Sensors and Materials, Vol. 34, No. 12 (2022) 4639–4650
MYU Tokyo

S & M 3134

Soil CO_2 Concentration and Efflux in Pine Forest Plantation Region in South Korea

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(Received October 21, 2022; accepted December 8, 2022)

Keywords: forest soil, soil respiration, soil CO_2 storage, Korean pine, *Pinus koraiensis*

We conducted research to confirm the applicability of a soil CO_2 measurement system to estimate changes in the level of soil carbon storage. We monitored the soil surface CO_2 efflux (F_c), layer CO_2 concentration (C_c), temperature (T_s), and moisture (Θ) monthly from September 2018 to September 2020 at 18 locations in a 20-year-old *Pinus koraiensis* stand in South Korea. The recorded average F_c, C_c, T_s, and Θ were 519.8 mg C m^{-2} h^{-1}, 1775.7 ppm, 12.1 °C, and 13.9%, respectively. The observed F_c and C_c values increased during the growth season (April–October); however, F_c (Q_{10} = 2.19) was more sensitive to temperature changes than C_c (Q_{10} = 1.74). To investigate the effects of Θ on F_c and C_c, they were normalized at T_s = 10 °C to F_{10} and C_{10}. To perform regression analysis, F_{norm} and C_{norm} were calculated by normalizing F_c and C_c to minimize the temperature effects. This Θ did not explain F_{norm} and C_{norm} well as a single independent variable. However, according to the results of multiple nonlinear regression analyses, C_{10} and Θ explained approximately 70% of F_{10} ($p < 0.0001$). To estimate the precise levels of soil carbon storage, it is essential that various types of forest and climate conditions be monitored.

1. Introduction

CO_2 is a primary greenhouse gas.(1) Recently, the importance of climate change has been raised globally, and policies are being taken to pursue net zero emissions of CO_2 by 2050. Forests are the most significant source of carbon sequestration in the terrestrial ecosystem.(2) The United Nations Framework Convention on Climate Change (UNFCCC) recognizes forests as the key for carbon storage and emphasizes their effect on reducing the atmospheric CO_2 concentration.

Net carbon sequestration in forests can be represented by the net ecosystem production (NEP), i.e., the difference between total carbon sequestration and total carbon emission. The Intergovernmental Panel on Climate Change (IPCC) proposed calculating the carbon sequestration of forests from changes in the level of total carbon storage by dividing carbon storage into six categories: aboveground biomass, belowground biomass, deadwood, litter, soil,

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https://doi.org/10.18494/SAM4185

and harvested wood products. NEP is a useful indicator because it is possible to understand the role of forests in the carbon cycle from the estimated NEP.[3]

In accordance with the IPCC guidelines, in South Korea, the change in the level of carbon storage in aboveground and belowground biomasses is calculated using the average annual growth rate and site index for each dominant species.[4,5] However, the calculation of the change in the level of carbon storage in aboveground and belowground biomasses does not reflect the understory carbon storage.[6,7] In addition, the calculation of carbon storage in deadwood, litter, and soil assumes the annual change in the level of carbon storage to be zero because of the lack of research relevant to these forms of carbon storage.[6,7] Therefore, there may be a large difference between the actual and estimated amounts of carbon sequestration, but owing to the difficulties in continuously measuring the levels of carbon storage of deadwood, litter, and soil, this has not yet been studied. It is particularly difficult to accurately estimate the level of soil carbon storage because the formation and decomposition of organic carbon in the soil depend on seasonal effects and microbial activity, and show great spatial heterogeneity.[8–13]

Despite relevant research being carried out on the measurement of forest soil respiration using a soil chamber system, there has been little research on the comparison and quantification of rates of soil respiration through continuous measurement in various ecosystems. Studies measuring the CO_2 concentration in the soil layer are also scarce. The soil layer CO_2 concentration (C_c) results from the transfer of CO_2 from the atmosphere to the soil through photosynthesis and respiration. CO_2 in the soil affects its chemical properties and fertility, thus impacting the productivity of forests and the long-term carbon cycle process. Moreover, the current atmospheric CO_2 concentration continues to increase, which may lead to changes in the rates of photosynthesis, respiration, and soil organic carbon stock.[14,15] Microorganisms that use carbon stored in the soil for respiration show an exponential increase in respiration rate as the temperature increases; therefore, an increase in temperature is predicted to change the amount of carbon stored in the soil and the CO_2 concentration in the atmosphere. For these reasons, measuring C_c will help understand the forest carbon cycle and how CO_2 is released into the atmosphere. This study presents a method of estimating the rates of soil respiration and CO_2 stock in a forest accurately using a soil surface CO_2 efflux (F_c) and C_c measurement system. In addition, we estimate the rate of soil respiration and the level of soil CO_2 storage using soil climatic factors.

2. Materials and Methods

2.1 Study site

The study site was a 20-year-old *Pinus koraiensis* Siebold and Zucc. (Korean pine) stand located in the experimental forest of the National Institute of Forest Science (38˚00058.700 N, 127˚48031.200 E; 370 m elevation) in Gangwon Province, Korea. Its soil type was Mui Series (coarse loamy, mixed, Typic Humudepts) according to the U.S. Soil Taxonomy. The average organic matter content and bulk density of the soil were 4.4% and 0.98 g m^{-3}, respectively, at a soil depth of 0–30 cm, and the slope gradient ranged from 21 to 57% in this study site. The dominant forest species in the study site was *P. koraiensis* with a stocking density of 448.6 trees per ha and a timber volume of 279.9 m^3 per ha. The 30-year mean annual precipitation was 1358.7 mm with average minimum and maximum temperatures of –18.5 and 35.2 °C, respectively.

We monitored the soil temperature (T_s) and moisture (Θ), F_c, and C_c once a month from September 2018 to September 2022, excluding the winter season (December–February; 18 measurement days). In the study site, we selected 18 measurement points randomly (Fig. 1). Every measurement was conducted between 11:00 and 14:00 (GMT +9).

2.2 Soil CO_2 efflux measurement using soil chamber system

Closed dynamic chambers were used to calculate the soil CO_2 efflux (Fig. 2).[16] In this method, the flux was calculated from the rate of change in CO_2 concentration (ppm) as

$$F_{c,s} = \frac{\partial[\mathrm{CO_2}]_c}{\partial t}\left(\frac{m_w}{m_v}\right)\left(\frac{V}{A}\right), \tag{1}$$

where V is the total chamber volume of the system, A is the area covered by the chamber, m_w is the molecular weight, and m_v is the CO_2 volume.

Using closed dynamic chamber methods, we installed 18 soil collars on the study site. We used a GMP343 (Vaisala CARBOCAP®, Helsinki, Finland) CO_2 measuring instrument, which uses nondispersive IR (NDIR) methods to measure the CO_2 concentration by drawing in CO_2 without gas capture (Fig. 2). The factorial calibration of the instrument was conducted using the correct gas at various concentrations (0, 200, 370, 600, 1000, and 4000 ppm and 2 ± 0.5%). In

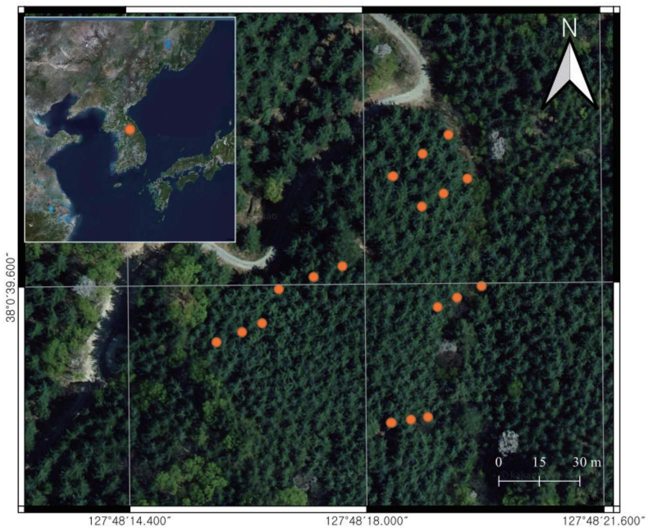

Fig. 1. (Color online) Location of the measurement points (orange dots) in *P. koraiensis* stand in Gangwon Province, Korea.

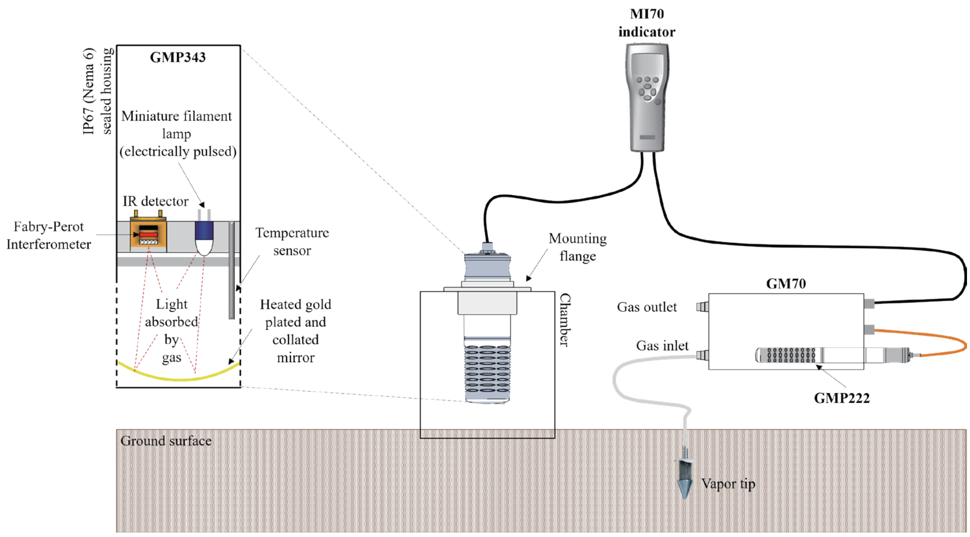

Fig. 2. (Color online) Schematic of the F_c and C_c measurement system.

addition, calibration was performed at various temperatures (–30, 0, 25, and 50 °C). The accuracy at 25 °C and 1013 hPa after factory calibration with 0.5% gases was determined to be ± (3 ppm + 1% of reading) at 0–1000 ppm and ± (5 ppm + 2% of reading) at 0–2000 ppm and 0–2% gases. The CO_2 concentration was measured simultaneously with the temperature and confirmed in real time using an MI70 indicator (Vaisala, Finland). In this study, data were measured and stored at 5 s intervals for 5 min. The soil surface CO_2 efflux was calculated as F_c from the linear increase in CO_2 concentration as follows:

$$F_c = \text{Soil surface } CO_2 \text{ efflux}\left(\text{mg C m}^{-2}\text{h}^{-1}\right) = E_x + E_i, \tag{2}$$

where E_x is the increase in soil CO_2 efflux measured at 5 s intervals, and E_i is the initial soil CO_2 efflux. We monitored the soil CO_2 efflux over time and calculated a linear regression line up to the point where the rate of soil CO_2 efflux starts to decrease.

2.3 Soil CO_2 concentration measurement

C_c was measured using a handheld CO_2 probe (GM70, probe type GMP 222, range: 0–5000 ppm, accuracy: range of ± 1.5%, reading of + 2%, Vaisala CARBOCAP®, Helsinki, Finland) for 5 min (Fig. 2). This measurement was performed immediately after measuring F_c to avoid disturbing the measurement of F_c due to air intake during C_c measurement. In total, 18 vapor tips (mesh-covered for air suction) were installed at a soil depth of 10–15 cm in July 2018. Silicon tubes (internal diameter of 3 mm) connected to the vapor tips extended from the soil surface. CO_2 gas from the perforated tube hole was measured for 5 min as the probe drew in gas from the soil.

2.4 Soil temperature and moisture

T_s was measured using a TP3001 digital thermometer and Θ was measured using probe sensors (TDR 300, FieldScout) in the form of volumetric water content (%). T_s and Θ were repeatedly measured five times around each soil collar. We inserted the temperature (14.5 cm length) and moisture probe sensors (approximately 19 cm length) into the soil surface vertically. T_s and Θ were measured immediately after measuring F_c and C_c.

2.5 Data analysis

All statistical analyses were conducted in R v. 3.6.0 and significance was set at $p \leq 0.05$. To assess the effects of soil temperature on the rate of soil respiration, the following first-order exponential function was fitted to the data:

$$F_c = \beta_0 \times \exp\left(\beta_1 \cdot T_s\right), \tag{3}$$

where β_0 and β_1 are the fitting parameters, and T_S is the measured soil temperature. Q_{10} was calculated as 2.19 for F_c and 1.74 for C_c using

$$Q_{10} = \exp\left(10 \cdot \beta_1\right). \tag{4}$$

Given that the rate of soil respiration in the research area was measured at different times of the day (11:00–14:00), it is probable that the temperature differed with the time of measurement. To control differences in T_s when analyzing the effects of Θ on F_c and C_c in the study site, F_c and C_c were normalized to the daily mean soil temperature using Q_{10} as follows:

$$F\left(C\right)_{norm} = F\left(C\right)_{10} \times Q_{10}^{\left(\left(T_{daymean} - T_s\right)/10\right)}, \tag{5}$$

where F_{10} and C_{10} are measured data normalized to a soil temperature of 10 °C using Eq. (6) and $T_{daymean}$ is the average T_s for the same measurement day.

$$F\left(C\right)_{10} = F_c \times \exp\left(\beta_1\left(T_s - 10\right)\right) \tag{6}$$

We performed single and multiple nonlinear regression analyses to estimate the relationships between F_c, T_s, Θ, and water content. Multiple nonlinear regression was used to estimate the combined effects of Θ and soil CO_2 concentration on F_c. The nonlinear regression model [Eq. (7)] used the Gaussian method,

$$F_{10} = a \times \exp\left(-0.5\left[\left(\frac{x-x_0}{b}\right)^2 + \left(\frac{y-y_0}{c}\right)^2\right]\right), \quad (7)$$

where x is C_{10} and y is Θ.

3. Results

3.1 Seasonal variations in T_s and Θ

From September 2018 to September 2020, the average T_s in the study site from 11:00 to 14:00 was 12.1 °C and the average Θ was 13.9% (Fig. 3). The average T_s recorded a maximum of 22 °C in July 2019 and a minimum of 3.2 °C in December 2018 (Fig. 3). The annual plant growth period is from April to October; T_s began to increase in April and decreased to the level in the pre-growth period after October (Fig. 3). The average Θ recorded a maximum of 21.1% in August 2020, when there was an unusually large amount of precipitation during the rainy season, but there was no clear tendency for Θ to be high during the rainy season throughout the study period (Fig. 3).

3.2 Soil respiration and CO_2 production

During the study period, the average F_c was 519.8 mg C m^{-2} h^{-1}, the average F_{10} was 823.5 mg C m^{-2} h^{-1}, and the average F_{norm} was 612.4 mg C m^{-2} h^{-1} [Fig. 4(a)]. The average C_c was 1775.7 ppm, the average C_{10} was 2317.3 ppm, and the average C_{norm} was 1988.6 ppm [Fig. 4(b)]. F_c recorded a low of 125.1 mg C m^{-2} h^{-1} in December 2018 and a high of 1110.4 mg C m^{-2} h^{-1} in September 2019 [Fig. 4(a)]. C_c reached a low of 766.4 ppm in March 2019 and a high of 3291.9 ppm in July 2019 [Fig. 4(b)]. There appears to be a lag time of approximately two months from

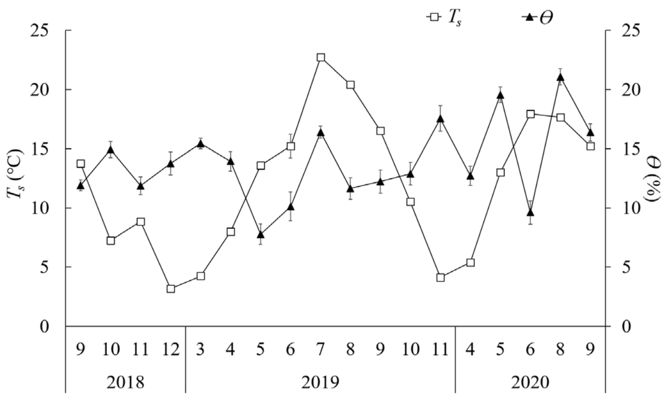

Fig. 3. Seasonal variations in T_s and Θ from September 2018 to September 2020. Each value shows the average of the 18 data points for that day. Error bars represent the standard error.

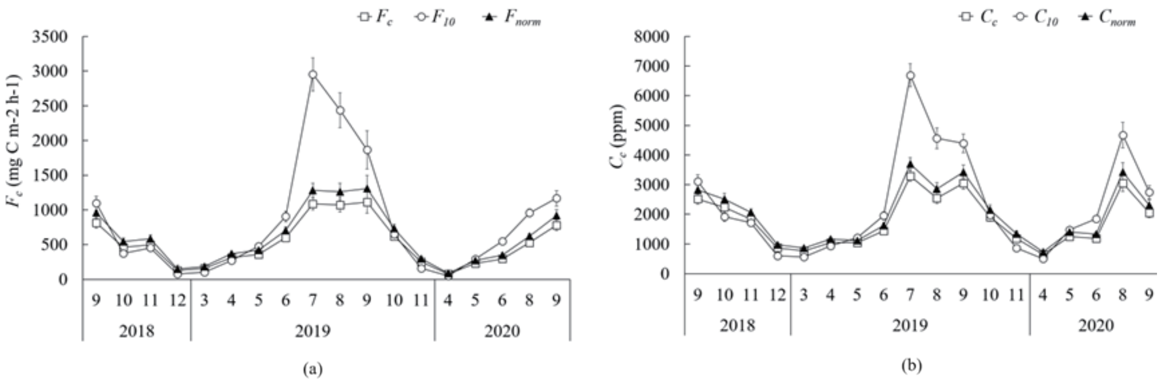

Fig. 4. Seasonal variations in (a) F_c, F_{10}, and F_{norm} and (b) C_c, C_{10}, and C_{norm} from September 2018 to September 2020. Each value shows the average of the 18 data points for that day. Error bars represent the standard error.

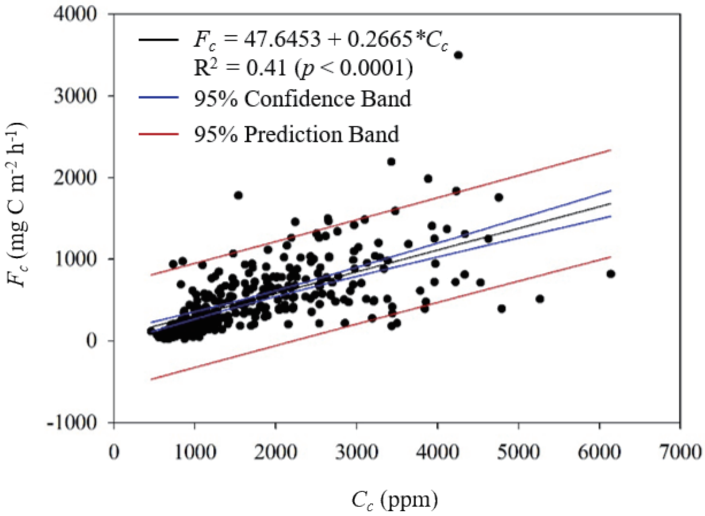

Fig. 5. (Color online) F_c as a function of C_c in the study site from September 2018 to September 2020.

the time C_c reached its peak to the time F_c reached its peak (Fig. 4). Nevertheless, the timing of the increases or decreases in C_c and F_c was found to be similar (Fig. 4). Although soil respiration is generally viewed as a consequence of soil CO_2 production by the root systems and microbial activity in the soil, C_c could only account for about 41% of F_c (Fig. 5).

3.3 Relationship among F_c, C_c, T_s, and Θ

T_s explained C_c ($R^2 = 0.41$) better than F_c ($R^2 = 0.33$) as a single independent variable [$p <$ 0.0001; Figs. 6(a) and 6(b)]. Therefore, we explored the possibility that C_c can represent CO_2 production by root respiration and microbial activity in the soil. However, Θ did not explain well the variances of F_{norm} and C_{norm}, which minimized the effect of T_s change (Table 1). From these results, even with F_c and C_c normalized, Θ has poor explanatory power as a single variable.

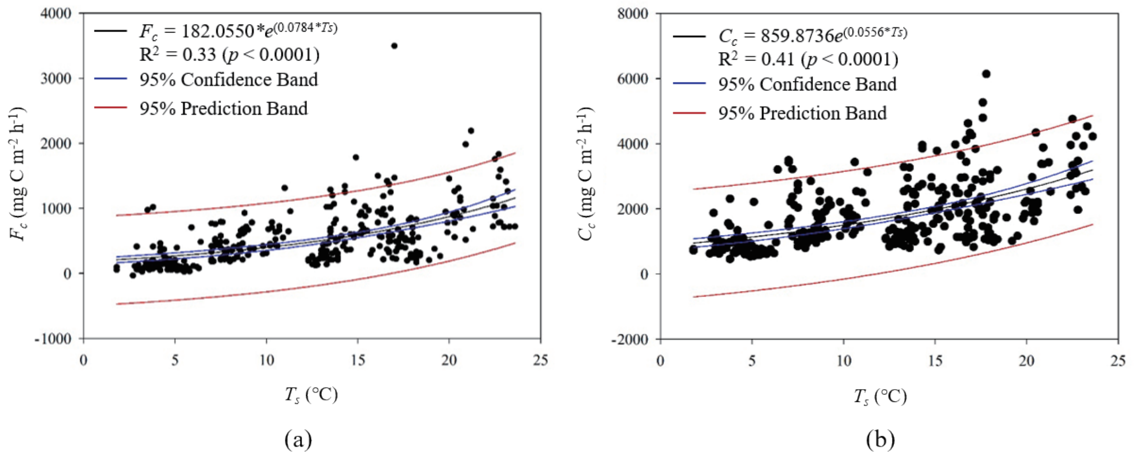

Fig. 6. (Color online) (a) F_c and (b) C_c as functions of T_s in the study site from September 2018 to September 2020.

Table 1
Results of nonlinear regression analysis to estimate the responses of F_{norm} and C_{norm} to Θ.

Dependent variables (Average ± S.E.)	Eq. (3)[a]		
	R^2	F	p
F_{norm} (612.4 ± 27.5 mg C m^{-2} h^{-1})	0.0463	7.7754	0.0005
C_{norm} (1988.6 ± 63.6 ppm)	0.0107	1.7279	0.1793

[a] $R = a\Theta^2 + b\Theta + c$

We conducted a nonlinear regression analysis to estimate the response of F_{10} to C_{10} and Θ (Fig. 7). F_c appears to be more sensitive to changes in Θ when C_c is high and decreases when Θ is below 15% (Fig. 7). However, our regression model had limitations in explaining all the variations in F_c ($R^2 = 0.7$, $p < 0.0001$). These results demonstrate that to estimate the rate of soil respiration accurately, it is necessary to consider dependent variables such as physical soil characteristics and topography in addition to T_s, Θ, and the level of soil CO_2 production.

4. Discussion

The vegetation type and topographical features affect the physicochemical properties of soil, and such effects are reflected in soil respiration, thus causing spatiotemporal inhomogeneity in soil respiration.[11–13] The nonuniformity of soil respiration is a major factor in identifying the carbon balance in the soil and lowers the accuracy of predicted changes in the percentage of atmospheric and stored carbon under the effects of environmental fluctuations, such as climate change. As soil respiration is dependent on temporal and spatial characteristics, continuously accumulating soil respiration data for various forest environments is necessary for understanding forest soil respiration. However, such research has been sporadic in South Korea.

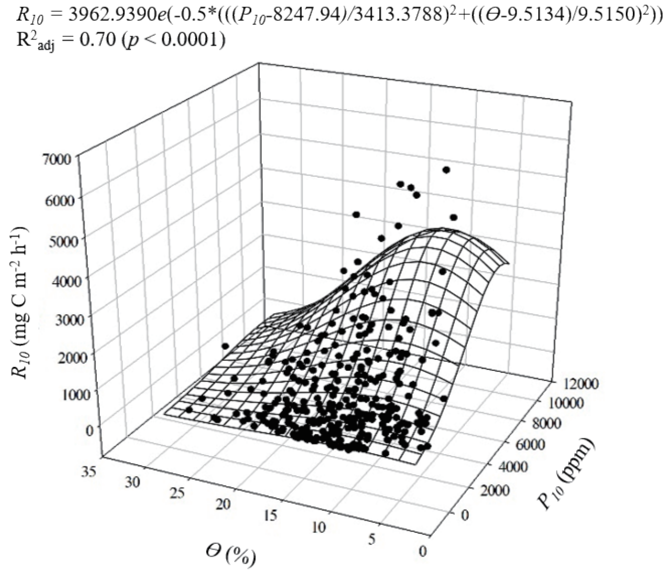

Fig. 7. Scatter plots including regression model to estimate the response of F_{10} to C_{10} and Θ from September 2018 to September 2020 in the study site.

The results of this study may also be considered as those of a sporadic study on soil respiration. However, it is meaningful to present our result for soil respiration. The average F_c was 519.8 mg C m^{-2} h^{-1} in this study. Pyo *et al.* reported that the average F_c was 570 mg C m^{-2} h^{-1} in a *P. koraiensis* stand in South Korea.(17) Also, Ivanov *et al.* reported that F_c was about 713.25 mg C m^{-2} h^{-1} in four *P. koraiensis* stands (with ages of 50, 80, 130, and 200 years) in Russia at an annual temperature of 4 °C.(18)

In general, F_c, which is used to estimate soil respiration, reflects the activities of roots and microorganisms that depend on the environmental conditions of forests, and reflects the gas exchange between the soil and the atmosphere.(19,20) Although soil respiration is considered as a direct result of soil CO_2 production, C_c only explained about 41% of F_c in this study. This may be due to the failure to consider the physical properties of soil such as pore characteristics. CO_2 produced in the soil is released to the surface through a gas exchange process between the soil and the atmosphere and in a manner dependent on the size and continuity of soil pores, the size of soil particles, and air-filled porosity.(20–22) Therefore, it is necessary to consider the physical properties of soil when estimating the amount of soil respiration in a forest.

Soil respiration depends on the weather, location, and environmental conditions. In general, the rate of ecological respiration increases significantly during the rainy season, when there is intensive rainfall.(23,24) A low soil moisture content inhibits root growth and activity, but when a sufficient soil moisture content is recovered during the rainy season, the roots actively respire to obtain water and nutrients from the soil.(25–27) In this study, F_c was highest when the soil moisture content was 10–15%. Previous studies found that the fine root growth of *P. koraiensis* increased significantly during and after the rainy season.(28,29) However, F_c significantly decreased when the soil moisture content increased to a value above 15%.

C_c represents not only the CO_2 production but also the storage of CO_2 in soil. However, studies have recently reported that the increases in temperature and atmospheric CO_2 concentration and the changes in precipitation patterns due to climate change can significantly affect the carbon storage capacity of soil.[14,15] If rates of soil CO_2 emission are excessively high, soil can instead act as a source of carbon emission. Therefore, it is necessary to establish a system for monitoring soil respiration and CO_2 storage. Our study found that C_{10} and soil moisture could explain approximately 70% of F_{10}. Therefore, the monitoring system used in this study will help understand the role of soil in the carbon cycle during a changing climate. Furthermore, it will be helpful in the future development of an optimal soil respiration evaluation model that considers the physical properties of forest soil.

5. Conclusion

In this study, we estimated the rate of soil respiration accurately by measuring soil CO_2 efflux and soil CO_2 concentration. The average CO_2 concentration at a soil depth of 10–15 cm was found to be more than four times higher than the atmospheric CO_2 concentration. This indicates that forest soil stores a large amount of carbon. Our results also showed that soil CO_2 efflux (Q_{10} = 2.19) is more sensitive to temperature changes than soil CO_2 concentration (Q_{10} = 1.74). Therefore, it is necessary to monitor soil CO_2 efflux continuously to understand the response of soil respiration to increases in temperatures caused by climate change. In addition, soil CO_2 concentration and moisture content accounted for 70% of the soil CO_2 efflux. Measuring the soil CO_2 concentration will help understand the carbon cycle in forest soil. The monitoring system in this study can be used to estimate the changes in the level of carbon storage in forest soil.

Acknowledgments

This research was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT; NRF-2021R1A2C2008002).

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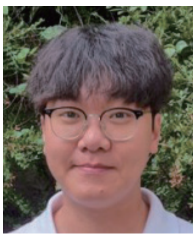

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Supplementary

Table S1
Averages and standard errors (±S.E.) of T_s, Θ, F_c, and C_c at various measurement points during study period.

Measurement point	T_s (°C)	Θ (%)	F_c (mg C m^{-2} h^{-1})	C_c (ppm)
1	12.04 ± 1.31	14.11 ± 1.06	459.65 ± 66.97	1325.55 ± 135.78
2	12.34 ± 1.34	14.63 ± 0.99	458.41 ± 73.38	1812.65 ± 212.57
3	12.17 ± 1.31	13.91 ± 0.83	678.75 ± 113.22	1779.71 ± 216.94
4	12.09 ± 1.41	16.81 ± 0.84	344.38 ± 58.65	1318.43 ± 118.27
5	12.27 ± 1.45	22.63 ± 1.18	271.31 ± 41.80	2158.86 ± 280.02
6	11.89 ± 1.39	15.07 ± 0.80	373.52 ± 63.50	1662.14 ± 236.59
7	11.63 ± 1.42	13.37 ± 0.97	455.11 ± 70.19	1937.82 ± 268.11
8	11.82 ± 1.34	11.90 ± 1.13	465.51 ± 85.17	1573.57 ± 219.96
9	12.02 ± 1.36	12.65 ± 0.97	502.86 ± 98.59	1292.43 ± 123.95
10	11.99 ± 1.38	16.13 ± 0.96	328.07 ± 48.88	1676.57 ± 205.31
11	12.22 ± 1.36	10.02 ± 0.93	651.64 ± 108.75	2010.95 ± 298.04
12	12.31 ± 1.36	12.91 ± 0.89	493.23 ± 62.17	1302.26 ± 130.01
13	11.78 ± 1.36	12.51 ± 0.83	709.36 ± 104.63	2110.50 ± 275.08
14	11.60 ± 1.43	11.83 ± 0.98	939.27 ± 189.56	2371.74 ± 275.00
15	11.74 ± 1.39	15.26 ± 0.86	557.87 ± 91.08	1557.99 ± 172.56
16	12.49 ± 1.40	12.25 ± 0.95	577.34 ± 75.72	1694.14 ± 222.33
17	12.58 ± 1.40	10.89 ± 0.91	463.14 ± 79.51	2461.32 ± 297.38
18	12.67 ± 1.40	12.94 ± 0.94	626.79 ± 115.65	1916.38 ± 226.11
Sum	12.09 ± 0.33	13.88 ± 0.27	519.79 ± 23.37	1775.71 ± 56.51