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온대 낙엽 활엽수림에서의 강수량에 따른 메탄 흡수 감소

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Precipitation Decreases Methane Uptake in a Temperate Deciduous Forest

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ABSTRACT

Soil moisture regulates the fate of methane (CH_4) in forest soil via biological and chemical processes. The instant effect of variable precipitation on CH_4 uptake is, however, unclear in the forest ecosystems. Here, we measured CH_4 flux in a temperate forest soil immediately after variable volume of water applications equivalent to 10, 20 40, and 80 mm m^{-2} day^{-1} precipitation. CH_4 uptake was significantly higher when the water was not applied. The CH_4 uptake decreased significantly with increasing water application. CH_4 uptake was linked with air filled porosity and water filled porosity. CH_4 uptake response to actual precipitation intensity was in agreement with CH_4 uptake results in this study. CH_4 uptake decreased 55% at highest precipitation intensity. Since annual CH_4 flux is calculated with interpolation of weekly or biweekly field observations, instant effect of precipitation can mislead the interpolated annual results.

Key words : Methane; precipitation; intensity; temperate forest; uptake

1. Introduction

Methane (CH_4) with the atmospheric concentration of approximately 1.8 mg/L is the second most abundant greenhouse gas in the atmosphere after carbon dioxide (CO_2) (IPCC 2014). CH_4 contributes to 32% of the current radiative forcing and its global warming potential is 25 times higher than CO_2 (IPCC 2014). It explains approximately 18% of the recent increase in global temperature. Forest soils are recognized as an important sink for CH_4 (Reeburgh 2003). Approximately 9 to 42 Tg of CH_4 is oxidized in unsaturated soils worldwide per year (Kirschke et al., 2013). Temperate forest's ecosystems contribute 30-50% of total soil-based CH_4 sink worldwide (Dutaur and Verchot., 2007; Ojima et al., 1993).

CH_4 is produced by methanogens under anaerobic condition in subsoil and oxidized by methanotrophs under aerobic condition in topsoil (Le Mer and Roger 2001). CH_4 emission from the temperate forests is linked with biological, chemical, and physical changes in soil. It is mainly controlled by organic carbon substrate, soil temperature, soil water content, and so on (Smith et al., 2003; Von Fischer and Hedin., 2007). CH_4 production depends on the availability of organic carbon for methanogens, which is produced under anaerobic decomposition of organic matter such as plant biomass, leaf litter, and fine roots in soil (Dalal et al., 2008). Soil temperature controls microbial growth rate and subsequently CH_4 emission. Thirty degrees in Celcius is reported optimal temperature for microbial activity in soil (Gütlein et al., 2017; Moore et al., 2018). Soil water content in the forest soil controls diffusive transport of CH_4 in soil (Wei et al., 2018).

Soil submersion in water triggers methanogenic activity

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due to the formation of an anaerobic condition and it decreases methanotrophic activity by reducing the oxidized zone. CH_4 oxidation occurs at 20 to 60% of soil water content in dry season and it decreases at higher than 60% of soil water content in rainy reason (Castro et al., 1995). Temperate forest regions with lower precipitation are known for CH_4 oxidation (Castro et al., 1995). CH_4 oxidation is suppressed in wet summer due to the inhibition of oxygen diffusion and CH_4 production in anoxic microsites (Itoh et al., 2009). Forest soils can emit CH_4 in wet summer (e.g. Keller and Reiners., 1994; Weitz et al., 1999; Davidson et al., 2004; Vasconcelos et al., 2004; Teh et al., 2005). CH_4 dynamics in forest soils may differ in regions with heavy summer precipitation. Itoh et al. (2009) reported CH_4 oxidation -0.45 kg ha^{-1} y^{-1} in a dry season and CH_4 emission 1.80 kg ha^{-1} y^{-1} in a rainy season. Wetting of dry soils generally increases the microbial activity within minutes (Borken et al., 2003; Lee et al., 2004; Sponseller 2007) or hours (Pulleman & Tietema., 1999; Prieme & Christensen., 2001). Diffusion of CH_4 from the atmosphere into soil usually explained with Fick's first law (Ishizuka et al., 2000; Nakano et al., 2004; Wang et al., 2014). Soil water content controls CH_4 uptake by regulating CH_4 diffusion from the atmosphere into mineral soils (Castro et al., 1994; Czepiel et al., 1995; Whalen and Reeburgh., 1996). Soil wetting and drying experiments revealed significant reduction in CH_4 uptake with wetting (Kim et al., 2012). Kessavalou et al., (1998) reported that CH_4 uptake declined by about 60% after rewetting of dry soil. To best of our knowledge instant effect of variable intensity of precipitation on CH_4 uptake has not been reported. Moreover, CH_4 fluxes in forest soils are monitored weekly or biweekly using manually closed chamber method and then results are interpolated to estimate annual fluxes. Instant change in CH_4 flux due to precipitation may mislead the total annual CH_4 flux. Precipitation varies throughout a year and this variation affects soil moisture, which thereby affects CH_4 uptake or emission. The objectives of this study were to investigate the instant effect of variable precipitation on CH_4 uptake and to estimate the contribution of precipitation in reducing net CH_4 uptake in temperate forest. We hypothesized that CH_4 emission will occur when it starts to rain because rain water will replace CH_4 present in subsoil. CH_4 uptake may decrease after precipitation due to water-filled pore space and in result limited space for atmospheric CH_4 uptake.

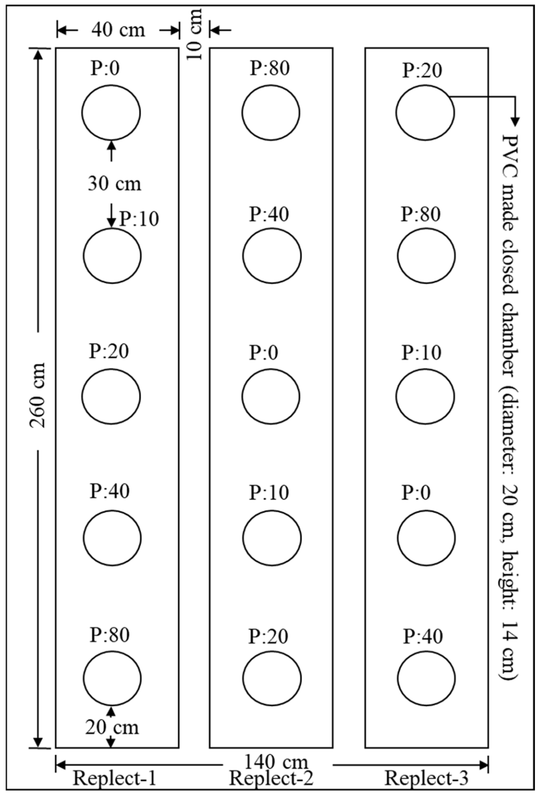

Fig. 1. On field experimental treatments to determine the effect of variable precipitation on CH_4 uptake.

2. Materials and Methods

The experiment was conducted in a mature Platanus occidentalis forest on Hanyang University campus, Seoul, Republic of Korea (37°33'33"N, 127°02'47"E). The soil texture was sandy loam with sand, silt, and clay proportions of 55.1, 33.8, and 11.1%, respectively. Daily temperature and precipitation varied between -18.6 to 36.7°C and 0.1 to 260 mm, respectively (Korea Metrological Administration 2010-2017).

Three experimental plots were located as shown in Fig. 1. Each plot was 40 × 260 cm and distance between two adjacent plots was 10 cm. Each plot comprised with five treatments such as P-0, P-10, P-20, P-40, and P-80, where (P) is precipitation and the number followed by P is amount of the water equivalent to precipitation (mm day^{-1}). The water 0.34, 0.67, 1.35, and 2.69 L was sprayed in P-10, P-20, P-40, and P-80, respectively. Water was sprayed inside the chamber bases on alternate gas sampling days. When water was not sprayed we assume no precipitation (NP), henceforth mentioned as (NP-0, NP-10, NP-20, NP-40, and NP-80). To minimize soil disturbance, one plot was exclusively dedicated for soil sampling and remaining two plots were used for gas sampling. P-0 was used as control treatment and water was not sprayed in this treatment. The volume of water for corresponding precipitation that was calculated by using guidelines of food and agriculture organization (Dastane 1978). The volume of water used in this experiment was within the range of average daily precipitation 0.1 to 260 mm in 2010-2017 (Korea Metrological Administration 2010-2017). The volume of water corresponded to precipitation below 10 mm was too low to spray on given surface area of chamber. Precipitation above 80 mm was much higher than the volume of closed chamber above ground. Therefore, treatments for precipitation below 10 mm and above 80 mm were not installed were not installed.

Five polyvinyl chloride (PVC) chamber bases of (20 cm diameter and 20 cm height) were randomly inserted 5 cm into the ground in each plot. An air-tight lid made of PVC was kept on the chamber base for one hour and a 30 mL gas sample was collected from the chamber at 0, 15, 30, 45 and 60 min after chamber closure. All gas samples were stored in 25 mL glass vials sealed with aluminum caps and gray butyl septa. Samplings were conducted between 09:00 to 10:00 between 14^{th} September to 15^{th} October in 2018 every third day. Gas samples were analyzed using a gas chromatograph (YL 6100, Young Lin Instrument Co., Korea) equipped with a flame ionization detector and GS-Alumina Agilent column (length, 50 m; inner diameter, 0.53 mm). The temperatures of the column, injector, and detector were 120, 250, and 250°C, respectively. Helium was used as the carrier gas at a flow rate of 30 ml min^{-1}.

Hourly CH_4 flux was calculated from the change in gas concentration over 60 min chamber closure for first experiment and 30 min closure for second experiment (Rolston 1986):

$$F = \frac{V}{A} \times \frac{dc}{dt} \times \left(\frac{273}{273+T}\right) \quad (1)$$

where F is the hourly CH_4 flux ($\mu g\ m^{-2}\ h^{-1}$), V is the gas volume (m^3), A is the area of the chamber base (m^2), and $\frac{dc}{dt}$ is the rate of CH_4 concentration change over a 60 min period in the chamber ($\mu g\ m^{-3}\ h^{-1}$).

Temperatures of ambient air, the air inside the chamber, and the soil were recorded at the time of CH_4 sampling. Soil temperature and water content were monitored at 10, 20, and 30 cm depth of one plot on each sampling day. Soil samples were collected inside the chambers using a sampling tube with 2.5 cm internal diameter and 100 cm height. Soil gravimetric water content (θ_g) was determined using the oven drying method at the controlled temperature of 105°C for 24 h. Bulk density (ρ_b) of soil was measured before and after the experiment at 10, 20 and 30 cm depth using core sampler. Soil samples for bulk density were collected outside and inside of each chamber before and after experiment, respectively. The volumetric water content (θ_v) was calculated as:

$$\theta_v = \rho_b \times \theta_g \quad (2)$$

Volumetric water content was converted into absolute air-filled porosity (AFP, $cm^3\ cm^{-3}$) knowing the bulk density (ρ_b) and the particle density of soil (ρs) with the equation (Epron et al., 2016):

$$AFP = (1 - \rho_b/\rho_s) - \theta_v \quad (3)$$

Soil particle density (ρ_s) was assumed 2.65 g cm^{-3} of rock, sand grains and other soil mineral particles (Gao et al., 2018; Zhu et al., 2013). The water-filled pore space (WFPS) was calculated with the equation (Gao et al., 2018):

$$WFPS = \theta_v/(1 - \rho_b/2.65) \quad (4)$$

Both AFP and WFPS were then converted in percent by multiplying with 100.

2.1. Statistical analysis

The SPSS 20 statistical software package was used for statistical analysis. Independent-sample t-test was used to test the significant difference between control and litter P-(0-80) and NP-(0-80) treatments. One-way ANOVA was used to test the significant difference between the results of CH_4 emission in all treatments of P-(0-80) and NP-(0-80). The difference level was set at $p<0.05$. linear regression analysis was performed to establish correlation between CH_4 uptake and (soil moisture content, soil temperature, AFP, and WFPS).

3. Results and discussion

Average CH_4 uptake in the entire experimental period was 30.6, 8.3, 5.6, 5.5, and 4.4 μg m^{-2} h^{-1} in P-0, P-10, P-20, P-40, and P-80, respectively. Average CH_4 uptake 29.3, 42.5, 44.4, 26.2, and 21.7 was observed in NP-0, NP-10, NP-20, NP-40, and NP-80, respectively (Fig. 2a). Average CH_4 uptake in P-0, P-10, P-20, P-40, and P-80 was 5, 80, 87, 79, and 80%, respectively, lower than NP-0, NP-10, NP-20, NP-40, and NP-80, respectively. Average CH_4 uptake in P-(10-80) was significantly lower than NP-(10-80) treatments (p=0.05). No significant difference was observed in control treatments P-0 and NP-0 (p=0.05). In all treatments, soil temperature decreased consistently throughout the experimental period (Fig. 2b). Maximal and minimal soil temperature was observed on September and October, respectively. Average soil temperature 17.9, 18.2, 18.5, 19.7, and 20.7°C was observed in P-0, P-10, P-20, P-40, and P-80, respectively. Relatively low temperature 16.4, 16.2, 16.1, 16.3, and 16.6 °C was observed in NP-0, NP-10, NP-20, NP-40, and NP-80, respectively. Soil temperature was not significantly different among the treatments in both P (0-80) and NP (0-80) (p=0.05). Soil temperature was positively correlated with CH_4 uptake in P-0, P-10, P-20, P-40, and P-80 (R^2=0.14, 0.49, 0.17, 0.44, and 0.12, respectively). Soil temperature was also positively correlated with CH_4 uptake in NP-0, NP-10, NP-20, NP-40, and NP-80 (R^2=0.74, 0.65, 0.57, 0.03, and 0.29, respectively). Average soil water content in entire experimental period was 20.8, 26.2, 24.4, 24.4, and 27.2% in P-0, P-10, P-20, P-40, and P-80, respectively. Average soil water content in NP-0, NP-10, NP-20, NP-40, and NP-80 was 22.3, 21.7, 20.5, 20.7, and 24.5, respectively. Statistically there was no significant difference in P (0-80) and NP (0-80) (p=0.05). Average soil water content was positively correlated with average CH_4 uptake in P-0, P-10, P-20, P-40, and P-80 (R^2=0.84, 0.61, 0.40, 0.64, and 0.13, respectively). Average soil water content was also positively correlated with average CH_4 uptake in NP-0, NP-10, NP-20, NP-40, and NP-80 (R^2= 0.40, 0.64, 0.10, 0.40, and 0.96, respectively).

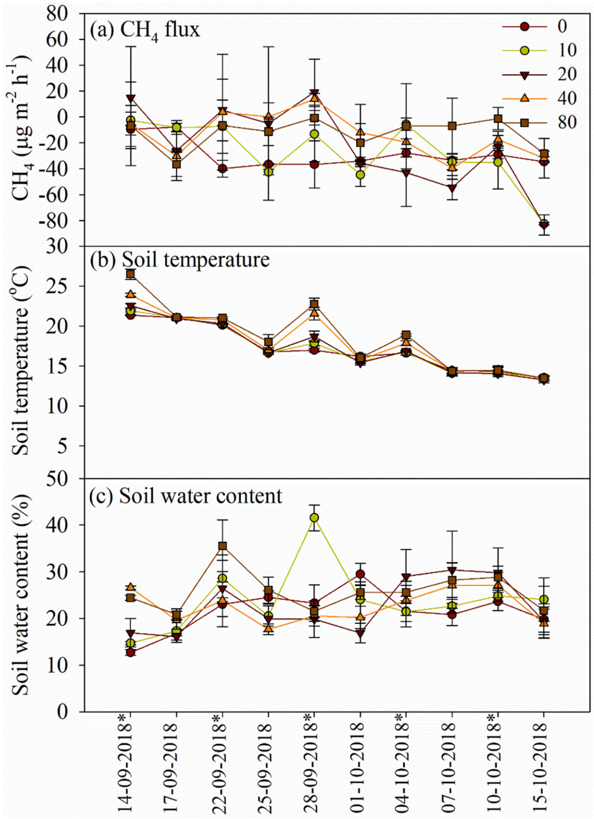

Fig. 2. (a), CH_4 flux; (b), soil temperature; and (c), soil water content with variable precipitation 0, 10, 20, 40, and 80 mm per day. Error bars represent ±1 standard error of mean. *water was applied on these dates.

Average soil air filled porosity in 0-10 cm soil depth was 48.1, 43.0, 36.2, 37.9, and 33.9%, in P-0, P-10, P-20, P-40, and P-80, respectively. AFP in 10-20 cm soil depth was 39.0, 23.3, 31.2, 25.9, and 21.2%, in P-0, P-10, P-20, P-40, and P-80, respectively. AFP in 20-30 cm soil depth was 40.7, 31.5, 33.6, 25.8, and 23.4%, in P-0, P-10, P-20, P-40, and P-80, respectively. Average AFP in all soil depths (0-30 cm) of P-10 treatment was not significantly different form P-0 (p=0.05). Average AFP in all soil depths (0-30 cm) of P-20, P-40, and P-80 treatment was significantly different form P-0 (p=0.05). CH_4 uptake was positively correlated with AFP in all soil depths (0-30 cm) and all treatments (Fig. 3). CH_4 uptake decrease significantly in P-80 due to lowest AFP. CH_4 uptake was weakly correlated with AFP (P-80) in all soil depths (0-30 cm). Average AFP in soil depths 0-10, 10-20, and 20-30 cm in NP-0, NP-10, NP-20, NP-40, and NP-80 treatments was (50.2, 46.6, 41.78, 39.5,

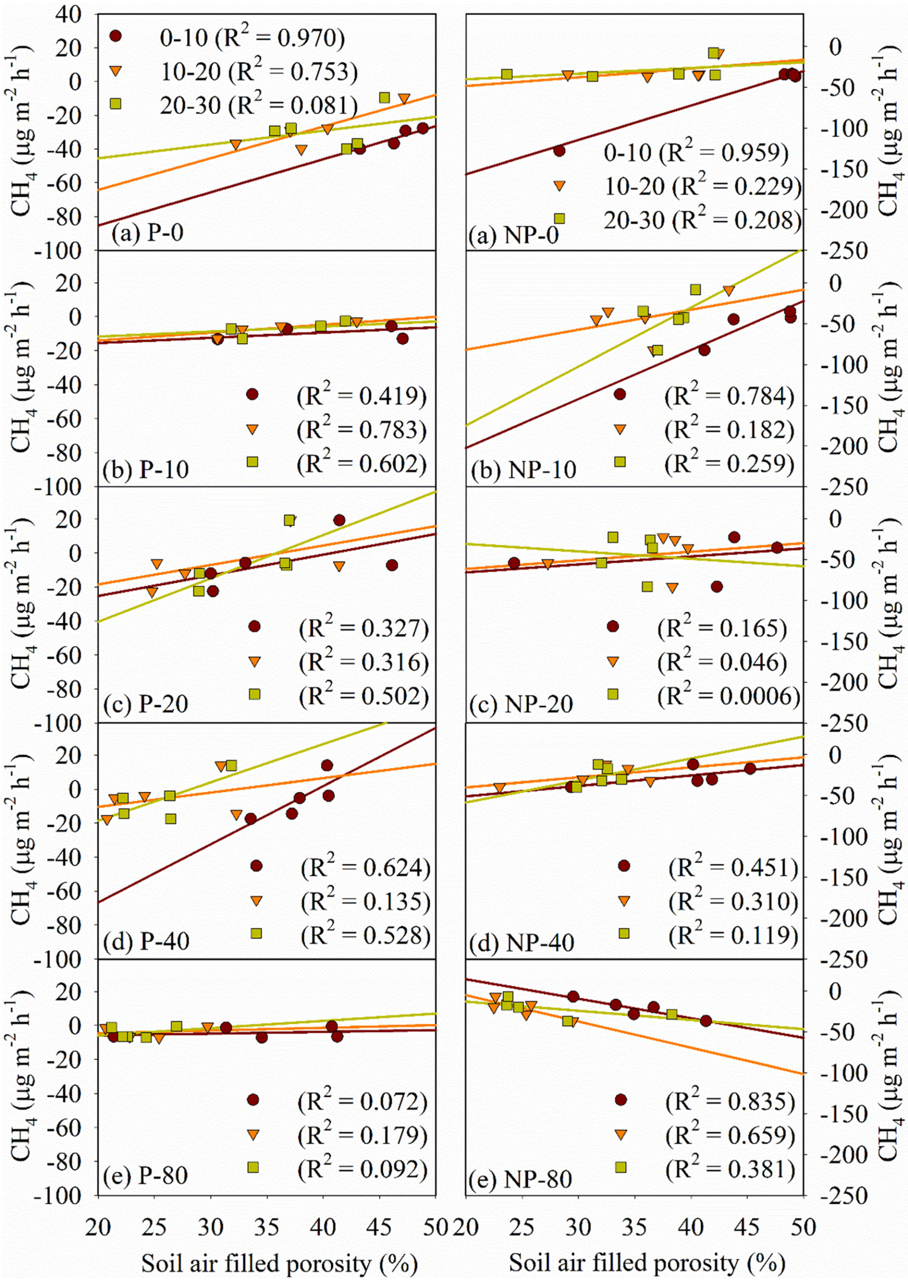

Fig. 3. Relationships (a-e, P (0-80) and a-e, NP (0-80)) between CH_4 emission and soil air filled porosity in different soil depths (0-10, 10-20, and 20-30 cm).

and 35.2%), (37.8, 36.0, 36.3, 31.3, 25.2%), and (35.6, 38.3, 34.8, 32.0, 27.9%), respectively. Average AFP soil depth 0-10 cm in treatments NP-40 and NP-80 were only significantly different from NP-0 (p=0.05). All other treatments NP (10-80) in all depths (0-30 cm) ware not significantly different from NP-0. This indicates soil water content was significantly evaporated form all treatments NP- (10-80) and all soil depths (0-30 cm). CH_4 uptake increased significantly in NP-(10-80) as compare to P- (10-80) due to increase in AFP. CH_4 uptake was positively correlated with AFP in NP-(0-40) and negatively correlated in NP-80 in all soil depths 0-30 cm. Negative correlation in NP-80 was due to lowest AFP as compared to NP-(0-40). Soil CH_4 uptake significantly increased as AFP increased (Díaz et al., 2018).

Relationship between WFPS and CH_4 uptake in all treatments was exactly opposite to relationship between

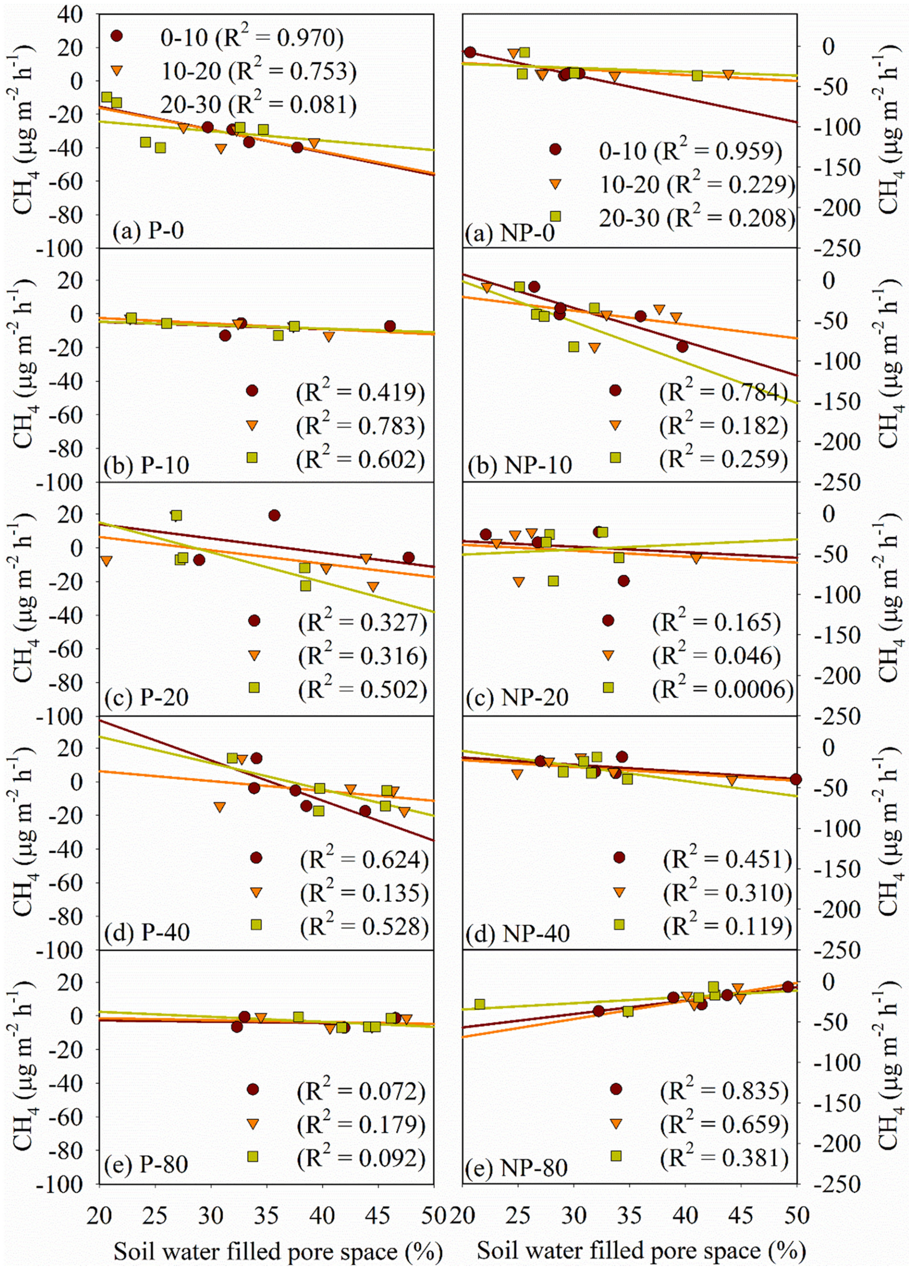

Fig. 4. Relationships (a-e, P-(0-80) and NP-(0-80)) between CH_4 emission and soil water filled pore space in different soil depths (0-10, 10-20, and 20-30 cm).

AFP and CH_4 uptake (Fig. 4). CH_4 uptake was negatively correlated with WFPS in all treatments P-(0-80) and NP-(0-40). CH_4 uptake was positively correlated with WFPS in all treatments NP-80). Positive correlation in NP-80 was due to highest WFPS as compared to NP-(0-40). WFPS in all soil depths (0-30 cm) of P-(10-80) and NP-(10-80) was not significantly different from P-0 and NP-80, respectively (p=0.05).

Immediate effect of water application on CH_4 reduction was prominent. CH_4 uptake in P-(10-80) was extrapolated to actual precipitation in 2017 (Fig. 5). Hourly precipitation varied between 0.0042 to 6.021 mm m^{-2} h^{-1} (Korea Metrological Administration 2017). Estimated daily CH_4 uptake due to precipitation was calculated by extrapolation of field results. Since, average CH_4 uptake in P-(20-80) was not significantly different from each other, CH_4 uptake at P-

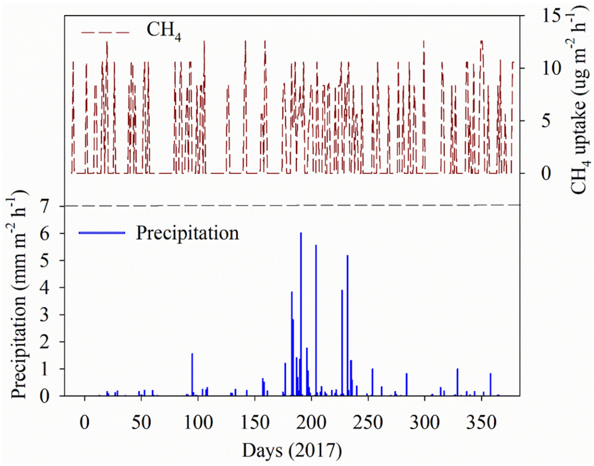

Fig. 5. Average daily precipitation, estimated average daily CH_4 uptake, South Korea.

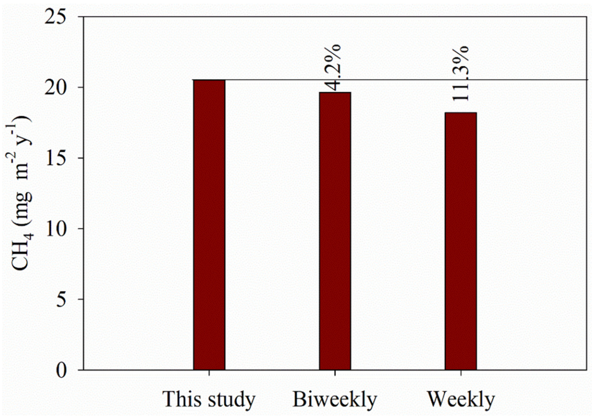

Fig. 6. Estimated total CH_4 uptake (2017) in this study and its difference (%) with weekly and biweekly sampling frequencies.

80 was assumed same for precipitation above 80 mm m^{-2} h^{-1}. Minimal and maximal CH_4 uptake 4.4 and 12.6 μg m^{-2} h^{-1} was observed at precipitation 80 and 0.1 mm m^{-2} h^{-1}, respectively.

Effect of CH_4 sampling frequency (weekly and biweekly) on estimated total CH_4 uptake 2017 was compared (Fig. 6). The most common CH_4 sampling frequencies in temperate forests have been reported weekly and biweekly (Brumme and Borken., 1999; Kim et al., 2016; Kirschke et al., 2013). We assumed that CH_4 uptake was measured on weekly or biweekly from the field. Weekly and biweekly data of daily CH_4 uptake was subtracted from estimated CH_4 uptake in 2017. After subtracting weekly and biweekly CH_4 uptake, total estimated CH_4 uptake was 18.2 and 19.7 mg m^{-2} y^{-1}, respectively. Total estimated CH_4 uptake in 2017 in this

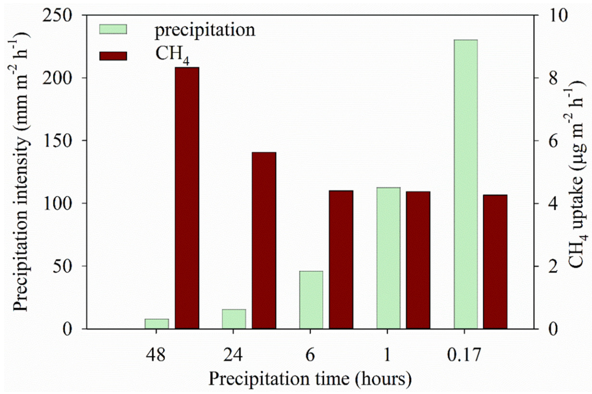

Fig. 7. CH_4 uptake at different intensities of precipitation.

study was decreased by 11.3 and 4.2%. Total estimated CH_4 uptake in this study was not significantly different from weekly and biweekly CH_4 uptake subtracted data (p=0.05).

CH_4 uptake at variable intensity of precipitation was calculated by interapolation of CH_4 uptake results in this study (Fig. 7). Maximal total precipitation in 2017 was 372.7, 370.1, 275, 112.5, and 39.2 mm in 48 h, 24 h, 6 h, 1 h, and 0.17 h, respectively (Korea Metrological Administration 2017). Precipitation intensity increased with decresing total precipitation time. Maximal and minimal precipitation was observed at 0.17 and 48 h, respectively. CH_4 uptake decreased with increasing precipitation intensity. CH_4 uptake in 24, 6, 1, and 0.17 h was 32.5, 47.2, 47.5, and 48.9% lower than CH_4 uptake in 48 h, respectively. CH_4 uptake in 6, 1 and 0.17 h was not significantely different from each other. CH_4 uptake esponse to precipitation intensity was in agreement with CH_4 uptake in this study.

Average annual CH_4 uptake in temperate forests of different countries varied between 240 to 5890 μg m^{-2} day^{-1} as shown in Table 1. Annual CH_4 uptake in the temperate forest of South Korea has been reported 1960 to 2920 μg m^{-2} day^{-1} with an average uptake 2440 μg m^{-2} day^{-1}. Mininal and maximal daily CH_4 uptake in this study was 186.2 and 957.0 μg m^{-2} day^{-1}, respectively. This indicates that the experimental results from this research is not very different from the previous reports. It also confirms that the experimental procedure in this research is sound and comparable to the others. Average CH_4 uptake in (P-0+NP-0) was compared with reduced CH_4 uptake due to variable precipitation intensities as shown in Fig. 8. Hourly CH_4 uptake was converted to daily uptake by multiplied with

Table 1. Summary of published CH_4 uptake in temperate forests

Countries	CH_4 uptake rate (μg m^{-2} day^{-1})		Forest types	References
	Range	Mean		
Canada	40-1100	570	Coniferous Deciduous	Lessard et al. (1994)
Denmark	140-330	240	Coniferous	Ambus and Christensen (1995)
	700-1070	890	Deciduous	Dobbie et al. (1996b)
	670-1370	1020	Coniferous	Priemé and Christensen (1997)
	170-2180	1180	Deciduous	Smith et al. (2000)
Germany	120-960	540	Coniferous	Butterbach-Bahl et al. (1998)
	1970	1970	Coniferous	Steinkamp et al. (2001)
	20-1030	530	Coniferous	Smith et al. (2000)
	30-680	360	Coniferous	Brumme and Borken (1999)
	250-3560	1910	Coniferous	Born et al. (1990)
Ireland	1340	1340	Coniferous	Butterbach-Bahl et al. (1998)
South Korea	1960	1960	Deciduous	Jang et al. (2006)
	2920	2920	Deciduous	Jang et al. (2011)
Norway	800-1400	1100	Coniferous	Sitaula et al. (1995)
	50-1900	970	Coniferous	Smith et al. (2000)
Poland	1000	1000	Mixed	Dobbie et al. (1996b)
	100-4580	2340	Deciduous	Smith et al. (2000)
Scotland	860-1060	960	Coniferous	Macdonald et al. (1996)
	10-3300	1400	Deciduous	Dobbie et al. (1996b)
	2190-2970	2580	Deciduous	Dobbie and Smith (1996a)
	70-1170	620	Coniferous	Macdonald et al. (1997)
Sweden	380	380	Coniferous	Klemedtsson and Klemedtsson (1997)
	2280-3670	700	Coniferous	Smith et al. (2000)
	0-600	300	Deciduous	Yavitt et al. (1993)
	2100-6900	4500	Deciduous	Goldman et al. (1995)
Japan	7600	7600	Mixed	Ishizuka et al. (2000)
	5890	5890	Coniferous	Tamai et al. (2003)
Russia	2950-8960	5010	Coniferous	Nakano et al. (2004)
UK	1080-3240	1080	Mixed	Smith et al. (2000)
	1060-2650	1610	Deciduous	Bradford et al. (2001)

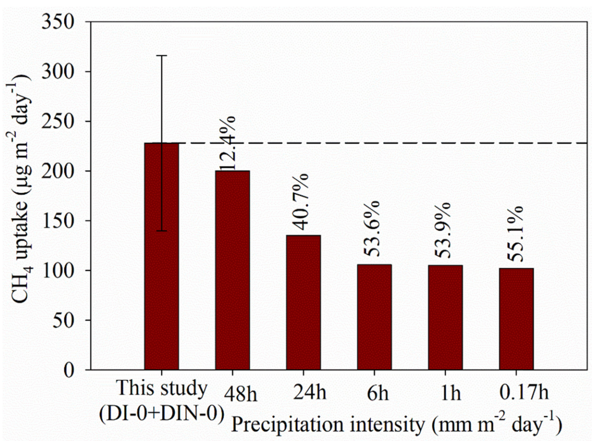

Fig. 8. Comparison of CH_4 uptake in this study with reduced CH_4 uptake due to variable precipitation intensity. Error bar represent ±1 standard error of mean.

twentyfour hours. Daily CH_4 uptake decreased with increasing precipitation intensity from 48 h to 6 h. CH_4 uptake reduction in 6 h, 1 h, and 0.17 h was not significantly different from eachother. Maximal and minimal decreased in CH_4 uptake was observed at 0.17h and 48h precipitation intensity, respectively.

4. Conclusion

We measured CH_4 uptake in temperate plantation from different treatments of variable precipitation, i.e., 0, 10, 20, 40, and 80 mm m^{-2} day^{-1}. CH_4 flux was observed immediately after water application in P-(10-80) and observed after two days interval when water was not applied NP-(0-80). CH_4 uptake in P-(10-80) was significantly lower than NP-(10-80). In our first hypothesis we assumed CH_4 emission may occur because rain water will replace CH_4 present in subsoil. Throughout the experimental period temperate forest soil was CH_4 sink rather than source. CH_4 uptake decreased significantly due to increasing water application in P-(10-80). We also hypothesized that CH_4 uptake will decrease with increasing WFPS, in P-80 WFPS was 53% higher than P-0 CH_4 uptake decreased 85.6% in P-80. This decrease in CH_4 uptake was positively correlated with air filled porosity and negatively correlated with water filled pore space. Soil texture at experimental site was sandy loam, which is relatively coarse texture further studies needed to establish if the relationship between variable precipitation to CH_4 uptake holds true across different soil texture classes. Our results can be used as a reference for regions with similar conditions. This study demonstrated the effects of variable precipitation on net daily CH_4 uptake and it may help in calculating more accurate net annual CH_4 sink in temperate forests in the world.

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