Study on Principles of Soil Respiration Monitoring and Calibration Improvement Methods

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Abstract. Soil respiration has an important impact on global climate change and the carbon cycle. Therefore, it is necessary to accurately analyze the principles of soil respiration monitoring. Various monitoring principles tend to deliver partially different results. In order to reduce the difference, it is necessary to explore the ways to improve the principles. The present studies focus mainly on different methods of soil respiration monitoring, but rarely on their relative principles. This paper makes comparison between the dynamic airtight chamber method, the dynamic open chamber method, the gas well method and the model method based on the domestic and foreign literature, and further discusses the calibration improvement methods according to the relevant principles, aiming to reduce the result difference between different monitoring principles.

1. Introduction

The soil is a huge carbon pool with a total carbon reserve of 1394Pg C (1Pg = 10\textsuperscript{15}g)\textsuperscript{[1]}, which is about twice that in the atmosphere (750Pg C) and three times that in the total terrestrial biomass (560 Pg C)\textsuperscript{[2]}. The CO\textsubscript{2} released by soil respiration accounts for 60%-90% of the total released in the terrestrial ecosystem\textsuperscript{[3]}. The annual CO\textsubscript{2} emission of soil into the atmosphere is about 68Pg C, second only to the global plant total primary productivity (GPP: 100-120 Pg C a\textsuperscript{-1}), slightly higher than the net primary productivity of the global terrestrial ecosystem (NPP: 50-60 Pg C a\textsuperscript{-1}), and far greater than the amount of CO\textsubscript{2} released by fuel combustion (5.2 Pg C)\textsuperscript{[4]}. CO\textsubscript{2} is the main greenhouse gas in the atmosphere\textsuperscript{[5]}, and its massive emission is also the main cause of the current climate deterioration\textsuperscript{[9]}. Therefore, effective soil respiration monitoring methods are crucial to the study of the global carbon cycle and climate change.

Soil respiration monitoring can be dated back to the early 19th century\textsuperscript{[10, 11]}. For more than 200 years, a lot of research on soil respiration has been conducted at home and abroad\textsuperscript{[8]}. The lye absorption method (the earliest method of soil respiration monitoring) was proposed by Lundwgarth\textsuperscript{[14]}. After that, the gas chamber method was widely used in the field of soil respiration monitoring\textsuperscript{[15]}. Gas well method can analyze CO\textsubscript{2} in the soil section\textsuperscript{[16]}. The vorticity correlation method can be used to monitor carbon flux in an ecosystem with a large area\textsuperscript{[17]}. Bekku et al.\textsuperscript{[18]} found that the results obtained by the four monitoring principles, namely, the lye absorption method, the dynamic open airflow method, the closed gas tank method and the dynamic closed tank method, were quite different based on indoor stimulation experiments.
At present, the gas chamber method and gas well method are mainly used in soil respiration monitoring \[^{[19]}\]. The principles of various soil respiration monitoring methods have some problems: 1) The gas chamber method does not consider the influence of turbulence and CO\textsubscript{2} emitted by soil on soil respiration inhibition \[^{[12, 25]}\]; 2) This method is affected by the calculation model and its diffusion coefficient D is vulnerable to the soil environment. Therefore, analyzing the working principles of various soil respiration monitoring methods is beneficial the improvement of the applicability and reliability of soil respiration monitoring \[^{[6-7]}\]. By analyzing the monitoring methods commonly used in recent research at home and abroad, the paper proposes the problems of different monitoring methods and their corresponding calibration improvement methods so as to further improve the accuracy of soil respiration monitoring.

2. Comparative analysis of different soil respiration monitoring methods

2.1 Static gas chamber method

The static gas chamber method mainly includes the static lye absorption method and the static airtight chamber method. The former one means to absorb the CO\textsubscript{2} in the container using alkali or solid alkali particles, and calculate the CO\textsubscript{2} emission rate within the measurement time based on the formula \[^{[20]}\].

The latter one means to measure the CO\textsubscript{2} concentration in a closed static tank at intervals using gas chromatography or infrared gas chromatography so as to calculate the soil carbon flux. Its calculation is generally based on the following formula.

\[
F_g = \rho_g \cdot \frac{V}{A} \cdot \frac{T_0}{T} \cdot \frac{P}{P_0} \cdot \frac{dC_t}{t} \tag{1}
\]

In the formula, \(F_g\) (\(\mu\text{mol m}^{-2} \text{s}^{-1}\)) refers to the emission flux of the gas; \(\rho_g\) is the gas density under standard conditions; \(V\) is the air volume in the gas chamber; \(A\) is the bottom area of the gas chamber; \(C_t\) is the volume mixing ratio of the gas measured at the time \(t\) (\(t\) refers to the time); \(T_0\) is the absolute temperature of the air under standard conditions; \(P_0\) is the air pressure under the standard state; \(P\) is the air pressure at the sampling site; \(T\) is the absolute temperature at the time of sampling \[^{[12]}\].

The static lye absorption method cannot conduct continuous measurement in a short time, which is its biggest drawback; in addition, its titration result has certain errors compared with the infrared measurement result. The main problems of the static airtight chamber method are: 1) It greatly changes the physical environment of the soil surface, failing to consider the atmospheric turbulence; 2) After the closure of air chamber, CO\textsubscript{2} will accumulate inside the chamber. Higher CO\textsubscript{2} concentration will inhibit the soil respiration, resulting in a smaller measured soil respiration rate.

2.2 Dynamic airtight chamber method

The dynamic airtight chamber method means to continuously monitor the CO\textsubscript{2} changes in a pair of gas chambers using infrared gas analysis, and then conducts calculation using the corresponding gas model. Dynamic airtight chamber method is used in more than 90% of recent international publications for soil respiration monitoring \[^{[31]}\]. This paper mainly introduces the monitoring principles of the dynamic open tank method, which generally uses the increase rate of CO\textsubscript{2} concentration in the gas chamber to estimate the soil respiration rate \[^{[21]}\].

The dynamic airtight chamber method uses the exponential function to calculate the flux:

\[
C' = C'_0 + [C'_0 - C'_s]e^{-\alpha t} \tag{2}
\]

In the formula, \(C'\) is the CO\textsubscript{2} mole fraction after the dilution correction of instantaneous water vapor in the chamber; \(C'_0\) is the rectified CO\textsubscript{2} concentration value on the soil surface below the chamber; \(\alpha\) is the rate constant. When \(C'\) is close to the ambient level (\(C'_0\)), the flux is estimated when the chamber is closed, using the initial slope of the function (\(\partial C'/\partial t\) at \(t = 0\)).

\[
\frac{\partial C'}{\partial t} = \alpha[C'_s - C'_0]e^{-\alpha t} \tag{3}
\]
According to the ideal gas formula, $P_0$ refers to the air pressure ($P_a$), $R$ is the gas constant, and $T_0$ is the absolute temperature (K):

$$ f_c = \frac{VP_0(1-W_0)}{RST_0} \frac{\partial C'}{\partial t} $$

In the formula, $f_c$ refers to the CO$_2$ flux in the soil; $V$ is the volume; $W_0$ is the initial water vapor molar volume fraction; $S$ is the soil surface area in the gas chamber; $\partial C'/\partial t$ is the initial change of the CO$_2$ mole fraction after dilution correction.

The dynamic airtight chamber method is the mostly widely applied method, but it also has some problems: 1) During monitoring, the changes of near-ground micro-meteorological conditions and the blocked air-atmosphere exchange in the airtight chamber weaken the gas turbulence, thereby reducing the rate of soil respiration emissions, i.e., atmospheric turbulence cannot be taken into consideration\cite{32}; 2) Within 30s interval time, due to the airtightness of the air chamber, the CO$_2$ emitted at this time will inhibit the soil respiration\cite{31}.

2.3 Open dynamic air chamber method

The open-air chamber method means to set an air inlet and an outlet at the chamber, and to calculate the CO$_2$ flux using the difference method. During the monitoring process, the soil respiration releases CO$_2$ into the chamber, while the air flows into the chamber through the inlet and then flows out through the outlet. Since the CO$_2$ concentration of the air in the outflow chamber is higher than that in the inflow chamber, CO$_2$ gas differential method can be used to calculate soil respiration:

$$ F = \frac{\mu_e c_0 - \mu_e c_e}{A} $$

In the formula, $F$ refers to the soil respiration rate; $c_0$ is the CO$_2$ concentration of the air leaving the chamber; $c_e$ is the CO$_2$ concentration of the air entering the chamber; $\mu_e$ is the flow rate of the air entering the chamber; $\mu_0$ is the flow rate of the air leaving the chamber; $A$ is the area of soil covered by the air chamber. Since CO$_2$ is increased due to soil respiration, $\mu_e$ and $\mu_0$ are different. The open dynamic air chamber method requires a high level of flow rate measurement of the air entering and leaving the air chamber, which poses greater difficulty to calculation.

2.4 Gas well method

The gas well monitoring method means to calculate the soil respiration rate through the gas diffusion gradient by burying a CO$_2$ sensor beneath the soil. This method can continuously and automatically monitor the change of soil respiration rate at different scales. The formula is as follows:

$$ F_s = -D_s \frac{\Delta C(z)}{\Delta z} $$

In the formula, $F_s$ refers to the soil respiration rate ($\mu$mol m$^{-2}$ s$^{-1}$); $D_s$ is the diffusion coefficient of CO$_2$ in the soil (m$^2$ s$^{-1}$); $C$ is the CO$_2$ concentration in the soil ($\mu$mol m$^{-3}$); $\Delta C/\Delta z$ is the CO$_2$ concentration gradient in the vertical direction of the soil\cite{23}.

The gas well monitoring method can solve the problems of increasing CO$_2$ on the soil surface and higher pressure in the gas chamber during the measurement using the chamber method, and can accurately monitor the soil respiration rate\cite{26}. However, there are some new problems: 1) Diffusion coefficient is affected by factors including soil properties and soil moisture, leading to unsatisfactory calculation results; 2) CO$_2$ in the soil is not be completely discharged into the atmosphere, and some CO$_2$ remains in the soil. The gas well method also calculates the remaining CO$_2$ concentration, leading to estimation bias\cite{24}.

3. Calibration improvement analysis of different soil respiration monitoring principles

3.1 Static airtight chamber method
The static airtight chamber method changes the physical state of the monitored earth’s surface, and the results are greatly affected by human factors. However, its ease operation leads to its wide application in the early stage. It is mainly calibrated using the following methods.

3.1 Static lye absorption method
This method means to determine the carbon flux by using the lye of a certain concentration. It is affected by multiple factors, including the amount of lye, the depth of the respiratory chamber, the absorption area of the lye, the distance of the lye from the ground, and the measurement area. In order to make the method more accurate, it is necessary to precisely control the concentration and amount of lye (general lye concentration: 1mol L\(^{-1}\), volume: 20~30ml) and the monitoring area (the lye absorption area should not be smaller than 6% of the monitoring area\(^{[35]}\)).

3.1.2 Static airtight chamber method
The principle of this method is to determine the CO\(_2\) concentration in the static airtight chamber using gas chromatography and infrared spectroscopy, and to calculate the CO\(_2\) emission rate of soil using the time variation law. Therefore, in order to improve data accuracy, it is necessary to replenish gas after monitoring so that the soil respiration rate is not affected by excessive accumulation of CO\(_2\) in the gas chamber.

3.2 Dynamic airtight chamber method
The dynamic airtight chamber method is currently the most widely used monitoring method. Methods for improvement and calibration include limiting the monitoring time, setting special air chambers and water vapor calibration\(^{[31]}\). The calibration method developed by Li-Cor Biosciences in the United States has achieved good monitoring results\(^{[33]}\).

3.2.1 Limiting monitoring time
The dynamic airtight chamber method considers the influence of the gas chamber on the gradient of CO\(_2\) discharged by soil. Therefore, the measurement time is generally recommended to be limited between 1 minute and 30 seconds and 3 minutes so as to keep the CO\(_2\) concentration change in the gas chamber as small as possible and minimize the above-mentioned impact.

3.2.2 Setting special air chambers
In order to prevent pressure gradients and wind outdoor, pressure exhaust ports are designed for the inlet and outlet of the chamber\(^{[25]}\). The patented pressure ventilation opening designed for the automatic soil gas flux system mainly aims to address the internal and external air pressure imbalance due to CO\(_2\) emission in the gas chamber. In order to rapidly mix the emitted CO\(_2\), a patented technology unique to the LI-COR chamber is also designed.

3.2.3 Water vapor calibration
The gas in the chamber is mainly composed of air, CO\(_2\) and water vapor. It is feasible to conduct calculation using the mass balance equation of “storage=flow-outflow”, and use water vapor to calibrate the CO\(_2\) concentration.

3.3 Dynamic open-air chamber method
During the operation of this method, the difference between flow rates of the inflow and outflow air will cause pressure difference between the air inside and outside the chamber\(^{[25]}\), leading to an additional airflow between the air chamber and the soil, therefore causing significant errors in CO\(_2\) flux measurement. This method is generally improved and calibrated using the following measures.

(1) Special inlet and outlet devices that can ensure no pressure gradient in the relatively enclosed chamber. Measurement is conducted by using the closed-loop system and IRGA. In this way, each
analyzer requires only one flow controller and the time required to close the chamber is also reduced, which is conducive to the accurate measurement of IRGA data;

(2) Reduce the height of the automatic air chamber, thereby reducing the air volume and the time required for the chamber to reach a steady state \[29\].

3.4 Gas well method
The gas well method calculates the soil respiration rate using diffusion gradients. Its sensors are buried beneath the soil, which can eliminate the influence of surface CO₂ emission on the monitoring results. This method is generally calibrated using the following methods.

(1) An accurate diffusion calculation model can describe the soil respiration rate more accurately;

(2) In the gas well method, the accurate calculation of the diffusion coefficient \(D_s\) ultimately affects the accurate evaluation of the soil respiration rate. \(D_s = \varepsilon D_o\); \(C\) is the CO₂ concentration (\(\mu\)mol m\(^{-3}\)) at the depth of \(z\) (m). The five commonly used methods for calculating \(\varepsilon\) are as follows \[13, 26, 27\]:

\[
\begin{align*}
\varepsilon &= 0.66(\varphi \cdot \theta) \\
\varepsilon &= (\varphi \cdot \theta)^{1.5} \\
\varepsilon &= (\varphi \cdot \theta)^{10/3} \\
\varepsilon &= 0.66(\varphi \cdot \theta)(\frac{\varphi \cdot \theta}{\phi})^{12-m/3} \\
\varepsilon &= \frac{(\varphi \cdot \theta)^{2.5}}{\phi}
\end{align*}
\]

In the formula, \(\theta\) refers to the volumetric water content of the soil (cm\(^3\) cm\(^{-3}\)); \(\varphi\) is the soil porosity (\(\varphi = \rho_b / \rho_m\); \(\rho_b\) is the soil bulk density (g cm\(^{-3}\)); \(\rho_m\) is the specific gravity of the soil; for the mineral soil, \(\rho_m = 2.65\) g cm\(^{-3}\)); \(m\) is the constant number of 3.

4. Conclusion and problems

4.1 Conclusion
The impact of CO₂ emissions from soil respiration on global climate change is a major driver for the study of soil respiration \[28\]. Some researchers have found that there is a close relationship between soil respiration and global warming. However, due to the complexity of terrestrial ecosystems and the different study progress of soil respiration in different regions, it is difficult to effectively analyze soil respiration data obtained using the existing soil respiration monitoring principles on a global scale.

There are various methods for monitoring soil respiration and calculating the soil respiration rate, and all of them have their respective advantages and disadvantages. In the actual monitoring process, due to the limitations of monitored soil environment and the inappropriate selection of monitoring principles, many monitoring results fail to accurately reflect the soil respiration rate.

4.2 Problems
(1) Most current mainstream soil respiration monitoring methods fail to consider the impact of CO₂ accumulation and discharge in the gas chamber and the turbulence on the soil surface, leading to monitoring inaccuracy. Future research shall pay attention to whether soil respiration rate monitoring needs to consider the effects of CO₂ respiratory inhibition and the turbulence.

(2) Soil respiration is heterogeneous in time and space. The data obtained from single point monitoring is difficult to be used to analyze the dynamic changes of soil respiration in a large scale. At present, soil respiration monitoring mainly adopts single-point monitoring or small-scale multi-point
monitoring, which cannot be used to analyze and characterize spatial changes, exerting a great impact on global climate change assessment. Therefore, it is necessary to take into consideration the time and spatial heterogeneity of different soil respiration monitoring methods.

(3) It is necessary to explore a more accurate, long-term and efficient soil respiration monitoring method based on the current methods and to appropriately select monitoring methods used in different soil environments by summarizing the advantages of different methods so as to calculate the soil respiration rate more accurately.

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