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Dynamics of soil carbon dioxide during a storm event

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Introduction

In general, soil carbon dioxide (CO_2) is produced by two major processes, the respiration of plant roots and the decomposition of soil organic substances. Because the produced CO_2 is essentially biogenic, its concentration is affected by soil environmental factors such as temperature and moisture status, as well as the amount of CO_2 sources.

Many studies showed clear seasonal trends of CO_2 concentration in soil atmosphere corresponding to seasonal variation of soil temperature (*e.g.* Gunn and Trudgill, 1982; Buyanovsky and Wagner, 1983; Fernandez and Kosian, 1987; Castelle and Galloway, 1990; Hamada and Tanaka, 1997; 2001). In contrast, few studies reported the daily variation due to much less fluctuation in soil environmental conditions as well as in the CO_2 concentration. During a storm event, however, soil water content rapidly increases so that CO_2 production rate could considerably change within a short period. In some cases, soil temperature also changes as the wetting-front percolates downward through the soil profile. Moreover, the increase of soil water inevitably accompanies the decrease of soil air. This would temporarily heighten the CO_2 concentration because CO_2 diffusion through soil air toward the atmosphere is inhibited.

From the hydrological point of view, soil CO_2 is one of the major sources of dissolved carbonate species in groundwater. Several studies using stable carbon isotope ratio suggested that the origin of dissolved carbonate species in many aquifers was not the carbonate minerals contained in the aquifers but the biogenic soil CO_2 (*e.g.* Wood and Petraitis, 1984; Mizutani and Yamamoto, 1993; Ishii *et al.*, 1996). Large storm events often cause intensive groundwater recharge, so that CO_2 concentration during the storm event is important to evaluate the recharge of carbonate species into groundwater.

In this report we show the results of an intensive field measurement on CO_2 concentration in soil air during a large storm event and discuss the influences of soil environmental factors on the CO_2 dynamics.

Methods

An observation site was established in the middle of a small coniferous forest, which consists of red pine and some other broadleaf trees and is adjoining on the south side of the Terrestrial Environment Research Center, University of Tsukuba. The center is located at N36°7' E140°6' and at 27 m a.m.s.l., about 50 km northeast of Tokyo. Based on the long-term meteorological data at the center, the mean annual air temperature is 13.3°C and annual precipitation is in the range of 1200 to 1600 mm. The *Kanto Loam*, blackish and loamy volcanic ash soil, covers the study area 1-2 m thick, overlying the *Joso Clay* layer.

The concentration of CO_2 in soil air was measured according to the method presented by Hamada and Tanaka (1995). Soil air collection probes were installed to the depths ranging from 0.1 to 1.0 m. Soil air was extracted by a hand pump through the collection probe and directly introduced into a CO_2 detection tube (Gastec GV-100), which is a kind of disposable chromatographic glass tubes widely used for soil CO_2 measurement (*e.g.* Miotke, 1974; Gunn and Trudgill, 1982; Buyanovsky and Wagner, 1983; Fernandez and Kosian, 1987; Castelle and Galloway, 1990; Zabowski and Sletten, 1991; Fernandez *et al.*, 1993). The measured value by the tube was corrected to the true value according to Hamada and Tanaka (1995).

Manual-type tensiometers were installed to the depths corresponding to the CO_2 measurement. Pressure head of soil water was converted to volumetric water content using soil water retention curves obtained beforehand and shown in Hamada *et al.* (1998). Temperatures in the atmosphere and in the soil at several depths were automatically recorded every two hours. The depth of water table in an observation well was also measured manually.

To show clearly the effect of the increase of soil water, the relative diffusion coefficient D_s/D_a, the ratio of diffusion coefficient of CO_2 in soil (D_s) to that in free air (D_a), was calculated by the following equation (Millington, 1959; Millington and Quirk, 1961):

$$D_s/D_a = \frac{\theta_a^2}{\theta_t^{2/3}}$$

where θ_a and θ_t are air-filled porosity and total porosity of the soil, respectively. The use of the equation was described as well by Hamada (1999).

Results and discussion

Field observation was performed from August 26 to 28, 1993, during a storm event associated with Typhoon No. 11, which directly hit the Metropolitan area of Japan. Two continuous rainfalls were observed during the event. The first one brought a rainfall of 25.6 mm in the evening on August 26; the second one was much heavier, 149.4 mm in the daytime on August 27. The storm event produced 175-mm rainfalls in total.

Field observation began at the noon on August 26 and continued for 48 hours until the noon on August 28. Manual measurement of CO_2 concentration in soil air and the environmental factors were made eleven times during the storm event. All the results are compiled in Fig. 1. The eleven profiles of CO_2 concentration, three-phase distribution, and D_s/D_a are plotted against depth separately. Temporal variations of rainfall, atmospheric and soil temperature, and the depth of water table are also shown. Profiles 1 to 4 correspond to the first continuous rainfall, while Profiles 5 to 11 show the soil conditions related to the second one.

Relatively small amount of rainfall on August 26 caused slight increase in CO_2 concentration throughout the profile (Profiles 1 to 3). After the rain stopped, the concentration dropped (Profiles 3 to 4). Volumetric water content of the top 0.3 m soil changed similarly during this period, influencing D_s/D_a at these depths. Little change was observed in soil temperature. The temporary increase in CO_2 could be attributed to the inhibition of soil CO_2 from diffusing into the atmosphere due to the temporary drop of D_s/D_a. On the other hand, the observed profiles indicate that the change in diffusion coefficient only in the topsoil could cause CO_2 increase in the whole soil profiles. This suggests the importance of soil physical characteristics near the ground surface to evaluate the CO_2 concentration in deep soils.

During a short unrainy period between the two rainfalls (Profiles 4 to 5), CO_2 concentration slightly changed at some depths but no consistent trend was observed. As the second rainfall much heavier than the first one continued, CO_2 concentration and the volumetric water content began to rise again. At the peak of rainfall intensity (Profiles 7 to 9), the conscentration rapidly increased and reached around 0.5% below 0.2 m deep. The D_s/D_a was almost zero throughout the soil profile due to nearly saturated conditions. At that time water table also began to rise. Finally the water table rose from 1.73 m to 0.84 m below the ground surface during the storm event. Prior to the groundwater rise, the increase in soil temperature also started. At depths of 0.1 and 0.5 m, the temperatures rose from 22.6 and 19.4°C to 23.5 and 21.6°C, respectively. After the second rain stopped, the decline in volumetric water content and the complementary increase in D_s/D_a were observed at shallow depths (Profiles 9 to 11). Notwithstanding, soil CO_2 kept in high concentrations around 0.5% even at the last measurement (Profile 11), at which more than half a day had passed after the rain ceased.

Comparing to the first rain, soil CO_2 dynamics during the second rain was different in two points. First is that the magnitude of CO_2 increase was much larger; the second is that the high CO_2 concentration was kept for some time after the storm. The former must be related to much higher volumetric water content and the D_s/D_a nearly zero during the heavy rain. The latter could partly be attributed to soil physical properties such as the hysteresis in soil water retention, but some other biotic processes in the soil activated by the increase of temperature and moisture content would play a role. In addition, the change in soil water chemistry and the supply of fresh soluble organic substance might occur and affect the CO_2 production. Indeed, the increase of soil water alone can promote the biological activities in a dry soil. In the summer of 1993, however, the climate condition was extremely moist so that the direct effect of increasing soil water on biotic CO_2 production was probably smaller than that in dry summers. Consequently, the high concentrations after the storm should be attributed not only to the increase of soil water content, but also the changes in temperature and water chemistry which could encourage the CO_2 production. Nevertheless, it is important to notice that soil temperatures do not always rise during a storm event. If the infiltration water is cooler than the soil, the temperature will be lowered. Therefore, the effect of temperature change during a storm depends on the temperature of the infiltration water. The increase of soil water simply enhances the CO_2 concentration except for badly-drained clayey soils in which aerobic biological processes are inhibited.

In this study, the interval of CO_2 measurement was limited in 2-4 hours because we had to extract soil air at least 100 cm^3 from each depth every time by hand. The collection of soil air more or less disturbs CO_2 distribution. For further and more frequent observations, some methods of CO_2 measurement without soil air collection are needed, like a CO_2 sensor which can be installed directly to the soil and automatically measures and records the CO_2 concentration. Dynamics of CO_2 during a storm event is important to know the supply of dissolved carbonate species to groundwater. In future,

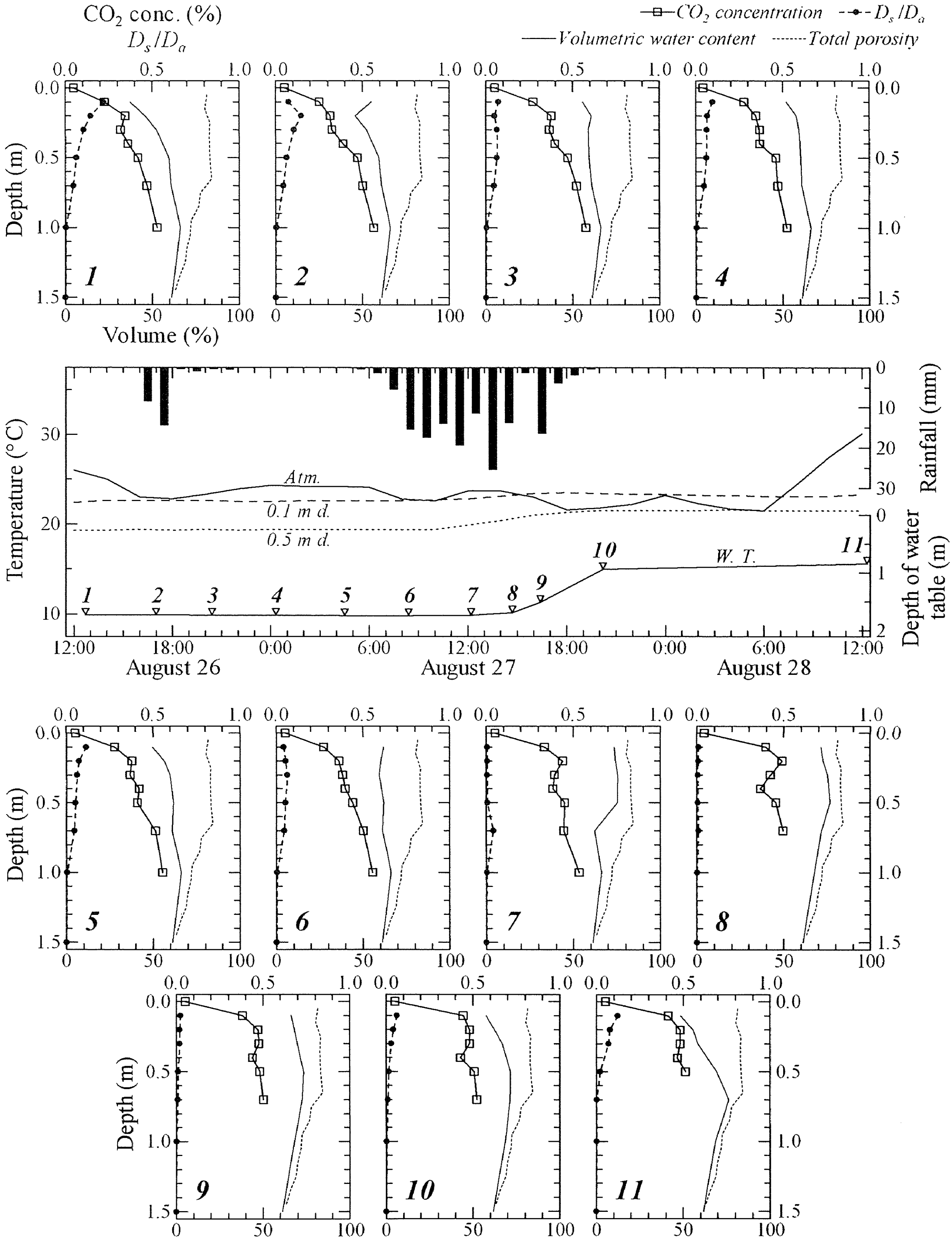

Fig. 1. Temporal variations and observed profiles of CO$_2$ concentration in soil air and other environmental factors during the storm event associated with Typhoon No. 11, 1993.

storm observations should be performed under different climate, vegetation, soil, and rainfall intensity using automated devices.

Conclusions

Based on the results of field observation on CO_2 concentration in soil air and other environmental factors in a forest soil during a storm event, the following concluding remarks are derived. Relatively small amount of rainfall could heighten the CO_2 concentration throughout the soil profile by decreasing the diffusion coefficient in the topsoil, but its effect is likely to disappear quickly. Heavy storms which are accompanied by large changes in soil temperature and/or soil water chemistry cause larger and more continuous change in the CO_2 concentration, by strongly inhibiting CO_2 diffusion at the beginning and altering CO_2 production at the end.

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References

Buyanovsky, G. A. and Wagner, G. H. (1983): *Soil Sci. Soc. Am. J.*, **47**, 1139-1145.

Castelle, A. J. and Galloway, J. N. (1990): *Soil Sci. Soc. Am. J.*, **54**, 252-257.

Fernandez, I. J. and Kosian, P. A. (1987): *Soil Sci. Soc. Am. J.*, **51**, 261-263.

Fernandez, I. J., Son, Y., Kraske, C. R., Rustad, L. E. and David, M. B. (1993): *Soil Sci. Soc. Am. J.*, **57**, 1115-1121.

Gunn, J. and Trudgill, S. T. (1982): *Catena*, **9**, 81-94.

Hamada, Y. (1999): Ph.D. thesis, University of Tsukuba, 194 p.

Hamada, Y., Indra, A. R. F. and Tanaka, T. (1998): *Bull. Environ. Res. Center*, **23**, 1-10 (*in Japanese*).

Hamada, Y. and Tanaka, T. (1995): *J. Jpn. Assoc. Hydrol. Sci.*, **25**, 123-130 (*in Japanese with English abstract*).

Hamada, Y. and Tanaka, T. (1997): *J. Jpn. Assoc. Hydrol. Sci.*, **27**, 3-16 (*in Japanese with English abstract*).

Hamada, Y. and Tanaka, T. (2001): *Hydrol. Processes*, **15**, 1829-1845.

Ishii, T., Kazahaya, K., Yasuhara, M., Marui, A. and Sato, T. (1996): *Geogr. Rev. Jap.*, **69A**, 493-503 (*in Japanese with English abstract*).

Millington, R. J. (1959): *Science*, **130**, 100-102.

Millington, R. J. and Quirk, J. P. (1961): *Trans. Faraday Soc.*, **57**, 1200-1207.

Miotke, F. D. (1974): *Carbon dioxide and the soil atmosphere*. Abh. Karst-u Hohlenkunde Ser. A, 9, 49 p.

Mizutani, Y. and Yamamoto, K. (1993): *J. Groundwater Hydrol.*, **35**, 77-86 (*in Japanese with English abstract*).

Wood, W. W. and Petraitis, M. J. (1984): *Water Resour. Res.*, **20**, 1193-1208.

Zabowski, D. and Sletten, R. S. (1991): *Soil Sci. Soc. Am. J.*, **55**, 1456-1461.

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