Assessment of the soil CO_2 gradient method for soil CO_2 efflux measurements

N. Pinginths[1,3], *M.Y. Leclerc[1],, J.P. Beasley[2] G. Zhang[1],C. Senthong[3]

[1]Lab for Environmental Physics, The University of Georgia, Griffin, Georgia, USA, [2]Crop and Soil Sciences Department, The University of Georgia, Tifton, Georgia, USA, [3] Department of Agronomy, Chiang Mai University, Chiang Mai, Thailand

*Corresponding author: Natchaya@uga.edu

Abstract

This paper uses a refined soil gradient method to estimate CO_2 efflux. To do so, six different models are used to determine the relative gas diffusion coefficient (ξ). A weighted harmonic averaging is used to estimate soil CO_2 diffusion coefficient, yielding a better estimate of CO_2 efflux. The resulting soil CO_2 efflux results are then compared to the soil CO_2 efflux measured with a soil chamber method. Depending on the choice of ξ model used, the estimated soil CO_2 efflux using the gradient method reasonably approximate the efflux obtained using the soil chamber method. In addition, the estimated soil CO_2 efflux obtained by this improved method is well described by an exponential function of soil temperature at a depth of 0.05 m with the temperature sensitivity (Q_{10}) of 1.81 and a linear function of soil moisture at a depth of 0.12 m, in general agreement with previous findings. These results suggest that the gradient method emerges as a practical cost-effective mean to measure soil CO_2 emissions. Results from the present study suggest that the gradient method can be used successfully to measure soil CO_2 efflux provided proper attention is paid to the judicious use of the proper diffusion coefficient.

Introduction

❖ Concerns over global climate change have generated an interest in quantifying the role of agricultural soils as sources/sinks of atmospheric CO_2.

❖ This incentive has spurred research in evaluating soil carbon budgets and in elucidating the factors influencing soil carbon storage in agricultural ecosystems (Lokupitiya and Paustian, 2006; Van Oost et al., 2007).

❖ Small changes in soil CO_2 released to the atmosphere can potentially contribute to a positive feedback between increasing temperature and enhanced soil CO_2 efflux as this can play a role in global warming.

❖ Reducing uncertainties associated with measurements of soil CO_2 are needed to improve the robustness of the carbon budget of terrestrial ecosystems.

Objectives

❖ To evaluate the feasibility of using the soil gradient method to estimate soil CO_2 efflux by comparing estimated soil CO_2 efflux results from different models in the relative gas diffusion coefficient calculation with the soil CO_2 efflux measured using the Li-8100 soil chamber.

❖ To understand the soil CO_2 efflux response to soil temperature (Ts) and soil moisture (θ).

Site, Materials, and Methods

Non-irrigated peanut field at the SWGA Research and Education Center, Plains, GA (Fig.1).

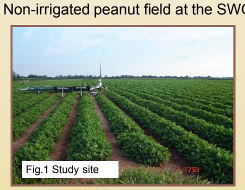

Fig.1 Study site

Fig.2 An automatic weather station

An automatic weather station (Fig. 2) monitored air temperature and RH, wind speed and direction, solar radiation and rainfall.

Acknowledgements: This research was funded by the Georgia Peanut Commission and the National Peanut Board. We would like to thank the Royal Golden Jubilee (RGJ) program of Thailand Research Fund (TRF) for providing a Ph.D. research scholarship. We wish to express our sincere appreciation to Mr. Bill Miller and Mr. Rod Madsen from LI-COR Inc. and Ms. Penny Hickey from Vaisala Inc. for kindly help and many suggestions regarding the operation of the devices. We also wish to thank the staff of the SWGA Research and Education Center for their logistical support in conducting this research on the premises.

Soil CO_2 efflux-gradient method

Fick's first law:

$$F_s = -D_s \frac{\partial C}{\partial z} \quad \text{and} \quad D_s = \xi D_a$$

D_s for the entire soil profile was estimated based on harmonic averaging of individual diffusivity of each layer.

$$D_s = \frac{\sum_{k=1}^{n} \Delta z_k}{\sum_{k=1}^{n} \frac{\Delta z_k}{D_{sk}(\theta_k)}}$$

D_{sk} represents D_s for the discrete layer k of thickness z, and θ for θ_k , n is the number of layers within the entire soil profile.

Six different models were used to compute ξ.

$$\xi = 0.66(\varphi - \theta) \quad \text{(Penman, 1940)}$$

$$\xi = (\varphi - \theta)^{1.5} \quad \text{(Marshall, 1959)}$$

$$\xi = \frac{(\varphi - \theta)^{10/3}}{\varphi^2} \quad \text{(Millington and Quirk, 1961)}$$

$$\xi = 0.66(\varphi - \theta)\left(\frac{\varphi - \theta}{\varphi}\right)^{12-3/3} \quad \text{(Moldrup et al., 1997)}$$

$$\xi = \varphi^2\left(\frac{\varphi - \theta}{\varphi}\right)^{2.9S} \quad \text{(Moldrup et al., 1999)}$$

$$\xi = \frac{(\varphi - \theta)^{2.5}}{\varphi} \quad \text{(Moldrup et al., 2000)}$$

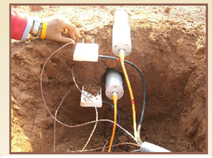

Fig.3 Soil CO_2 gradient system.

- GMP343 (Vaisala Corp., Vantaa, Finland) and θ at depth of 0.02 and 0.12 m (Fig. 3)
- T_s at depth of 0.02, 0.05, 0.12, and 0.30 m
- 30-min average

F_s is the soil CO_2 efflux (μmol m^{-2} s^{-1})
D_s is the soil CO_2 diffusion coefficient (m^2 s^{-1})
D_a is the CO_2 diffusion coefficient in the free air (m^2 s^{-1})
C is the CO_2 concentration at a certain depth of soil (μmol m^{-3})
z is the depth (m)
ϕ is the porosity (0.54 in this site)
S is silt + sand content (0.70 in this site)
ξ is the gas tortuosity factor

Soil CO_2 efflux-chamber method

Fig.4 Li-8100 soil CO_2 flux system

- Five soil collars were inserted into the soil in the vicinity of the soil CO_2 gradient system in the sampling plot.
- Periodic measurements of soil CO_2 efflux were made using a Li-8100 soil CO_2 flux system (Licor, Lincoln, NE) equipped with a 10 cm survey chamber (Fig. 4).
- In the present analysis, we used the average of the measurements across all five collars in the same 30-min period.

Results

Results show a better agreement with soil chamber measurements when the weighted harmonic averaging is used (Fig.5). Furthermore, the six different models were compared to estimate the relative gas diffusion coefficient. The estimated soil CO_2 efflux using the soil gradient method was found to differ between 3 and 173% from the mean of soil CO_2 efflux values across all five collars obtained using the soil chamber method depending on the choice of the model used (Table 1).

Variations in soil CO_2 efflux were dependent on changes in Ts and θ. The functional relationships of soil CO_2 efflux to Ts and θ can be described well by exponential and linear equation, respectively.

The counterclockwise hysteresis in the relationship between half-hourly soil CO_2 efflux and soil Ts at the 0.02 m depth suggests a differential response of soil CO_2 efflux to soil warming and to soil cooling (Fig. 6).

Table 1 Summary of parameters describing the linear regression relationships between soil CO_2 efflux from Li-8100 chamber and estimated CO_2 efflux by gradient method with different gas diffusivity model.

Gradient Method	Estimated Soil CO_2 Flux (μmol m^{-2} s^{-1})			Parameter		
Gas Diffusivity Model	Max	Min	Average	Slope	Intercept	R^2
Penman (1940)	4.22	1.08	2.54	2.73±0.22	0.07±0.20	0.61
Marshall (1959)	4.04	1.06	2.44	2.59±0.20	0.09±0.19	0.62
Millington and Quirk (1961)	2.56	0.74	1.56	1.58±0.12	0.13±0.11	0.66
Moldrup et al. (1997)	1.69	0.51	1.03	1.03±0.07	0.10±0.07	0.67
Moldrup et al. (1999)	2.98	0.83	1.81	1.88±0.13	0.11±0.13	0.64
Moldrup et al. (2000)	2.53	0.68	1.53	1.61±0.12	0.08±0.11	0.63
Soil Chamber Method	1.52	0.53	0.91			

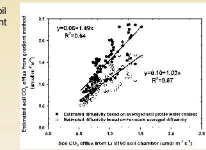

Fig. 5 Relationship between soil CO_2 efflux from Li-8100 chamber and estimated CO_2 efflux using the gradient method and two approaches for estimating soil gas diffusivity, based on averaged soil profile water content and based on harmonic averaged diffusivity.

Table 2 Fit of equation $F_s(T_s)=ae^{bTs}$ to access the relationship between Fs and soil temperature and $F_{s,E}/F_s(T_s)=c+d\theta$ to access the relationship between temperature normalized efflux and soil water content.

Soil Temperature Soil Depth (m)	Parameter			
	a	b	Q_{10}	R^2
0.02	0.54±0.03	0.02±0.00	1.24	0.27
0.05	0.23±0.02	0.06±0.00	1.81	0.54
0.12	0.14±0.01	0.08±0.00	2.23	0.53
0.30	0.07±0.02	0.11±0.01	3.03	0.28
Soil Water Content Soil Depth (m)	**Parameter**			
	c	d		R^2
0.02	0.41±0.03	9.61±0.42		0.59
0.12	1.50±0.07	17.61±0.54		0.74

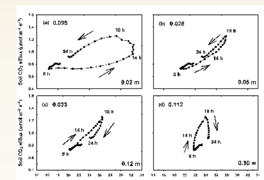

Fig. 6 Relationship between soil CO_2 efflux determined with the gradient method using the Moldrup et al. (1997) model to obtain and soil temperature at the depths of (a) 0.02, (b) 0.05, (c) 0.12, and (d) 0.30 m. The arrows indicate the direction of the hysteresis effect. The numbers indicate the mean absolute residual. Residual values calculated as the difference between measured soil CO_2 efflux and modeled values were used to assess the magnitude of hysteresis.

Conclusions

❖ The choice of the relative gas diffusion coefficient model was demonstrated to be important when the soil CO_2 gradient method is performed.

❖ The weighted harmonic averaging of soil CO_2 diffusion coefficient produces the soil CO_2 efflux comparable to that of the soil chamber method.

❖ The functional relationships of soil CO_2 efflux to soil temperature and soil moisture and the existence of hysteresis between soil CO_2 efflux and soil temperature from this study are consistent with previous findings, confirming that the soil gradient method combined with weighted harmonic averaging for diffusion coefficients can reliably be used to measure soil CO_2 emissions.

❖ For the purpose of minimizing errors potentially leading to a low correlation between soil CO_2 efflux data obtained using the soil chamber method and the soil gradient method, the authors recommend that the soil CO_2 concentration be measured at several depths to provide more CO_2 efflux values at various soil levels to allow the determination of the CO_2 efflux at the surface.

❖ The implication from the present study is to combine both the soil chamber method and the soil gradient method, i.e., to get an average of soil CO_2 efflux through multi-spatial samples with the soil chamber method and correct the continuous point soil CO_2 efflux measurement of the soil gradient method based on the linear relationship between the soil CO_2 effluxes from each method.

Referernces

Lokupitiya, E. and Paustian, K. 2006. Agricultural soil greenhouse gas emissions: a review of national inventory methods. *J. Environ. Qual.* **35**, 1413-1427.

Van Oost , K., Quine, T.A., Govers, G., De Gryze, S., Six, J., and co-authors. 2007. The impact of agricultural soil erosion on the global carbon cycle. *Science* **318**, 626-629.