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**PAPER**

**Effect of wind turbulence on monitoring soil CO₂ flux using the closed gas chamber method**

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**Abstract**

This study evaluated the performance of closed chamber monitoring of soil carbon dioxide (CO₂) flux in a wind turbulence environment to improve the accuracy of constructing an ecosystem carbon budget. The effect of wind turbulence–induced barometric pressure fluctuations on soil CO₂ emissions was explored using soil pore pressure difference data from different monitoring sites in the field, and the factors associated with errors in the monitoring of closed gas chambers were analysed. Subsequently, a gas chamber measurement error study was conducted in conjunction with the flux calculation model based on the phenomena observed in the field. The results showed that the simply designed closed gas chamber exerted a strong isolation effect on wind turbulence and did not simulate the actual monitoring environment. The error of the linear flux model in a turbulent wind environment for 10 min was 3%–7% greater than that in the absence of wind (error of 12%), and the calculation error of the exponential fitting model in a turbulent environment was also close to 10%. In addition, the error in the calculation model was positively correlated with the wind turbulence intensity and soil dispersion coefficient. Therefore, for a windy environment, the closed gas chamber and flux calculation models must be improved. Otherwise, a large deviation between the monitored flux and actual values will occur.

**1. Introduction**

Soil carbon dioxide (CO₂) gas emissions are a crucial component of the terrestrial carbon cycle. Globally, the estimated soil CO₂ released into the atmosphere is 98 ± 12 Pg C (Bond-Lamberty and Thomson 2010), approximately 15 times the current annual amount released from fossil fuel burning (Denman et al 2007, Goffin et al 2015). Therefore, accurate measurement of the flux of stable micro gas (CO₂) from the Earth’s surface is important for assessing the global carbon revenue and greenhouse effects caused by greenhouse gases (Abassi et al 2021, Forde et al 2019, Knorr et al 2005, Sahoo and Mayya 2010, Sanz–Cobena et al 2021) and provides important data for the implementation of carbon balancing programmes.

In the past few decades, there has been an increase in the number of soil CO₂ flux monitoring technology, from alkali solution absorption to chromatography, box law, and micro gas simultaneous methods; however, the current monitoring technology primarily used is based on air chambers. This method is widely used in carbon cycling and other environment-related studies (Norman et al 1997, Davidson et al 2002, Xu et al 2006, Sahoo and Mayya 2010, Jacinthe 2015, Poblador et al 2017, Buragiene et al 2019, Rittl et al 2020, Zhang et al 2022). The gas chamber used for monitoring soil CO₂ flux is divided into a closed chamber system (also known as a transient or unstable system) and an open chamber system (also known as a steady-state system).
transport process was divided into three control states. (computational model used in the closed air chamber and air chamber design were primarily analysed. Furthermore, the underestimation effect of closed air chamber measurements has been studied. However, the performance of a closed air chamber in a field monitoring environment and explored the influence of air pressure fluctuations caused by wind turbulence during actual field measurements is inevitable; therefore, this study evaluates the performance of closed air chamber used to measure the carbon flux in the wind environment and the design of the air chamber.

The enhancement effect of air pressure fluctuations on gas transport in porous media has been previously investigated (Maier et al 2012, Poulsen et al 2017, Pourbakhtiar et al 2017, Levintal et al 2019) and the gas transport process was divided into three control states (figure 1) based on wind speed and soil permeability. However, the performance of a closed air chamber in a fluctuating pressure environment has not been studied. Furthermore, the underestimation effect of closed air chamber measurements has been studied. However, the computational model used in the closed air chamber and air chamber design were primarily analysed (Livingston and Hutchinson 1995, Gao and Yates 1998, Livingston et al 2006, Sahoo and Mayya 2010) but the actual environmental disturbance causing an error in the measurement value of the air chamber was not studied.

In this study, we determined the efficiency of the air chamber design by observing the soil pore pressure at different measurement points in the field and examined the shielding effect of the air chamber against wind turbulence in a turbulent wind environment in conjunction with the differential pressure values recorded by the sensors. We assessed, based on field measurement phenomena and mathematical modelling analysis, the bias in flux measurements of a closed air chamber when used in an environment where wind turbulence causes fluctuations in surface air pressure.

2. Method

To understand the bias in the measurements of confined air chambers owing to wind turbulence under natural conditions, we collected field measurement data and analysed them using a flux calculation model. First, we collected data on near-surface wind speed, soil pore pressure, and other factors that can generate errors in the field monitoring environment and explored the influence of air pressure fluctuations caused by wind turbulence on soil CO$_2$ gas emissions. Next, based on the phenomenon observed in the field-measured data combined with the closed flux calculation model, the relationship between wind turbulence and the closed air chamber monitoring the soil carbon flux was evaluated.

2.1. Field site description

Field data acquisition experiments were conducted in the autumn and winter of 2021. The collection point was located within the Maple Gardens of Zhejiang Agriculture and Forestry University ($30^\circ 15'N$ 119°43'E, 60 m a.s.l.). The garden plantings were primarily *Acer cinnamomifolium*, *A. yangjuechi* (Fang and Chiu), *A. palmatum* Thunb., and *Koelreuteria paniculata* Laxm., and the soil surface cover was primarily *Festuca ovina* Linn. The soil
was clay loam (figure 2(a)), of which 0–8 cm was a humus layer and 10–30 cm was a deposition layer. The field experiment was divided into two parts: equipment deployment and data monitoring. To avoid any negative impact, we selected a flat land to deploy the equipment 1 month prior to commencement of the experiment. Two stainless-steel collars (inner diameter, 20 cm; height, 5 cm) and a polyvinyl chloride collar (inner diameter, 20 cm; height, 5 cm) were inserted into the soil and labelled 1, 2, and 3, respectively (figure 2(c)). The upper end of the collar was embedded in a stainless-steel capillary with (inner diameter, 8 mm; wall thickness, 1 mm; length, 130 mm). After completing the installation of the chamber collar base, 10 cm from the outer wall of the collar (on the side of the capillary), the soil layer was cut vertically at a depth of approximately 40 cm (figure 2(a)). Next, three stainless-steel capillaries (inner diameter, 8 mm; wall thickness, 1 mm; length, 200 mm) were inserted at depths of 10, 20, and 30 cm, and the other end was connected to a silicone tube (figure 2(b)).
2.2. Data monitoring device

After the equipment was deployed for 1 month, the field experiment was completed when the wind speed was high on 18th November, 28th November, and 5th December, 2021. A differential pressure sensor (HCS3051, Qingdao Huacheng M&C Equipment Co., Ltd, China) was used to collect differential pressure data from different soil layers. The accuracy of the differential pressure sensor was 0.075%, accounting for 200 Pa. Before the experiment was performed, the differential pressure sensor was calibrated; the two ends of the sensor were inserted into the calibration system (Xu et al. 2006, Mohr et al. 2020), and the pressure difference value was recorded. Next, the high-pressure side (H) was connected to a silicone tube that was inserted 10, 20, and 30 cm from the soil surface according to the monitoring needs, and the low-pressure side (L) was connected to the stainless-steel capillary on the soil surface; data were logged at 1 s intervals (figure 2(b)). Simultaneously, a three-dimensional anemometer (EC-A3, Jinhzhou sunshine Meteorological Technology Co., Ltd, China) was installed on flat ground 1 m from the ground next to the stainless-steel collar. Specific locations are shown in figure 2(c). The wind speed data were collected on-site in real time and logged at 1 s intervals. A cylindrical closed gas chamber (diameter, 20 cm; height, 12 cm) with a designed balanced differential pressure function and without a designed balanced differential pressure function was used for CO2 flux monitoring, and an IRAG Infrared CO2 Concentration Sensor (DCO2-TFW1, Beijing Dihui Technology Co., Ltd, China) was installed in the centre of the gas chamber (5 cm). The CO2 concentration data were logged at 2 s intervals.

2.3. Gas transport model

According to the literature (Levintal et al. 2019, Maier et al. 2012), the gas transmission mechanism in the wind-induced porous medium will be different for the gas permeability of different soils (figure 1). When the gas permeability or wind speed is greater than a certain value (Regime 3), gas transport is dominated by advection mechanisms. Gas transmission in porous media (soil) is typically described by the advection-diffusion equation (Hamamomo et al. 2009, Pourbakhtiar et al. 2017):

\[
\frac{\partial C}{\partial t} = D_t \frac{\partial^2 C}{\partial z^2} - \nu \frac{\partial C}{\partial z} + S(z)
\]

where \(C\) [g/m³] is the mass concentration of CO2 gas in the medium, \(\theta\) [m³/m³] is the effective porosity of the medium, \(\nu\) [m/s] is the convection velocity, \(t\) [s] is time, \(S\) [g m⁻³ s⁻¹] is the gas source term, and \(z\) [m] is the soil depth. \(D_t\) [m²/s] is the diffusion coefficient of CO2 gas in the soil medium.

In Regime 2, the gas transport mode was dominated by the dispersion mechanism, that is, the vertical transport of air mass flow in the soil caused by the fluctuation of air pressure on the soil surface. With the alternation of pressure fluctuations, gas convection also alternates up and down; thus, the net vertical airflow into and out of the soil is zero (Maier et al. 2012, Pourbakhtiar et al. 2017). This implies that the movement of gas in porous media caused by pressure fluctuations because of wind turbulence can be regarded as a dispersion process, and the gas transport equation is as follows (Goffin et al. 2015, Pourbakhtiar et al. 2017):

\[
\frac{\partial C}{\partial t} = D_t \frac{\partial^2 C}{\partial z^2} + S(z)
\]

where \(D_t\) [m²/s] is the effective diffusion coefficient (or ‘apparent diffusion coefficient’) of CO2 in the soil medium, representing the sum of molecular diffusion and mechanical dispersion. The specific equation is as follows (Auer et al. 1996, Bear 2013):

\[
D_t = D_s + \alpha |\nu|
\]

where \(D_s\) [m²/s] is the soil molecular diffusion coefficient, which can be estimated from the molecular diffusion coefficient \((D_0)\) in air. Two well-known \(D_t\) models are the King (1905) and Millington and Quirk (1961) models: \(D_t = \theta^0\) and \(D_t = \theta^2 / \varphi^3\), respectively. \(\theta\) [m³/m³] is the effective porosity of the medium, and \(\varphi\) [m³/m³] is the total porosity of the medium. \(\alpha |\nu|\) [m²/s] velocity-dependent dispersion term, which is velocity-dependent or mechanical dispersion. \(\alpha\) is the dispersion, which reflects the complexity of pore space connectivity at the research scale. In uniform media, the value of \(\alpha\) is very small. If there is no gas advection in the medium, the effective diffusion coefficient is the molecular diffusion coefficient \(D_s\). At this time, the gas transport mechanism becomes diffusion-dominated, that is, the Regime 1 phase (figure 1). However, in the case of pressure fluctuations, the net speed may be zero, but |\(\nu|\) is not zero, at which time \(D_t > D_s\) (Auer et al. 1996).

2.4. Closed chamber monitoring model

According to the law of species mass conservation and the monitoring principle of the closed gas chamber, the model was established; that is, the mass of the gas emitted from the soil was equal to the mass of the gas accumulated in the gas chamber. Additionally, some assumptions were made to facilitate the model analysis: CO2 gas mixing in the gas chamber is instantaneous and uniform at any time. The relationship equation is as follows:
where $M_{i}$ [g] is the mass of CO$_2$ gas emitted by the soil, $M_{a}$ [g] is the mass of CO$_2$ gas accumulated in the gas chamber, $V$ [m$^3$] is the volume of the gas chamber, $C(0)$ [g/m$^3$] is the CO$_2$ concentration at the soil interface, $A$ [m$^2$] is the contact area between the gas chamber and soil, $t$ [s] is the measurement time, and $f$ [g m$^{-2}$ s$^{-1}$] is the CO$_2$ gas flux. Thus, equation (4) can be rewritten as follows:

$$\frac{V}{A} \frac{\partial C(0)}{\partial t} = D_{z} \frac{\partial C}{\partial z} \bigg|_{z=0}$$

(5)

This equation can then be solved using Laplace transform combined with equations (2) and (5).

$$C(z, p) = \frac{C_{0}^{(z)}(z)}{p} + C_{0}^{(z)}(0) \frac{\theta A \exp(-qz)}{Vp(q + \theta A/V)}$$

(6)

where $C_{0}^{(z)}(0)$ is the spatial derivative of the initial concentration of CO$_2$ in the soil when $z = 0$ and $q$ is defined as $\sqrt{\theta p / D_{z}}$. Subsequently, the inverse Laplace transform of equation (6) can be used to obtain the distribution function of CO$_2$ gas concentration in soil with space and time, and that combined with the gas flux expression at $t = 0$, that is, Fick’s first law, the distribution function of CO$_2$ gas concentration with time at $z = 0$ can be obtained (see Livingston et al (2006) for detailed derivation steps).

$$C(0, t) = C_{0}^{*} + \tau \int_{0}^{\infty} A \left[ 2 \sqrt{\pi \tau} \frac{t}{\sqrt{\tau}} + \exp \left( \frac{t}{\tau} \right) \text{erfc} \left( \frac{t}{\sqrt{\tau}} \right) - 1 \right]$$

(7)

where,

$$\tau = \frac{V^2}{\theta D_{z} A^2}$$

(8)

### 2.5. Data analysis

The field-measured results were saved and pre-processed using Microsoft Excel 2020 and subsequently mapped and analysed using MATLAB (MathWorks, r2020b, Natick MA, USA). Mathematica 12 was used to construct the closed gas chamber monitoring model and conduct error analysis.

### 3. Result

#### 3.1. Turbulence effect of wind

Relevant data monitoring experiments were conducted when the wind speed had a significant effect on them. Notably, 1) the underground differential pressure vent pipe installed 1 month in advance was partially blocked (20 cm for position 1; 20, and 30 cm for position 3), and the data could not be collected as planned. To avoid a change in the planning of the experiment, the differential pressure ($\Delta P$) at 10 cm was measured for research; 2) to analyse the turbulence effect of wind, 10 min of wind speed (1 m on the surface) and the differential pressure on the soil layer (10 cm above and below, no monitoring room) were randomly selected. The results are shown in figure 3. As shown in figure 3(a), the fluctuation range of the wind speed was relatively stable, total wind speed fluctuated between 0 and 1 m s$^{-1}$, and wind speed in the vertical direction was relatively evenly distributed between −1 and 1 m s$^{-1}$. The pressure difference between the soil pore surfaces (10 cm) is shown in figure 3(b). Its value fluctuates between −0.4–0.4 Pa, and the positive pressure ratio is slightly higher than the negative pressure ratio. The correlation between the surface wind speed and soil pore pressure difference is shown in figure 3, demonstrating a significant correlation between the vertical wind speed and pressure difference ($R^2 = 0.17, \ P < 0.001$). The main reason for this correlation is that the turbulence of the wind is the impetus of the fluctuation of the surface air pressure, which leads to a change in the air pressure in the soil (Levintal et al 2019).

#### 3.2. Analysis of closed gas chamber monitoring

##### 3.2.1. Gas chamber without the design of an equilibrium pressure function

The data in figure 4 show the variation in the differential pressure on the soil layer when the total wind speed fluctuates significantly (in the range of 0 ~ 3 m s$^{-1}$). This phenomenon will increase the effective diffusion rate of soil gases and the gas transport rate, which likewise affects evaporation from the soil surface and temperature distribution on irregular soil surfaces. For some traditional simple closed gas chambers (without pressure balance inside and outside the gas chamber), the monitoring error is significantly high, such as a pressure change of 0.5 Pa results in a 20%–70% deviation in CO$_2$ flux measurements (Xu et al 2006).
On the one hand, the monitoring chamber may isolate the wind turbulence, reducing the gas exchange rate of the soil boundary layer. To explore this problem, we selected the time period during which the wind turbulence phenomenon was prevalent. We placed the closed air chamber on the pre-installed stainless-steel collar, and determined its isolation turbulence effect according to the pressure difference fluctuation value.

Figure 4 shows that during the first 5 min, when the monitoring point was not covered with an air chamber, the differential pressure values on the soil surface fluctuated significantly with wind turbulence. The surface wind speed was high (0–100 s), and the pressure difference also showed an upward trend. At 100–200 s, the wind speed, and the pressure difference also decreased. After 200 s, the wind speed increased instantaneously, and the pressure difference increased immediately. There was a strong correlation between the two variables ($R^2 = 0.2$, $P < 0.001$). At approximately 300 s, a closed gas chamber (without equilibrium differential pressure) was placed on the collar. At this time, the surface wind speed remained at a high level (figure 4(a)), but the differential pressure value was significantly less than that of during the period of 200–300 s. When the closed gas chamber was removed at 450 s, the differential pressure on the soil surface immediately increased. Thus, in an environment with wind turbulence, the use of a closed chamber with unbalanced differential pressure for...
monitoring soil carbon fluxes will have a strong insulating effect on wind turbulence, reducing the rate of exchange of soil gases with the external environment and affecting the measurement results.

On the other hand, when placing and removing the air chamber, the monitoring point produces an abnormal differential pressure, which also affects soil gas emissions. If these influencing factors are not considered when designing the monitoring air chamber, the measured flux results will not represent the actual values. First, when the monitoring chamber was closed and the gasket was compressed, the air pressure within the chamber increased instantaneously (figures 4(b) and 5). At this point, a large amount of gas was pressed into the soil layer to eliminate the increased pressure in the chamber, which affected the original diffusion gradient of CO₂. As the adjustment of CO₂ under the influence of chamber pressure is primarily a diffusion process, it may take a long time to recover once disturbed (Hutchinson and Livingston 2001, Xu et al 2006). Second, in the measurement process, the evaporation of water and the increase in temperature in the soil also lead to an imbalance in chamber pressure in the air chamber with unbalanced pressure. According to the ideal gas law (PV = nRT), we estimated that the pressure in the closed gas chamber would change by approximately 333 Pa every time the temperature fluctuates by one degree. In addition, water vapour evaporation can easily cause a change in steam pressure in the closed chamber. These effects cause the monitoring chamber to be under overpressure, which may lead to a serious underestimation of soil carbon flux (Xu et al 2006).

Figure 4. Total wind speed (a) at 1 m from the soil and pressure difference (b) between the soil–air interface and 10 cm below the interface; values marked ‘close chamber’ and ‘open chamber’ represent the pressure difference for the air chamber (the function of equilibrium pressure is not designed) on the soil surface. Relationship (c) between soil pore pressure difference (ΔP) and wind speed.
Therefore, when using this type of air chamber to monitor soil gas flux and the ambient air pressure changes, the measurement deviation is very large. As the air chamber is isolated from the external environment and the pressure suppression effect of the air chamber is significant, the air pump effect or pressure pump effect caused by wind turbulence is significantly weakened, and the underestimation error increases by several orders of magnitude.

### 3.2.2. Gas chamber with the designed equilibrium pressure function

When we found that the closed gas chamber without a balanced differential pressure function had a significant isolation effect on wind turbulence, to further understand the effect of a windy environment on the monitoring closed gas chamber with balanced differential pressure function, we simultaneously conducted a control group experiment in the pre-set area. We considered that the other variables were constant, except for the design of the monitoring gas chamber. Figure 6(a) shows the total wind speed at 1 m on the surface during the experiment, and figure 6(b) shows the soil pore pressure difference data of monitoring points 1, 2, and 3 at the same time point; the soil surface without air chamber cover and the soil surface with closed air chamber cover, in which the closed air chamber is divided into balanced and unbalanced pressure differences. According to the data in figure 6(b), in the wind turbulence environment at the same time point, the fluctuation amplitude of the soil pore pressure difference without an air chamber cover was significantly higher than that of with an air chamber cover, which is consistent with the aforementioned analysis results from different times before and after the same place (figure 4). The closed air chamber isolated a part of the wind turbulence. Based on the pressure difference monitoring data for the two closed gas chambers with unbalanced pressure and balanced pressure, the fluctuation amplitude of the pressure difference of the gas chamber with a balanced pressure design is less than that of the gas chamber with a balanced pressure design. Thus, the isolation effect of the former on wind turbulence is higher than that of the latter. However, based on the soil pore pressure difference measured for the balanced pressure chamber and without gas chamber, the fluctuation amplitude of the former is significantly lesser than that of the latter. Thus, even the designed monitoring chamber with balanced pressure has a significant isolation effect in high-frequency wind turbulence conditions.

Therefore, monitoring instruments that use only a simple ventilation tube to negate the effect of the differential pressure within and outside the air chamber are effective in environments with no disturbance or large timescale pressure changes, that is, where the frequency of perturbed pressure changes in the environment is low. However, under the influence of a strong wind turbulence, the fluctuation frequency of the surface pressure is high, which may lead to the rapid alternation of positive or negative pressure disturbances. Under this condition, the simple balance device had lost its functionality (figure 6). Studies have described this phenomenon both theoretically (Young et al 2001) and experimentally (Kutsch et al 2001).

### 3.3. Relationship between wind turbulence and CO2 concentration in the air chamber

To explore whether the closed gas chamber had an isolation effect on wind turbulence, we also studied the relationship between wind turbulence and CO2 concentration in the different gas chambers, that is, the relationship between wind turbulence and soil emissions. As shown in figure 7, during the first 30 s, because the
closed gas chamber was placed on the collar for gas monitoring, the CO₂ concentration changed within the chamber slowly, and the total wind speed was relatively low. At 40 s, the wind speed increased significantly, and the CO₂ in the air chamber designed with equilibrium pressure changed immediately, showing an upward trend (the slope of the CO₂ concentration increased); however, the concentration in the air chamber with unbalanced pressure increased slightly. The reason for this phenomenon may be that the downward pressure generated by the air chamber (unbalanced pressure) placed on the collar inhibited the diffusion of soil CO₂. When the total wind speed increased again at 100 s, the CO₂ concentration in the closed chamber increased by varying degrees. The CO₂ concentration in the chamber with the equilibrium pressure increased significantly, which is consistent with the results reported by Bain et al (2005) and Xu et al (2006). Combined with the analysis of the soil pore pressure difference data for the closed air chamber in figure 6(b), when the wind turbulence causes the surface gas to fluctuate, resulting in the soil pore pressure difference fluctuation (positive and negative), the CO₂ concentration in the air chamber shows an upward trend. This phenomenon explains the aforementioned gas

Figure 6. Total wind speed (a) at 1 m from soil; at the same time, the pressure difference between the soil–air interface and 10 cm below the interface for the three conditions of no closed chamber, closed chamber with designed equilibrium pressure function, and closed chamber without designed equilibrium pressure function.

Figure 7. Relationship between gas chamber CO₂ concentration and wind. The grey line represents the actual wind speed 1 m from the soil; green and blue curves represent the change in value of CO₂ concentration in the closed air chamber with time in the environment with wind turbulence. The green curve represents the closed air chamber with designed equilibrium pressure function, and the blue curve represents the closed air chamber without designed equilibrium pressure function.
dispersion process; that is, with soil pressure fluctuation, gas convection also fluctuates, and the net vertical airflow into and out of the soil is zero. However, $|\nu|$ is not zero for $D_e > D_s$; this phenomenon shows that the uncertainty caused by wind turbulence on the measurement timescale should be considered when monitoring the gas flux in a closed gas chamber with balanced differential pressure, particularly in the selection and correction of the flux calculation model. This problem was discussed in detail in the calculation model analysis module.

### 3.4. Analysis of the flux calculation model

According to our results for wind turbulence and soil gas emissions, combined with those of the analysis of the gas transport control state diagram in figure 1, the gas dispersion effect caused by wind turbulence is more significant for the common soil (low gas permeability) flux monitoring environment than for the other studied environments. Furthermore, according to the mathematical model, the deviation of the measured value of the reasonably designed closed gas chamber under ambient pressure fluctuations caused by wind turbulence was analysed. First, the effective diffusion coefficient, $D_e$, was determined. According to different soil pore pressure differences, combined with Darcy’s law, the gas flow velocity $\nu$ can be calculated, and the formula is as follows:

$$\nu = \frac{k \, \partial p}{\varphi \, \mu \, \partial z}$$  \hspace{1cm} (9)

where $k$ [m$^2$] is the gas permeability, and $\mu (1.8 \times 10^{-5}$ kg m$^{-1}$s$^{-1}$) is the aerodynamic viscosity coefficient. The effective diffusion coefficient, $D_e$, can be obtained using equation (3) ($D_s$ is calculated by the Buckingham Palace model, $D_0$ is $1.64 \times 10^{-5}$ m$^2$ s$^{-1}$).

The CO$_2$ concentration data monitored in the field (figure 8) demonstrated that the CO$_2$ concentration in the air chamber increased non-linearly with time. At this time, CO$_2$ concentration inversion was carried out in combination with relevant soil parameters and flux values. It could be observed that the results of linear model deviated greatly from the actual values, while the inversion results of exponential model and polynomial model are better, with root mean square errors of 9.5 mg and 6.9 mg respectively. The results of the concentration segmentation simulation based on equation (7) were similar to the observed data, with a root mean square error of 4.6 mg. In environments with continuous wind turbulence, the non-linear increase in CO$_2$ concentration over time within the monitored air chamber is significant, and if a linear model is used for soil carbon flux estimation for this condition, the error will increase further. To explore the error caused by using a linear model to calculate the flux under the influence of continuous wind turbulence, we expanded and analysed a flux calculation model (equation (7)) according to the power series. The expansion formula is as follows:

![Figure 8. CO$_2$ concentration in the gas chamber as a function of time, where effective porosity of the soil is 0.48, effective diffusion coefficient of the gas is $3.6 \times 10^{-5}$ m$^2$ s$^{-1}$, and effective height of gas chamber $h$ is 0.12 m.](image)
At this time, the linear model was compared with equation (10). We observed that the equation of the linear model was simplified and that all high-order terms of the power series expansion were omitted, leading to the deviation of the calculated flux value, which is less than the actual flux value, leading to flux underestimation.

As shown in figure 9(a), in an environment without wind or pressure fluctuations, the error of the linear model was greater than 4% when the closed air chamber was continuously monitored for 1 min. If the wind causes surrounding pressure fluctuations, the linear model calculation error will be positively correlated with the pressure difference formed by the pressure fluctuation for 1 min, and a pressure difference of 1 Pa will increase the relative error by 1%. Simultaneously, the calculation error of the linear model increased with the measurement time of the air chamber. In a windless environment, the relative error exceeded by 12% when the measurement time was increased to 10 min, and for the same monitoring time, the relative error exceeded 16%.
in an environment of continuous wind (1 Pa differential pressure). In a gusty environment, the fitting effect of the linear model is very poor.

For some closed gas chambers fitted with the exponential model, the calculated value deviated significantly from the actual flux value in the wind turbulence environment. The exponential fitting model is expressed as follows:

\[ C(t) = C_i + [C(0) - C_i]e^{-Kt} \]  

(11)

where \( K \) is the diffusion rate constant, which is an integrated expression of the effective gas diffusion coefficient. This method often avoid the following phenomenon: over time, the accumulation of CO2 in the gas chamber leads to a rapid decline in the gas concentration gradient, which affects the fitting of the key parameter \( K \) of the calculation model. Therefore, the method obtain the change value of the gas concentration in a sufficiently short time for data fitting, usually approximately 10 s. This processing method is a recognised fitting method in the case of no wind or environmental disturbance, but in the case of wind fluctuation, the fitting value for the first few seconds is used to replace the main parameters of the latter for calculation, and the result deviates from actual values. To analyse the error in this section, we used the calculation model of equation (7) and the assumed soil parameters for the analysis. Assuming that there is no pressure fluctuation in the first 30 s of the measurement process, there is a pressure fluctuation (the pressure difference is 0.5, 1, 1.5, and 2 Pa). The error generated according to the calculation method adopted by the aforementioned model is shown in figure 10. If the monitored soil medium is relatively uniform, that is, when the dispersion coefficient \( (\alpha) \) is 0.1 m, air pressure fluctuation will occur on the soil surface, which causes the calculated value of gas flux to be significantly lower than that of the actual flux, and its underestimated value is positively correlated with the differential pressure. That is, the higher the pressure difference, the more evident the flux underestimation effect, and the underestimation value gradually increases with the increase in monitoring time.

However, the soil in the real environment is generally a non-uniform medium; thus, the dispersion coefficient \( (\alpha) \) will be greater than 0.1 m, with a range of 0.1–0.4 m. At this time, the wind turbulence in the monitoring environment caused fluctuations in the surface pressure, further increasing the measurement error of the closed chamber. As shown in figure 11, with an increase in the dispersion coefficient, when the monitoring time is up to 5 min in the environment with a 1.5 Pa pressure fluctuation, the error value (underestimation) of the aforementioned fitting method for calculating flux will increase from the original 3.1% to 9.2%. For soil with a dispersion coefficient of 0.4 m, the error (underestimated value) will exceed 10% in the environment with a differential pressure fluctuation of 2 Pa for 5 min.
4. Discussion

It is clear that wind turbulence can have an effect on the monitoring of soil fluxes in a confined air chamber. For a simple closed gas chamber without a balanced differential pressure treatment, the monitoring results do not represent the actual flux because any pressure change in the monitoring gas chamber leads to a strong response to the gas. In addition, the simple closed gas chamber exerts a strong isolation effect on wind turbulence, and the result obtained deviates from the actual flux. For a closed gas chamber with a simple design of balanced pressure difference, it also isolates the wind turbulence effect and alters the experimental results in some cases, such as the venturi effect caused by an unreasonable pressure balance opening. Bain et al (2005) and Xu et al (2006) have also mentioned this phenomenon. To test the pressure balance effect of the air chamber, studies have been conducted using the closed air chamber both indoors and outdoors. This method is more effective for studying an air chamber design, but it cannot further evaluate the relationship between wind turbulence and gas emissions. Mohr et al (2020) have connected one end of the differential pressure gauge to the calibration system and the other end to the soil to determine the enhancement effect of wind turbulence, which may effectively avoid the problem of wind blowing directly into the differential pressure pipe. However, there may be a delay in the wind turbulence effect, which amplifies the differential pressure effect. Therefore, to improve the method used to study whether the air pressure fluctuation caused by wind turbulence enhances soil gas emissions, causing monitoring errors in the closed gas chamber, the method of directly detecting the pressure difference between the upper and lower layers of soil was adopted in this study. We found that fluctuations in air pressure led to an increase in the CO2 concentration in the air chamber. This phenomenon can be interpreted as follows: when the soil pressure is greater than the atmospheric pressure, the gas flows out of the soil, and when the soil pressure is less than the atmospheric pressure, the gas enters the soil. In these two processes, the total volume of gas flowing in and out may remain constant. However, there are often considerable differences in specific gases. The CO2 concentration in the soil generally ranges from thousands of ppm to tens of thousands of ppm, which is several orders of magnitude higher than that in the atmosphere (400 ppm). This high CO2 concentration in the soil leads to a significant difference in the mass of CO2 gas entering and leaving the soil; that is, more CO2 flows out of the soil than that enters the soil, resulting in an increase in the CO2 concentration in the gas chamber.

Furthermore, the estimated annual CO2 emission from the soil into the atmosphere is 98 ± 12 Pg C (Bond-Lamberty and Thomson 2010), which is approximately 15 times the current annual emission from fossil fuel combustion (Denman et al 2007, Goffin et al 2015); that is, an underestimation error of 10% renders the soil CO2 emission equivalent to global fossil fuel emissions for 1 year. Therefore, for measurement in windy environments, either the air chamber must be improved or the calculation model must be modified. For computational models, model selection is based on experimental data and is not limited to linear and exponential models, whose polynomial models also show excellent computational results. In addition, in environments with high wind turbulence, calculating the flux data in segments may be considered to avoid a
uniform fit affecting the calculation result. If the soil respiration intensity is measured at a particular site, long-term monitoring should be used to eliminate errors by averaging multiple measurements. Regarding the monitoring gas chamber, open-type devices can be designed to ensure that the air pressure inside the chamber is consistent with that of the outside environment and to combine the air pressure fluctuations caused by wind turbulence and gas concentration data for flux calculations. In large turbulent environments, the introduction of the eddy covariance technique can be considered to complete the flux calculation within an area of few square metres.

5. Conclusion

In an environment with natural wind, wind-induced turbulence causes soil pore pressure to fluctuate, which enhances CO₂ emissions in the soil. This phenomenon explains the gas diffusion transport mechanism in low-permeability porous media, as described in various studies. If a simple closed air chamber is used to monitor the soil carbon flux in the wind-induced turbulence environment, there will be a significant error in the results because the simple closed air chamber exerts a significant isolation effect on wind turbulence. When selecting the flux calculation model for a closed gas chamber with a fully balanced differential pressure design, a model with a high fitting degree should be used, which reduces the error. In a wind-induced turbulence environment, the turbulence effect renders the linear flux calculation model unsuitable and adds to the increase in error. For the exponential fitting method, in a windy environment, the monitoring error of 5 min can be as high as 6%–10%; that is, there is an underestimation effect compared to the actual flux. If these problems are not solved, they will cause a hindrance in the determination of the ecosystem carbon budget, global carbon budget, and greenhouse effect caused by greenhouse gases. Therefore, for a windy environment, either the air chamber or the calculation model must be improved. Using only one flux calculation model is insufficient, and model selection should be based on experimental data. In environments with high wind turbulence, the flux data can be calculated in segments.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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