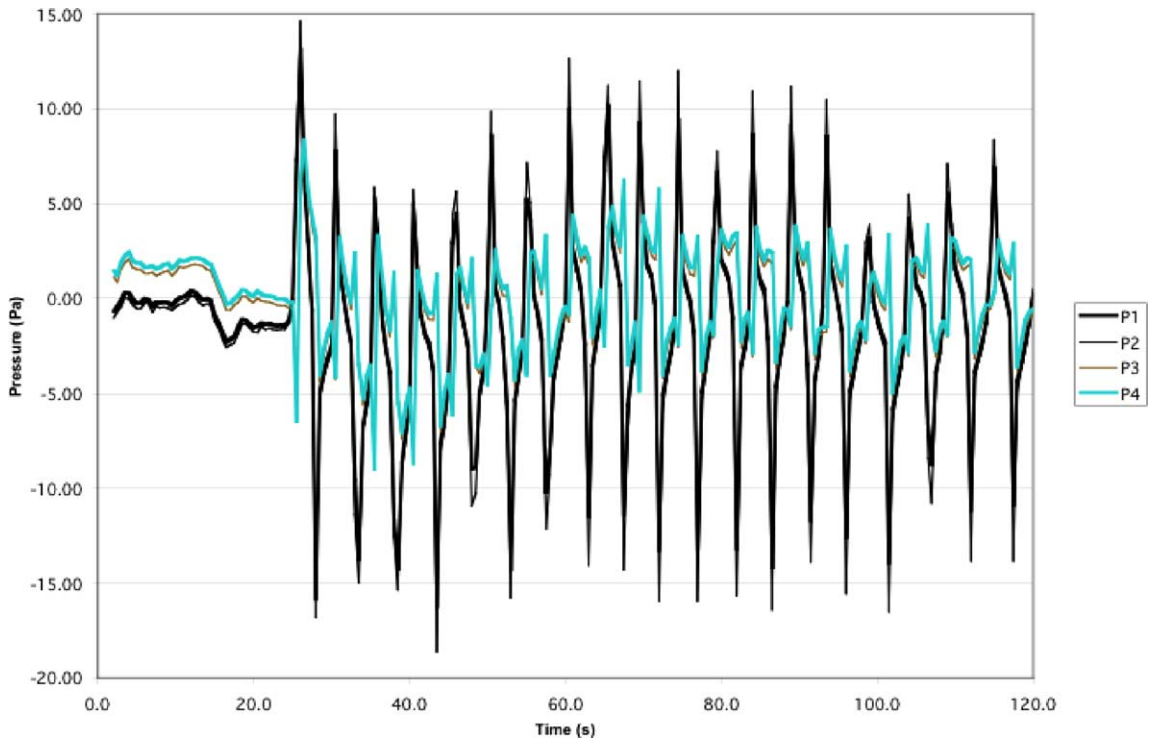


Fig. 4. Time series of pressure fluctuations under natural pumping (between time = 0 and 25 s) followed by artificial pumping (after time = 25 s). Traces in indicate pressure differences between the reference location and surface (P_2) and between reference location and soil depths of 15 cm (P_1), 45 cm (P_3), and 60 cm (P_4).

contributions to total variance from different frequencies were almost identical for the chamber port and the two buried ports, with the exposed port having slightly different total rms variance (slightly higher, 0.23 Pa versus 0.22 Pa, in one and lower, 0.20 versus 0.21, in the other) and slightly different spectral contributions to the total variance. For all ports in the first replication, the dominant five frequencies contributed approximately 75% to the total variance, with the three dominant frequencies (non-integer frequencies of 2.0, 1.0, and 4.4) contributing about 64% and retaining the same relative ranking for each port. Wind speed at the time of these measurements was approximately 2.1 m s^{-1} . In the second replication, under similar ambient wind (1.9 m s^{-1}) the ordering of dominant frequencies was uniform (but slightly different from the first replication) for all ports except the exposed surface port which had slightly higher contribution from lower frequencies. The presence of a lower frequency

in the output suggests a non-linear response of the system.

Similar results were obtained from an experiment with ports located at depths of 0 (surface), 15, 45, and 60 cm from the soil surface under the CO_2 flux chamber. The rms variances from the surface down were 0.96, 0.97, 0.92, and 0.93 Pa, respectively, with the spectral contributions from the first six frequencies contributing 92% of the total variance. Ordering of the first three frequencies (1, 5.4, and 7.9) was the same for the surface (under the CO_2 flux chamber) and at 60 cm depth, and these accounted for 75% of the variance. When the experimental region was artificially pumped as previously described, the results were markedly different. The rms variances from the surface down were 9.22, 8.28, 4.60, and 4.76 Pa, respectively. Non-integer frequencies of 24.0 and 24.2 (in that order) were dominant at all depths and accounted for 40, 40, 29, and 28% of the variance

with increasing depth. Two replications gave analogous rms profiles of 6.64, 4.87, 2.68, and 2.80 Pa and 7.52, 6.63, 3.79, and 3.89 Pa. These show a pattern of 10–20% reduction in variance in the first 15 cm and about 50–60% reduction at 45 cm with possible increase in variance in the next 15 cm. From this we conclude that natural fluctuations produce one-dimensional waves that propagate deep (beyond 60 cm) into the soil with relatively little attenuation or frequency change, but that a disturbance administered at a “point” produces a three-dimensional wave that attenuates with depth. The shift to higher frequencies in the artificially pumped case suggests the presence of non-linearities. Differences in soil moisture and soil density beyond 15 cm evidently have a significant impact on three-dimensional wave propagation, perhaps through wave reflection or other distortions caused by inhomogeneous conditions in the vertical direction. In retrospect, we also should have directly measured differential pressure fluctuations from different levels without referencing to the site upwind of the fence in order to eliminate contributions to the pressure fluctuations from background turbulence at the reference site.

4.3. CO₂ flux analysis

We fit a quadratic function to measured soil concentrations of CO₂ at 10 and 25 cm and ambient atmospheric concentrations to estimate the concentration gradient at the surface. Fluxes were then calculated by use of

$$F = \eta \tau C_0 D d\chi/dz, \quad (3)$$

where F is flux in kg CO₂ m⁻² s⁻¹, η the porosity (0.50), τ the tortuosity (0.66), C_0 the air density at standard temperature and pressure (1.2923 kg m⁻³), D the binary diffusion coefficient for CO₂ in air (0.138×10^{-4} m² s⁻¹), and $d\chi/dz$ is the vertical gradient of CO₂ concentration at the soil surface as estimated from the vertical profile of CO₂ concentration measurements in the soil (in (kg CO₂)(kg Air)⁻¹ m⁻¹). Tortuosity has been empirically determined for most soils to be between 0.01 and 0.66 (Bear, 1979). Holford et al. (1993) used a value of 0.26 for modeling diffusion of radon, but for an estimate of maximum diffusion we have used a value of 0.66. For the seven measurement times (i.e., those with no artificial pumping), the sites near the fence had diffusional mean (standard devi-

ation) fluxes of 0.0215 (± 0.0094) mg CO₂ m⁻² s⁻¹, and for the upwind site 0.0404 (± 0.0100) mg CO₂ m⁻² s⁻¹. If a mid-range value of tortuosity had been used in the calculations, the estimated flux would be about half the stated values.

Measurements with the CO₂ flux chamber for 10 2-min periods on September 16 and 17 produced mean (standard deviation) fluxes of 0.768 (± 0.190) ppm V s⁻¹, which (by use of chamber dimensions) translates into 0.225 (± 0.056) mg CO₂ m⁻² s⁻¹. These are about 5–10 times larger than the soil flux estimates made by the gradient diffusion method.

To further explore possible influence of pumping action on fluxes we calculated CO₂ flux dependence on rms pressure averaged over the measurement period. The dependence (Fig. 5a) was weak with large uncertainty ($R^2 = 0.42$) but gave flux increasing with rms pressure at a rate of 0.08 (mg CO₂ m⁻² s⁻¹) (Pa)⁻¹. Baldocchi and Meyers (1991) first reported such measurement taken at the floor of a forest canopy where the flux increased with standard deviation of pressure at a rate of 0.044 (mg CO₂ m⁻² s⁻¹) (Pa)⁻¹. We also evaluated the dependence of flux on the rate of pressure changes (Fig. 5b), for which we define a pumping rate as $|dp/dt|$. Results from the 10 experiments, shown in Fig. 5b, give a dependence of 0.18 (mg CO₂ m⁻² s⁻¹) (Pa s⁻¹)⁻¹ with $R^2 = 0.43$. To explore the relation of CO₂ flux to pressure fluctuations (as indicated by mean wind speed), we plotted flux as a function of mean wind speed over the measurement periods. The wind value for each measurement period was the mean of 2-min-mean wind speeds taken at four towers within 30 m of the flux measurements. Flux increases at increasing wind speed at a rate of 0.028 (mg CO₂ m⁻² s⁻¹) (m s⁻¹)⁻¹, but with substantial scatter ($R^2 = 0.14$) from the trend line (Fig. 5c).

If each of these relationships were linear (arguable assumption), then extrapolation to the ordinate intercept would give an estimate of the flux uninfluenced by pressure fluctuations. Elimination of pressure pumping as a physical process driving the flux leaves other possible causative factors including thermal expansion of soil air due to soil heating, flushing by evaporating water deep in the soil, or molecular diffusion. Intercept values for these three plots give fluxes of 0.15, 0.15, and 0.13 mg CO₂ m⁻² s⁻¹, which is about 60% of the mean measured flux. These values exceed our

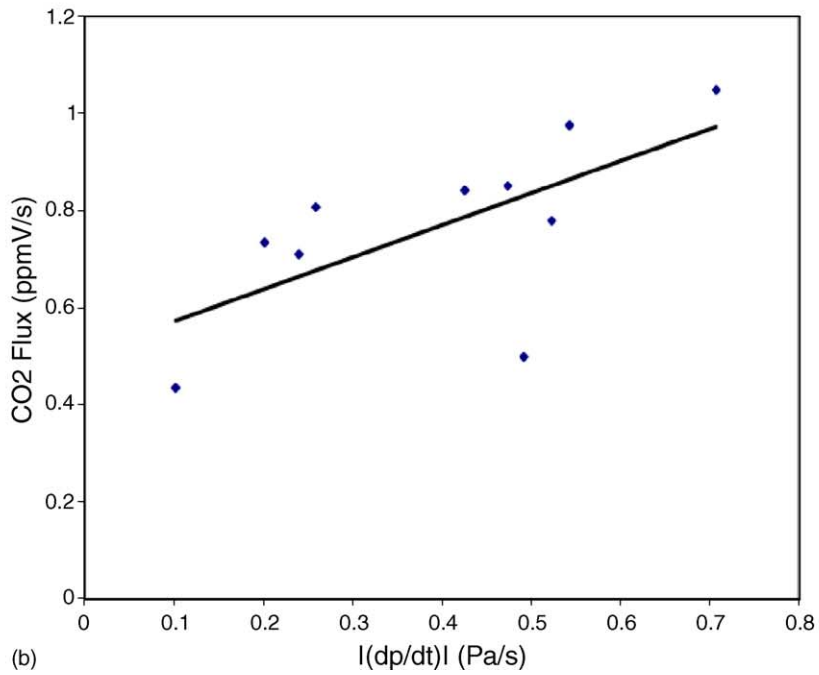
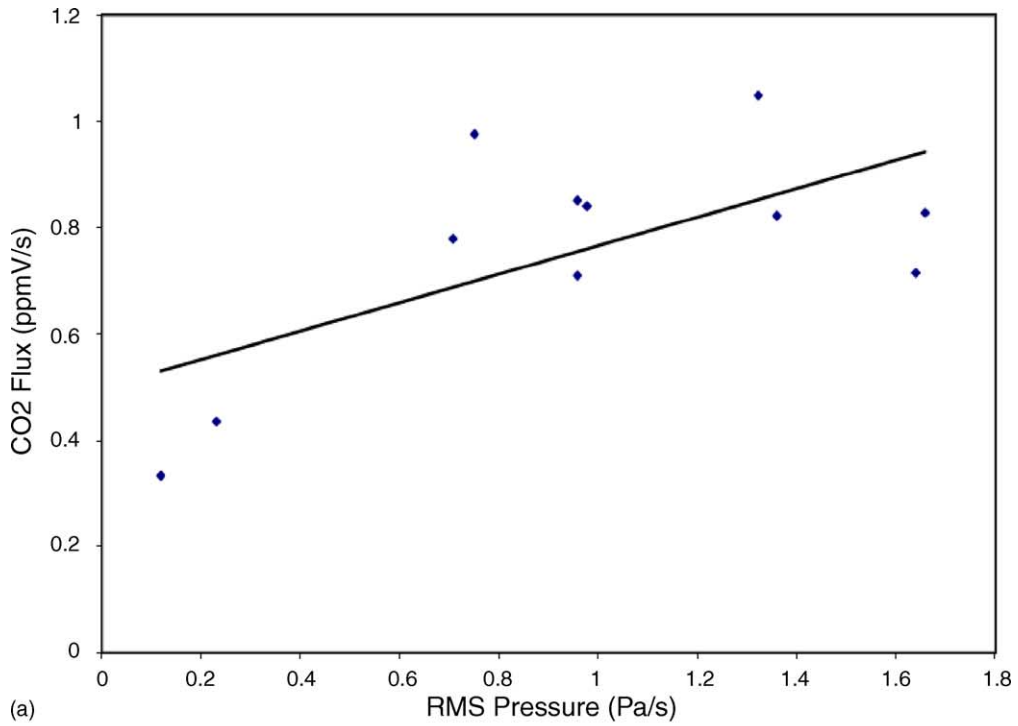


Fig. 5. Vertical flux of CO₂ from the soil surface as a function of (a) rms pressure, (b) pressure pumping rate, and (c) mean wind speed. All fluxes were determined from 10 2-min experiments with pressure and flux sampled at 2 Hz.

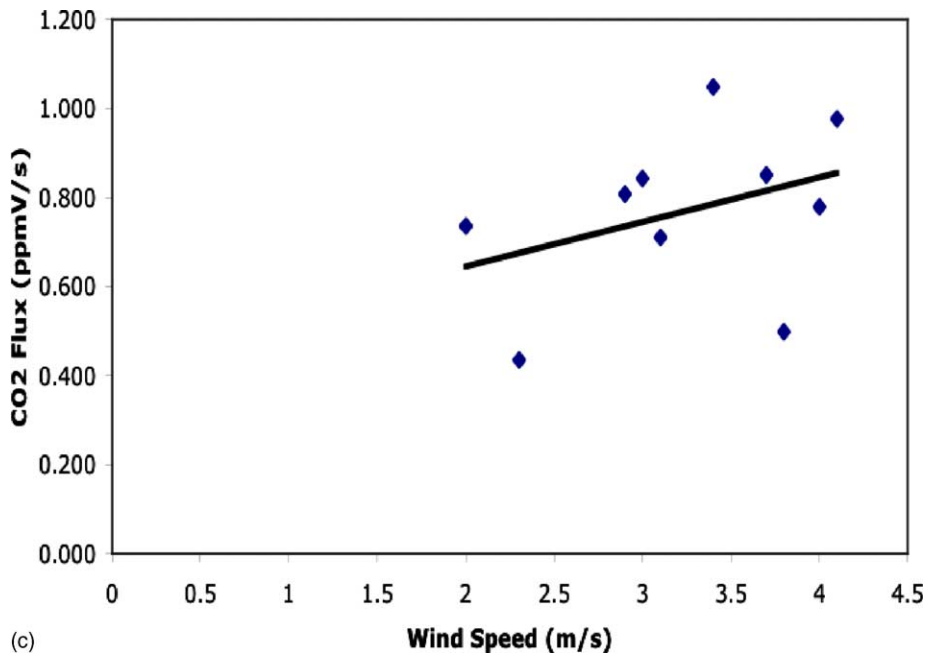


Fig. 5. (Continued).

estimated pure diffusion rate by about a factor of 3–7. From this we conclude that, for the site and weather conditions of our experiment, pressure pumping contributed significantly to the soil efflux of CO₂ but that other mechanisms (including diffusion) may have contributed up to 60% of our measured value. Our calculations suggest that major contributions came from processes other than diffusion.

5. Conclusions

Our measurements of high-frequency pressure fluctuations at and beneath the soil surface suggest that ambient atmospheric pressure fluctuations are likely to cause trace gas movement throughout the (unsaturated) porous medium. Concurrent measurements of CO₂ fluxes from the soil surface reveal systematic increases with increasing rms pressure, pumping rate, and mean wind speed. Our measurements taken over bare, dry soil have dependence on rms pressure approximately twice as large as those previously reported in a forest canopy, although this difference may not be significant given the large uncertainty of such measurements. Soil CO₂ fluxes measured under conditions

conducive to pressure pumping exceeded diffusional fluxes estimated by the gradient diffusion method by a factor of 10.

These studies corroborate past work demonstrating the importance of heterogeneous pressure fields in promoting gas movement in porous soils. They further suggest that fluctuations in the static pressure fields introduced by wind interactions with terrain and vegetation may lead to pressure pumping at the surface and hence large spatial inhomogeneities in soil fluxes of trace gases.

Acknowledgements

This research was supported by the Biological and Environmental Research Program (BER), US Department of Energy, through the Great Plains Regional Center of the National Institute for Global Environmental Change (NIGEC) under Cooperative Agreement No. DE-FC03-90ER61010, and by USDA/CSRS NRI Competitive Grant #96-35209-3892. Support from LI-COR, Inc. by loan of their LI-COR-6400 is greatly appreciated. Karen Bandhaur provided able assistance with data analysis.

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